HUMAN ANATOMY

Whitney Menefee, Julie Jenks, Chiara Mazzasette, &

Kim-Leiloni Nguyen

Reedley College, Butte College, Pasadena City College,
& Mt. San Antonio College

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Reedley College, Butte College, Pasadena City College, & Mt. San Antonio College via ASCCC Open Educational Resources Initiative

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Preface and Acknowledgements

The purpose of this textbook is to serve as a resource for students who are taking a first semester human anatomy course. All efforts were made to ensure the material covered in this resource is consistent, accurate, and accessible. This material was also designed to be equitable, diverse, and inclusive.

Image Accessibility

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Terminology

Bolded text is used to indicate vocabulary terminology. Students are encouraged to use this formatting to help them identify key words to know for learning anatomy.

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Whitney Menefee is a full-time biology instructor at Reedley College, where she teaches a variety of biology courses including human anatomy. She was born and raised in the Central Valley of California and is an alumnus of Reedley College (A.S. Biological Science) and California State University, Fresno (B.A. Natural Science, M.S. Biology). She has over 10 years of teaching experience and has been involved in the development of several OERs in the field of biology. She enjoys outdoor activities, especially boating with her husband and daughter.

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1: AN INTRODUCTION TO THE HUMAN BODY

1.1: Introduction to the Human Body

1.2: Overview of Anatomy and Physiology

1.3: Structural Organization of the Human Body

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1.1: Introduction to the Human Body

Figure 1.1.1: Blood Pressure. The image above shows a patient getting their blood pressure read by a health care professional. A proficiency in anatomy and physiology is fundamental to any career in the health professions. (Image credit:"100 Blood Pressure" by OpenStax and Bryan Mason/flickr is licensed under CC BY 4.0)

Chapter Learning Objectives

After studying this chapter, you will be able to:

- Distinguish between anatomy and physiology, and identify several branches of each
- Describe the structure of the body, from simplest to most complex, in terms of the six levels of organization
- Identify the functional characteristics of human life
- Define homeostasis and explain its importance to normal human functioning
- Use appropriate anatomical terminology to identify key body structures, body regions, and directions in the body

Though you may approach the subjects of anatomy and physiology strictly as a requirement for your field of study, the knowledge you gain in these subjects will serve you well in many aspects of your life. An understanding of anatomy and physiology is not only fundamental to any career in the health professions, but it can also benefit your own health. Familiarity with the human body can help you make healthful choices and prompt you to take appropriate action when signs of illness arise. Your knowledge in this field will help you understand news about nutrition, medications, medical devices, and procedures and help you understand genetic or infectious diseases. At some point, everyone will have a problem with some aspect of his or her body and your knowledge can help you to be a better parent, spouse, partner, friend, colleague, or caregiver.

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1.2: Overview of Anatomy and Physiology

By the end of the section, you will be able to:

- Compare and contrast anatomy and physiology, including their specializations and methods of study
- Discuss the fundamental relationship between anatomy and physiology

Human **anatomy** is the scientific study of the body's structures. Some of these structures are very small and can only be observed and analyzed with the assistance of a microscope. Other larger structures can readily be seen, manipulated, measured, and weighed. The word "anatomy" comes from a Greek root that means "to cut apart." Human anatomy was first studied by observing the exterior of the body and observing the wounds of soldiers and other injuries. Later, physicians were allowed to dissect bodies of the dead to augment their knowledge. When a body is dissected, its structures are cut apart in order to observe their physical attributes and their relationships to one another. Dissection is still used in medical schools, anatomy courses, and in pathology labs. In order to observe structures in living people, however, a number of imaging techniques have been developed. These techniques allow clinicians to visualize structures inside the living body such as a cancerous tumor or a fractured bone.

Like most scientific disciplines, anatomy has areas of specialization. **Gross anatomy** is the study of the larger structures of the body, those visible without the aid of magnification (Figure 1.2.1.a). Macro- means "large," thus, gross anatomy is also referred to as macroscopic anatomy. In contrast, micro- means "small," and **microscopic anatomy** is the study of structures that can be observed only with the use of a microscope or other magnification devices (Figure 1.2.1.b). Microscopic anatomy includes cytology, the study of cells and histology, the study of tissues. As the technology of microscopes has advanced, anatomists have been able to observe smaller and smaller structures of the body, from slices of large structures like the heart, to the three-dimensional structures of large molecules in the body.

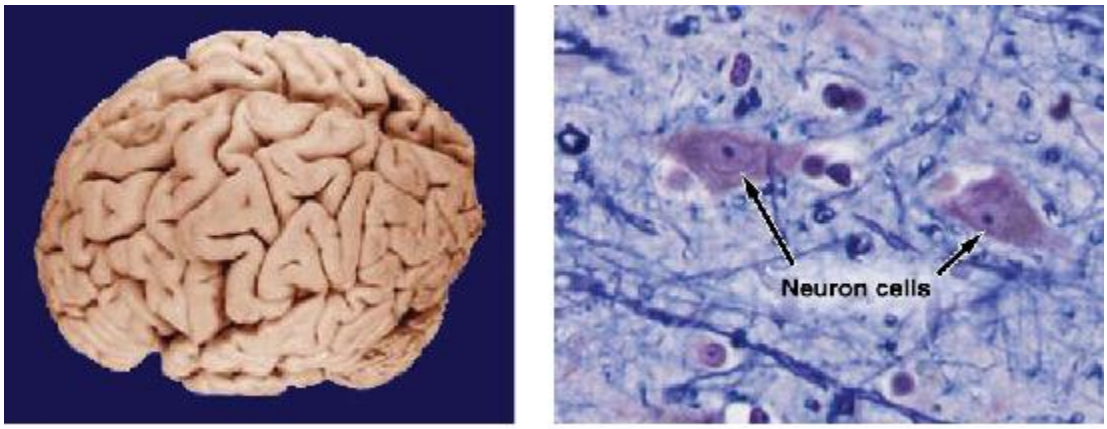

Figure 1.2.1: Gross and Microscopic Anatomy. (a) Gross anatomy considers large structures such as the brain. (b) Microscopic anatomy can deal with the same structures, though at a different scale. This is a micrograph of nerve cells from the brain. LM × 1600. (Image credits (a) "Brain" by WriterHound is licensed under CC BY 3.0 (b) Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Anatomists take two general approaches to the study of the body's structures: regional and systemic. **Regional anatomy** is the study of the interrelationships of all of the structures in a specific body region, such as the abdomen. Studying regional anatomy helps us appreciate the interrelationships of body structures, such as how muscles, nerves, blood vessels, and other structures work together to serve a particular body region. In contrast, **systemic anatomy** is the study of the structures that make up a discrete body system—that is, a group of structures that work together to perform a unique body function. For example, a systemic anatomical study of the muscular system would consider all of the skeletal muscles of the body.

Whereas anatomy is about structure, physiology is about function. Human **physiology** is the scientific study of the chemistry and physics of the structures of the body and the ways in which they work together to support the functions of life. Much of the study of physiology centers on the body's tendency toward homeostasis. **Homeostasis** is the state of steady internal conditions maintained by living things. The study of physiology certainly includes observation, both with the naked eye and with microscopes,

as well as manipulations and measurements. However, current advances in physiology usually depend on carefully designed laboratory experiments that reveal the functions of the many structures and chemical compounds that make up the human body.

Like anatomists, physiologists typically specialize in a particular branch of physiology. For example, neurophysiology is the study of the brain, spinal cord, and nerves and how these work together to perform functions as complex and diverse as vision, movement, and thinking. Physiologists may work from the organ level (exploring, for example, what different parts of the brain do) to the molecular level (such as exploring how an electrochemical signal travels along nerves).

Form is closely related to function in all living things. For example, the thin flap of your eyelid can snap down to clear away dust particles and almost instantaneously slide back up to allow you to see again. At the microscopic level, the arrangement and function of the nerves and muscles that serve the eyelid allow for its quick action and retreat. At a smaller level of analysis, the function of these nerves and muscles likewise relies on the interactions of specific molecules and ions. Even the three-dimensional structure of certain molecules is essential to their function.

While extensive study of both anatomy and physiology is required to fully understand the overall workings of the human body, this textbook will focus mainly on anatomy. By first studying anatomy, you will gain a comprehensive understanding of the structural characteristics of the human body, which will build a solid foundation for your proceeding studies of human physiology.

Concept Review

Human anatomy is the scientific study of the body's structures. In the past, anatomy has primarily been studied via observing injuries, and later by the dissection of anatomical structures of cadavers, but in the past century, computer-assisted imaging techniques have allowed clinicians to look inside the living body. Human physiology is the scientific study of the chemistry and physics of the structures of the body. Physiology explains how the structures of the body work together to maintain life.

Review Questions

Q. Which of the following specialties might focus on studying all of the structures of the ankle and foot?

A. microscopic anatomy

B. muscle anatomy

C. regional anatomy

D. systemic anatomy

Answer

Answer: C

Q. A scientist wants to study how the body uses foods and fluids during a marathon run. This scientist is most likely a(n) _____.

A. exercise physiologist

B. microscopic anatomist

C. regional physiologist

D. systemic anatomist

Answer

Answer: A

Critical Thinking Questions

Q. Name at least three reasons to study anatomy and physiology.

Answer

A. An understanding of anatomy and physiology is essential for any career in the health professions. It can also help you make choices that promote your health, respond appropriately to signs of illness, make sense of health-related news, and help you in your roles as a parent, spouse, partner, friend, colleague, and caregiver.

Q. For whom would an appreciation of the structural characteristics of the human heart come more easily: an alien who lands on Earth, abducts a human, and dissects his heart, or an anatomy and physiology student performing a dissection of the heart on her very first day of class? Why?

Answer

A. A student would more readily appreciate the structures revealed in the dissection. Even though the student has not yet studied the workings of the heart and blood vessels in her class, she has experienced her heart beating every moment of her life, has probably felt her pulse, and likely has at least a basic understanding of the role of the heart in pumping blood throughout her body. This understanding of the heart's function (physiology) would support her study of the heart's form (anatomy).

Glossary

anatomy

science that studies the form and composition of the body's structures

gross anatomy

study of the larger structures of the body, typically with the unaided eye; also referred to as macroscopic anatomy

homeostasis

steady state of body systems that living organisms maintain

microscopic anatomy

study of very small structures of the body using magnification

physiology

science that studies the chemistry, biochemistry, and physics of the body's functions

regional anatomy

study of the structures that contribute to specific body regions

systemic anatomy

study of the structures that contribute to specific body systems

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1.3: Structural Organization of the Human Body

By the end of the section, you will be able to:

- Describe the structure of the human body in terms of six levels of organization
- List the eleven organ systems of the human body and identify at least one organ and one major function of each

Before you begin to study the different structures and functions of the human body, it is helpful to consider its basic architecture; that is, how its smallest parts are assembled into larger structures. It is convenient to consider the structures of the body in terms of fundamental levels of organization that increase in complexity: atoms, molecules, organelles, cells, tissues, organs, organ systems, and organisms (Figure 1.3.1).

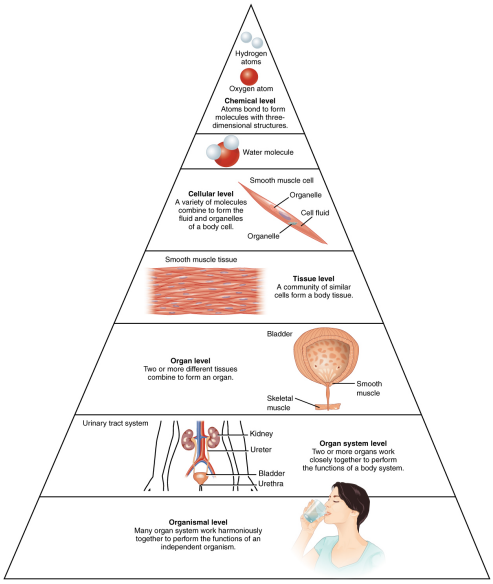

Figure 1.3.1: Levels of Structural Organization of the Human Body. The organization of the body often is discussed in terms of six distinct levels of increasing complexity, from the smallest chemical building blocks to a unique human organism. (Image credit: "Levels of Org in Body" by OpenStax is licensed under CC BY 4.0)

The Levels of Organization

To study the smallest level of organization, scientists consider the simplest building blocks of matter: atoms and molecules. The **chemical level** of organization considers these two building block as atoms bond to form molecules with three dimensional structures. All matter in the universe is composed of one or more unique pure substances called elements, familiar examples of which are hydrogen, oxygen, carbon, nitrogen, calcium, and iron. The smallest unit of any of these pure substances (elements) is an atom. Atoms are made up of subatomic particles such as the proton, electron and neutron. Two or more atoms combine to form a molecule, such as the water molecules, proteins, and sugars found in living things. Molecules are the chemical building blocks of all body structures.

The **cellular level** is considered when a variety of molecules combine to form the fluid and organelles of a body cell. A **cell** is the smallest independently functioning unit of a living organism. Even bacteria, which are extremely small, independently-living organisms, have a cellular structure. Each bacterium is a single cell. All living structures of human anatomy contain cells, and almost all functions of human physiology are performed in cells or are initiated by cells. A human cell, such as a smooth muscle cell, typically consists of flexible membranes that enclose **cytoplasm**, a water-based cellular fluid together with a variety of tiny functioning units called **organelles**.

The **tissue level** can be studied when a community of similar cells form a body tissue. A **tissue** is a group of many similar cells (though sometimes composed of a few related types) that work together to perform a specific function. For example, when many

smooth muscle cells come together both structurally and functionally, these cell collectively form a layer of smooth muscle tissue.

An **organ** is an anatomically distinct structure of the body composed of two or more tissue types, which forms the **organ level** of organization. Each organ performs one or more specific physiological functions. The human bladder, which is composed of smooth muscle tissue, transitional epithelial tissue, and several types of connective tissue serves the function of storing urine produced by the kidneys.

An **organ system level** is a group of organs that work together to perform major functions or meet physiological needs of the body. In the organ example above, both the kidneys and the bladder are organs of the urinary system. The kidneys produce urine, which is moved to the bladder by the ureters. Urine can then leave the bladder, and the body, through the urethra. These four organs work together to rid the body of liquid waste.

This book covers eleven distinct organ systems in the human body (Figure 1.3.2 and Figure 1.3.3). Assigning organs to organ systems can be imprecise since organs that "belong" to one system can also have functions integral to another system. In fact, most organs contribute to more than one system.

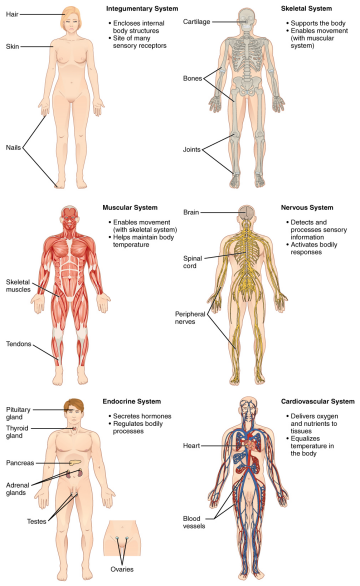

Figure 1.3.2: Organ Systems of the Human Body. Organs that work together are grouped into organ systems. Organ systems of the human body seen in the image above include the integumentary system, skeletal system, muscular system, nervous system, endocrine system, and the cardiovascular system. (Image credit: "Organ Systems I" by OpenStax is licensed under CC BY 3.0)

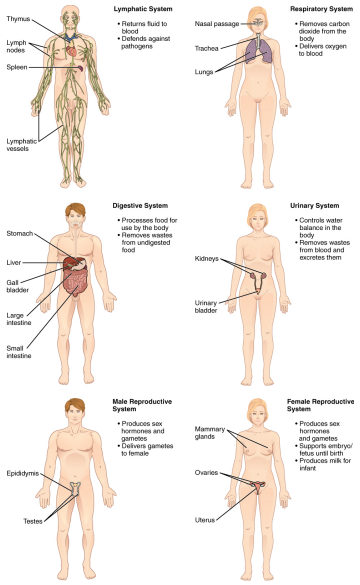

Figure 1.3.3: Organ Systems of the Human Body (continued). Organs that work together are grouped into organ systems. Organ systems of the human body seen in the image above include the lymphatic system, respiratory system, digestive system, urinary system and reproductive systems. (Image credit: "Organ Systems II" by OpenStax is licensed under CC BY 3.0)

The eleven distinct organ systems in the human body covered in this book seen in Figure 1.3.2 and Figure 1.3.3 include:

- The **integumentary system** functions to enclose internal body structures and is the site of many sensory receptors. Some organs of this system include skin, hair, and nails.
- The **skeletal system** supports the body and enables movement (with the help of the muscular system). Bones are the major organs of this system.
- The **muscular system** enables movement (with the help of the skeletal system) and also helps to maintain body temperature. Skeletal muscles are the major organs of this system, which are connected to bones by tendons.
- The **nervous system** detects and processes sensory information and activates bodily responses. The main organs that perform these functions are the brain, spinal cord, and peripheral nerves.
- The **endocrine system** is responsible for secreting hormones to regulate bodily processes. Some major organs of the endocrine system include the pituitary gland, thyroid gland, pancreas, adrenal glands, testes, and ovaries.
- The **cardiovascular system** delivers oxygen and nutrients to tissues while also removing wastes, and helps to equalize temperature in the body. This is accomplished by the heart and blood vessels.
- The **lymphatic system** functions to return fluids back to the blood and defends the body against pathogens. Major structures and organs of this system include the thymus, lymph nodes, the spleen, and lymphatic vessels.
- The **respiratory system** delivers oxygen to blood and removes carbon dioxide from the body. The nasal cavity, trachea, and lungs all work together to carry out these functions.
- The **digestive system** processes food for use by the body and removes wastes from undigested foods. Some organs of the digestive system include the stomach, liver, gallbladder, large intestine, and small intestine.
- The **urinary system** controls water balance in the body and removes wastes from the blood and excretes them. The kidneys and bladder are major organs of this system.
- The **reproductive system** produces sex hormones and gametes. The male reproductive system also functions to deliver gametes to the female, while the female reproductive system supports an embryo/fetus until birth and produces milk for an infant. Organs of the male reproductive system include the epididymis and testes. Organs of the female reproductive system include the mammary glands, ovaries, and the uterus.

While only some functions and major organs of each system have been listed above, each of these organ systems will be covered in much greater detail in the following chapters of this book.

The **organism level**, when many organ systems work harmoniously together to perform the functions of an independent organism, is the highest level of organization in the study of human anatomy. An **organism** is a living being that has a cellular structure and that can independently perform all physiologic functions necessary for life. In multicellular organisms, including humans, all cells, tissues, organs, and organ systems of the body work together to maintain the life and health of the organism.

Concept Review

Life processes of the human body are maintained at several levels of structural organization. These include the chemical, cellular, tissue, organ, organ system, and the organism level. Higher levels of organization are built from lower levels. Therefore, molecules combine to form cells, cells combine to form tissues, tissues combine to form organs, organs combine to form organ systems, and organ systems combine to form organisms.

Review Questions

Q. The smallest independently functioning unit of an organism is a(n) _____.

A. cell

B. molecule

C. organ

D. tissue

Answer

Answer: A

Q. A collection of tissues that performs a specific function is an _____.

A. organ

B. organelle

C. organism

D. organ system

Answer

Answer: A

Q. The body system responsible for structural support and movement is the _____.

A. cardiovascular system

B. endocrine system

C. muscular system

D. skeletal system

Answer

Answer: D

Critical Thinking Questions

Q. Name the six levels of organization of the human body.

Answer

A. Chemical, cellular, tissue, organ, organ system, organism.

Q. The female ovaries and the male testes are a part of which body system? Can these organs be members of more than one organ system? Why or why not?

Answer

A. The female ovaries and the male testes are parts of the reproductive system. But they also secrete hormones, as does the endocrine system, therefore ovaries and testes function within both the endocrine and reproductive systems.

Glossary

cardiovascular system
organ system that delivers oxygen and nutrients to tissues while also removing wastes, and helps to equalize temperature in the body

cell
smallest independently functioning unit of all organisms; in animals, a cell contains cytoplasm, composed of fluid and organelles

cellular level
a variety of molecules combine to form the fluid and organelles of a body cell

chemical level
atoms bond to form molecules with three dimensional structures

cytoplasm
a water-based cell fluid

digestive system
organ system that processes food for use by the body and removes wastes from undigested foods

endocrine system
organ system that is responsible for secreting hormones to regulate bodily processes

integumentary system
organ system that functions to enclose internal body structures and is the site of many sensory receptors

lymphatic system
organ system that returns fluids back to the blood and defends the body against pathogens

muscular system
organ system that enables movement and maintains body temperature

nervous system
organ system that detects and processes sensory information and activates bodily responses

organ
functionally distinct structure composed of two or more types of tissues

organ level
two or more different tissues combine to form an organ

organ system level
group of organs that work together to carry out a particular function

organelles
a variety of tiny functioning units within a cell

organism
living being that has a cellular structure and that can independently perform all physiologic functions necessary for life

reproductive system
: organ system that produces sex hormones and gametes

respiratory system
: organ system that delivers oxygen to blood and removes carbon dioxide from the body

skeletal system
: organ system that supports the body and enables movement

tissue
: group of similar or closely related cells that act together to perform a specific function

tissue level
: a community of similar cells form a body tissue

urinary system
: organ system that controls water balance in the body and removes wastes from the blood and excretes them

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1.4: Functions of Human Life

By the end of the section, you will be able to:

- Explain the importance of organization to the function of the human organism
- Distinguish between metabolism, anabolism, and catabolism
- Provide at least two examples of human responsiveness and human movement
- Compare and contrast growth, differentiation, and reproduction

The different organ systems each have different functions and therefore unique roles to perform in physiology. These many functions can be summarized in terms of a few that we might consider definitive of human life: organization, metabolism, responsiveness, movement, development, and reproduction.

Organization

A human body consists of trillions of cells organized in a way that maintains distinct internal compartments. These compartments keep body cells separated from external environmental threats and keep the cells moist and nourished. They also separate internal body fluids from the countless microorganisms that grow on body surfaces, including the lining of certain tracts, or passageways. The intestinal tract, for example, is home to even more bacteria cells than the total of all human cells in the body, yet these bacteria are outside the body and cannot be allowed to circulate freely inside the body.

At the cellular level, all cells have a cell membrane (also referred to as the plasma membrane) that keeps the intracellular environment—the fluids and organelles—separate from the extracellular environment. Blood vessels keep blood inside a closed circulatory system, and nerves and muscles are wrapped in connective tissue sheaths that separate them from surrounding structures. In the chest and abdomen, a variety of internal membranes keep major organs such as the lungs, heart, and kidneys separate from others.

The body's largest organ system is the integumentary system, which includes the skin and its associated structures, such as hair and nails. The surface tissue of skin is a barrier that protects internal structures and fluids from potentially harmful microorganisms and other toxins.

Metabolism

The first law of thermodynamics holds that energy can neither be created nor destroyed—it can only change form. Your basic function as an organism is to consume (ingest) energy and molecules in the foods you eat, convert some of it into fuel for movement, sustain your body functions, and build and maintain your body structures. There are two types of reactions that accomplish this: **anabolism** and **catabolism**.

- **Anabolism** is the process whereby smaller, simpler molecules are combined into larger, more complex substances. Your body can assemble, by utilizing energy, the complex chemicals it needs by combining small molecules derived from the foods you eat.
- **Catabolism** is the process by which larger more complex substances are broken down into smaller simpler molecules. Catabolism releases energy. The complex molecules found in foods are broken down so the body can use their parts to assemble the structures and substances needed for life.

Taken together, these two processes are called metabolism. **Metabolism** is the sum of all anabolic and catabolic reactions that take place in the body (Figure 1.4.1). Both anabolism and catabolism occur simultaneously and continuously to keep you alive.

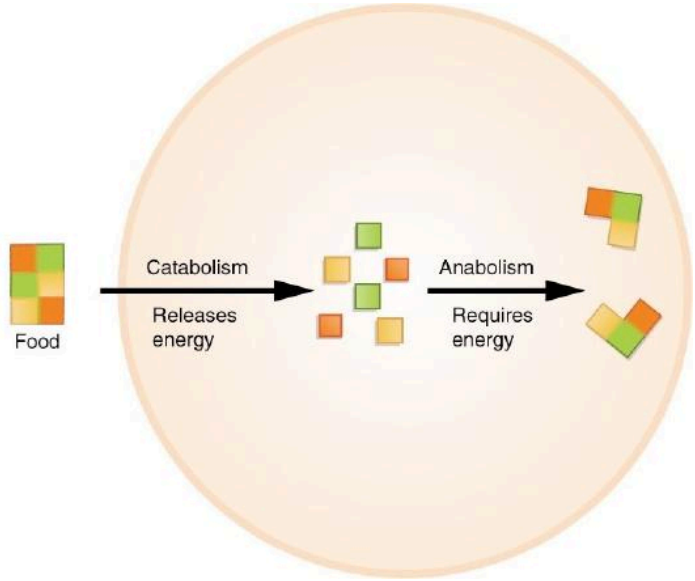

Figure 1.4.1: Metabolism. Anabolic reactions are building reactions, and they consume energy. Catabolic reactions break materials down and release energy. Metabolism includes both anabolic and catabolic reactions. (Image credit: "Metabolism" by Whitney Menefee is licensed under CC BY 4.0 / A derivative from the original work)

Every cell in your body makes use of a chemical compound, adenosine triphosphate (ATP), to store and release energy. The cell stores energy in the synthesis (anabolism) of ATP, then moves the ATP molecules to the location where energy is needed to fuel cellular activities. Then the ATP is broken down (catabolism) and a controlled amount of energy is released, which is used by the cell to perform a particular job.

Responsiveness

Responsiveness is the ability of an organism to adjust to changes in its internal and external environments. An example of responsiveness to external stimuli could include moving toward sources of food and water and away from perceived dangers. Changes in an organism's internal environment, such as increased body temperature, can cause the responses of sweating and the dilation of blood vessels in the skin in order to decrease body temperature, as shown by the runners in Figure 1.4.2.

Movement

Human movement includes not only actions at the joints of the body, but also the motion of individual organs and even individual cells. As you read these words, red and white blood cells are moving throughout your body, muscle cells are contracting and relaxing to maintain your posture and to focus your vision, and glands are secreting chemicals to regulate body functions. Your body is coordinating the action of entire muscle groups to enable you to move air into and out of your lungs, to push blood throughout your body, and to propel the food you have eaten through your digestive tract. Consciously, of course, you contract your skeletal muscles to move the bones of your skeleton to get from one place to another (as the runners are doing in Figure 1.4.2), and to carry out all of the activities of your daily life.

Figure 1.4.2: Marathon Runners. Runners demonstrate two characteristics of living humans—responsiveness and movement. Anatomic structures and physiological processes allow runners to coordinate the action of muscle groups and sweat in response to rising internal body temperature. (Image credit: "2010 IMT Des Moines Marathon" by Phil Roeder is licensed under CC BY 2.0)

Development, Growth, and Reproduction

Development is all of the changes the body goes through in life. Development includes the processes of differentiation, growth, and reproduction.

Differentiation is the process cells undergo to change from one cell type into another, typically from a generalized cell, such as a stem cell, into a more specialized cell type.

Growth is the increase in body size. Humans, like all multicellular organisms, grow by increasing the number of existing cells, increasing the amount of non-cellular material around cells (such as mineral deposits in bone), and, within very narrow limits, increasing the size of existing cells.

Reproduction is the formation of a new organism from parent organisms. In humans, reproduction is carried out by the male and female reproductive systems. Because death will come to all complex organisms, without reproduction, the line of organisms would end.

Concept Review

Most processes that occur in the human body are not consciously controlled. They occur continuously to build, maintain, and sustain life. These processes include: organization, in terms of the maintenance of essential body boundaries; metabolism, including energy transfer via anabolic and catabolic reactions; responsiveness; movement; and growth, differentiation, and reproduction.

Review Questions

Q. Metabolism can be defined as the _____.

A. adjustment by an organism to external or internal changes

B. process whereby all unspecialized cells become specialized to perform distinct functions

C. process whereby new cells are formed to replace worn-out cells

D. sum of all chemical reactions in an organism

Answer

Answer: D

Q. Adenosine triphosphate (ATP) is an important molecule because it _____.

A. is the result of catabolism

B. releases energy in uncontrolled bursts

C. stores energy for use by body cells

D. All of the above

Answer

Answer: C

Q. Cancer cells can be characterized as “generic” cells that perform no specialized body function. Thus cancer cells lack _____.

A. differentiation

B. reproduction

C. responsiveness

D. both reproduction and responsiveness

Answer

Answer: A

Critical Thinking Questions

Q. Identify three different ways that growth can occur in the human body.

Answer

A. Growth can occur by increasing the number of existing cells, increasing the size of existing cells, or increasing the amount of non-cellular material around cells.

Glossary

anabolism
assembly of more complex molecules from simpler molecules

catabolism
breaking down of more complex molecules into simpler molecules

development
changes an organism goes through during its life

differentiation
process by which unspecialized cells become specialized in structure and function

growth
process of increasing in size

metabolism
sum of all of the body’s chemical reactions

renewal
process by which worn-out cells are replaced

reproduction
process by which new organisms are generated

responsiveness
ability of an organisms or a system to adjust to changes in conditions

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1.5: Homeostasis

By the end of the section, you will be able to:

- Discuss the role of homeostasis in healthy functioning
- Contrast negative and positive feedback, giving one physiologic example of each mechanism

Maintaining homeostasis requires that the body continuously monitor its internal conditions. From body temperature to blood pressure to levels of certain nutrients, each physiological condition has a particular set point. A **set point** is the physiological value around which the normal range fluctuates. A **normal range** is the restricted set of values that is optimally healthful and stable. For example, the set point for normal human body temperature is approximately 37°C (98.6°F) Physiological parameters, such as body temperature and blood pressure, tend to fluctuate within a normal range a few degrees above and below that point. Control centers in the brain and other parts of the body monitor and react to deviations from homeostasis using negative feedback. **Negative feedback** is a mechanism that reverses a deviation from the set point. Therefore, negative feedback maintains body parameters within their normal range. The maintenance of homeostasis by negative feedback goes on throughout the body at all times, and an understanding of negative feedback is thus fundamental to an understanding of human physiology. While this textbook will not focus on physiology, the structure (anatomy) of the body is designed for the feedback that facilitates its proper function. Throughout this textbook it will be noted how anatomical systems interact to perform the functions (physiology) of the human body and keep it healthy.

Negative Feedback

A negative feedback system has three basic components (Figure $1.5.1.a$). A **sensor**, a specialized type of receptor, is a component of a feedback system designed to receive information to monitor a physiological value. This value is reported to the control center. The **control center** is the component in a feedback system that compares the value to the normal range. If the value deviates too much from the set point, then the control center activates an effector. An **effector** is the component in a feedback system that causes a change to reverse the situation and return the value to the normal range.

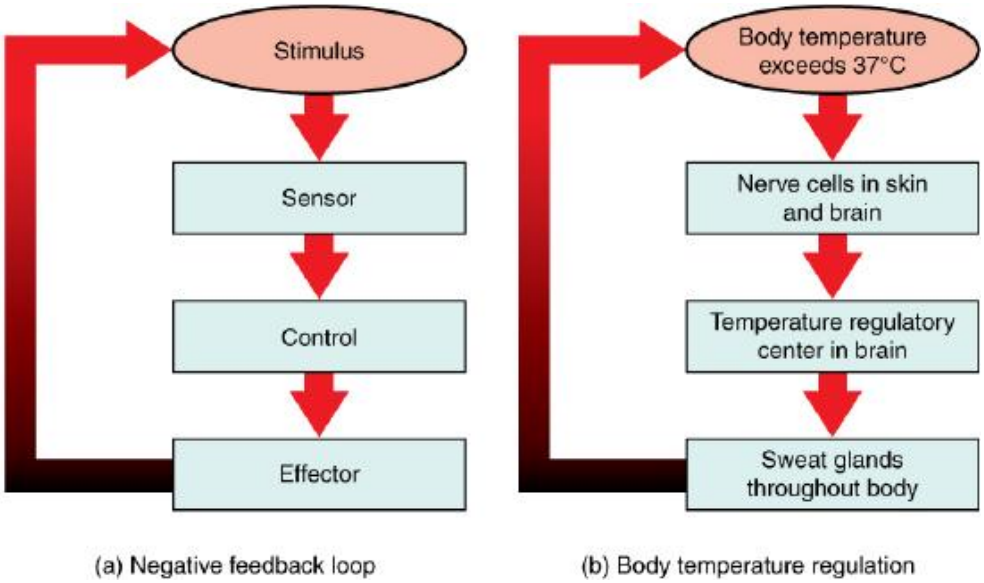

Figure $1.5.1$: Negative Feedback Loop. In a negative feedback loop, a stimulus—a deviation from a set point—is resisted through a physiological process that returns the body to homeostasis. (a) A negative feedback loop has three basic parts. (b) Body temperature is regulated by negative feedback. (Image credit: "Negative Feedback Loops" by OpenStax is licensed under CC BY 4.0)

In order to set the system in motion, a stimulus must drive a physiological parameter beyond its normal range (that is, beyond homeostasis). This stimulus is “heard” by a specific sensor. For example, in the control of blood glucose, specific endocrine cells in the pancreas detect excess glucose (the stimulus) in the bloodstream. These pancreatic beta cells respond to the increased

level of blood glucose by releasing the hormone insulin into the bloodstream. The insulin signals skeletal muscle fibers, fat cells (adipocytes), and liver cells (hepatocytes) to take up the excess glucose, removing it from the bloodstream. As glucose concentration in the bloodstream drops, the decrease in concentration—the actual negative feedback—is detected by pancreatic alpha cells, and insulin release stops. This prevents blood sugar levels from continuing to drop below the normal range.

Humans have a similar temperature regulation feedback system that works by promoting either heat loss or heat gain (Figure $1.5.1.b$). When the brain's temperature regulation center (nervous system) receives data from the sensors indicating that the body's temperature exceeds its normal range, it stimulates a cluster of brain cells referred to as the "heat-loss center." This stimulation has three major effects:

- Blood vessels in the skin begin to dilate allowing more blood from the body core to flow to the surface of the skin allowing the heat to radiate into the environment.
- As blood flow to the skin (integumentary system) increases, sweat glands are activated to increase their output. As the sweat evaporates from the skin surface into the surrounding air, it takes heat with it.
- The depth of respiration increases, and a person may breathe through an open mouth instead of through the nasal passageways. This further increases heat loss from the lungs.

In contrast, activation of the brain's heat-gain center by exposure to cold reduces blood flow to the skin, and blood returning from the limbs is diverted into a network of deep veins. This arrangement traps heat closer to the body core and restricts heat loss. If heat loss is severe, the brain triggers an increase in random signals to skeletal muscles, causing them to contract and producing shivering. The muscle contractions of shivering release heat while using up ATP. The brain triggers the thyroid gland in the endocrine system to release thyroid hormone, which increases metabolic activity and heat production in cells throughout the body. The brain also signals the adrenal glands to release epinephrine (adrenaline), a hormone that causes the breakdown of glycogen into glucose, which can be used as an energy source. The breakdown of glycogen into glucose also results in increased metabolism and heat production.

Positive Feedback

Positive feedback intensifies a change in the body's physiological condition rather than reversing it. A deviation from the normal range results in more change, and the system moves farther away from the normal range. Positive feedback in the body is normal only when there is a definite end point. Childbirth and the body's response to blood loss are two examples of positive feedback loops that are normal but are activated only when needed.

Childbirth at full term is an example of a situation in which the maintenance of the existing body state is not desired. Enormous changes in the mother's body are required to deliver the baby at the end of pregnancy. And the events of childbirth, once begun, must progress rapidly to a conclusion or the life of the mother and the baby are at risk. The extreme muscular work of labor and delivery are the result of a positive feedback system (Figure $1.5.2$).

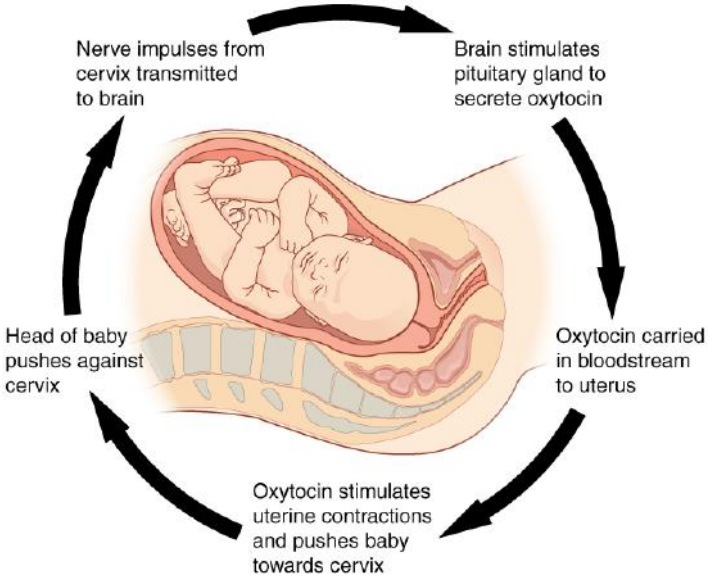

Figure 1.5.2: Positive Feedback Loop. Normal childbirth is driven by a positive feedback loop. A positive feedback loop results in a change in the body's status, rather than a return to homeostasis. (Image credit: "Pregnancy-Positive Feedback" by OpenStax is licensed under CC BY 4.0)

The first contractions of labor (the stimulus) push the baby toward the cervix (the lowest part of the uterus). The cervix contains stretch-sensitive nerve cells that monitor the degree of stretching (the sensors). These nerve cells send messages to the brain, which in turn causes the pituitary gland at the base of the brain to release the hormone oxytocin into the bloodstream. Oxytocin causes stronger contractions of the smooth muscles in of the uterus (the effectors), pushing the baby further down the birth canal. This causes even greater stretching of the cervix. The cycle of stretching, oxytocin release, and increasingly more forceful contractions stops only when the baby is born. At this point, the stretching of the cervix halts, stopping the release of oxytocin.

A second example of positive feedback centers on reversing extreme damage to the body. Following a penetrating wound, the most immediate threat is excessive blood loss. Less blood circulating means reduced blood pressure and reduced perfusion (penetration of blood) to the brain and other vital organs. If perfusion is severely reduced, vital organs will shut down and the person will die. The body responds to this potential catastrophe by releasing substances in the injured blood vessel wall that begin the process of blood clotting. As each step of clotting occurs, it stimulates the release of more clotting substances. This accelerates the processes of clotting and sealing off the damaged area. Clotting is contained in a local area based on the tightly controlled availability of clotting proteins. This is an adaptive, life-saving cascade of events.

Concept Review

Homeostasis is the activity of cells throughout the body to maintain the physiological state within a narrow range that is compatible with life. Homeostasis is regulated by negative feedback loops and, much less frequently, by positive feedback loops. Both have the same components of a stimulus, sensor, control center, and effector; however, negative feedback loops work to prevent an excessive response to the stimulus, whereas positive feedback loops intensify the response until an end point is reached.

Review Questions

After you eat lunch, nerve cells in your stomach respond to the distension (stimulus) resulting from the food. They relay this information to _____.

A. a control center

B. a set point

C. effectors

D. sensors

Answer

Answer: A

Stimulation of the heat-loss center causes _____.

A. blood vessels in the skin to constrict

B. breathing to become slow and shallow

C. sweat glands to increase their output

D. All of the above

Answer

Answer: C

Which of the following is an example of a normal physiologic process that uses a positive feedback loop?

A. blood pressure regulation

B. childbirth

C. regulation of fluid balance

D. temperature regulation

Answer

Answer: B

Critical Thinking Questions

Q. Identify the four components of a negative feedback loop and explain what would happen if secretion of a body chemical controlled by a negative feedback system became too great.

Answer

A. The four components of a negative feedback loop are: stimulus, sensor, control center, and effector. If too great a quantity of the chemical were excreted, sensors would activate a control center, which would in turn activate an effector. In this case, the effector (the secreting cells) would be adjusted downward.

Q. What regulatory processes would your body use if you were trapped by a blizzard in an unheated, uninsulated cabin in the woods?

Answer

A. Any prolonged exposure to extreme cold would activate the brain's heat-gain center. This would reduce blood flow to your skin, and shunt blood returning from your limbs away from the digits and into a network of deep veins. Your brain's heat-gain center would also increase your muscle contraction, causing you to shiver. This increases the energy consumption of skeletal muscle and generates more heat. Your body would also produce thyroid hormone and epinephrine, chemicals that promote increased metabolism and heat production.

Glossary

control center
compares values to their normal range; deviations cause the activation of an effector

effector
: organ that can cause a change in a value

negative feedback
: homeostatic mechanism that tends to stabilize an upset in the body's physiological condition by preventing an excessive response to a stimulus, typically as the stimulus is removed

normal range
: range of values around the set point that do not cause a reaction by the control center

positive feedback
: mechanism that intensifies a change in the body's physiological condition in response to a stimulus

sensor
: (also, receptor) reports a monitored physiological value to the control center

set point
: ideal value for a physiological parameter; the level or small range within which a physiological parameter such as blood pressure is stable and optimally healthful, that is, within its parameters of homeostasis

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1.6: Anatomical Terminology

By the end of the section, you will be able to:

- Demonstrate the anatomical position
- Describe the human body using directional and regional terms
- Identify three planes most commonly used in the study of anatomy
- Distinguish between the posterior (dorsal) and anterior (ventral) body cavities, identifying their subdivisions and representative organs found in each
- Describe a serous membrane and explain its function

Anatomists and health care providers use terminology that can be bewildering to the uninitiated. However, the purpose of this language is not to confuse, but rather to increase precision and reduce medical errors. For example, is a scar "above the wrist" located on the forearm two or three inches away from the hand? Or is it at the base of the hand? Is it on the palm-side or back-side? By using precise anatomical terminology, we eliminate ambiguity. Anatomical terms derive from ancient Greek and Latin words. Because these languages are no longer used in everyday conversation, the meaning of their words does not change.

Anatomical terms are made up of roots, prefixes, and suffixes. The root of a term often refers to an organ, tissue, or condition, whereas the prefix or suffix often describes the root. For example, in the disorder hypertension, the prefix "hyper-" means "high" or "over," and the root word "tension" refers to pressure, so the word "hypertension" refers to abnormally high blood pressure.

Anatomical Position

To further increase precision, anatomists standardize the way in which they view the body. Just as maps are normally oriented with north at the top, the standard body "map," or **anatomical position**, is that of the body standing upright, with the feet at shoulder width and parallel, toes forward. The upper limbs are held out to each side, and the palms of the hands face forward as illustrated in Figure 1.6.1. Using this standard position reduces confusion. It does not matter how the body being described is oriented, the terms are used as if it is in anatomical position. For example, a scar in the "anterior (front) carpal (wrist) region" would be present on the palm side of the wrist. The term "anterior" would be used even if the hand were palm down on a table.

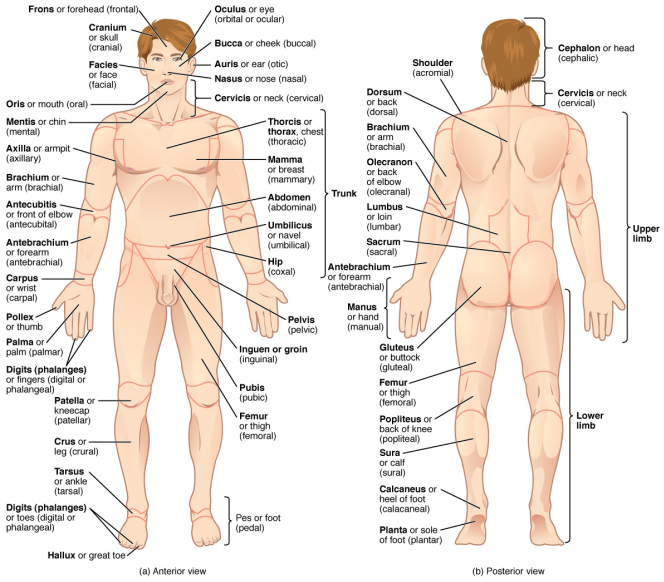

Figure 1.6.1: Regions of the Human Body. The human body is shown in anatomical position in an (a) anterior view and a (b) posterior view. The anatomical terms used for the regions of the body are labeled in boldface. (Image credit: "Regions of Human Body" by OpenStax is licensed under CC BY 3.0)

A body that is lying down is described as either prone or supine. **Prone** describes a face-down orientation, and **supine** describes a

face up orientation. These terms are sometimes used in describing the position of the body during specific physical examinations or surgical procedures.

Regional Terms

The human body's numerous regions have specific terms to help increase precision. Figure 1.6.1 has labeled each region with the correct anatomical term (seen in bold), while also listing the common name of the region. Additionally, the adjective form of the regional term is listed in parenthesis. Keep in mind that in the study of human anatomy, it is the bold terms listed in the figure that are used. Notice that the term "brachium" is reserved for the "upper arm" and "antebrachium" is used rather than "lower arm." Similarly, "femur" designates the upper portion of the lower limb and "crus" is reserved for the portion of the lower limb between the knee and the ankle. You will be able to describe the body's regions using the terms from the figure.

Directional Terms

Certain directional anatomical terms appear throughout this and any other anatomy textbook (Figure 1.6.2). These terms are essential for describing the relative locations of different body structures. For instance, an anatomist might describe one band of tissue as "inferior to" another or a physician might describe a tumor as "superficial to" a deeper body structure. Commit these terms to memory to avoid confusion when you are studying or describing the locations of particular body parts.

- **Anterior** (or **ventral**) describes the front or direction toward the front of the body. The toes are anterior to the foot.
- **Posterior** (or **dorsal**) describes the back or direction toward the back of the body. The popliteus is posterior to the patella.
- **Superior** (or **cranial**) describes a position above or higher than another part of the body proper. The orbits are superior to the oris.
- **Inferior** (or **caudal**) describes a position below or lower than another part of the body proper; near or toward the tail (in humans, the coccyx, or lowest part of the spinal column). The pelvis is inferior to the abdomen.
- **Lateral** describes the side or direction toward the side of the body. The pollex (thumb) is lateral to the digits.
- **Medial** describes the middle or direction toward the middle of the body. The hallux (big toe) is the medial toe.
- **Proximal** describes a position in a limb that is nearer to the point of attachment or the trunk of the body. The brachium is proximal to the antebrachium.
- **Distal** describes a position in a limb that is farther from the point of attachment or the trunk of the body. The crus is distal to the femur.
- **Superficial** describes a position closer to the surface of the body. The skin is superficial to the bones.
- **Deep** describes a position farther from the surface of the body. The brain is deep to the skull.

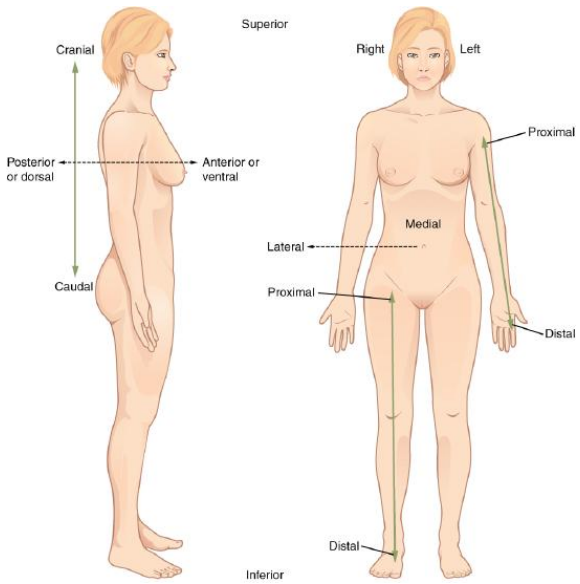

Figure 1.6.2: Directional Terms Applied to the Human Body. Paired, but opposite, directional terms are shown as applied to the human body at either end of the same arrow. (Image credit: "Directional Terms" by OpenStax is licensed under CC BY 3.0)

Body Planes

A section is a two-dimensional surface of a three-dimensional structure that has been cut. Modern medical imaging devices enable clinicians to obtain “virtual sections” of living bodies. We call these scans. Body sections and scans can be correctly interpreted, however, only if the viewer understands the plane along which the section was made. A **plane** is an imaginary two-dimensional surface that passes through the body. There are three planes commonly referred to in anatomy and medicine, as illustrated in Figure $1.6.3.a, b$.

- The **sagittal plane** is the plane that divides the body or an organ vertically into right and left sides. If this vertical plane runs directly down the middle of the body, it is called the midsagittal or median plane. If it divides the body into unequal right and left sides, it is called a parasagittal plane or less commonly a longitudinal section.
- The **frontal plane** is the plane that divides the body or an organ vertically into an anterior (front) portion and a posterior (rear) portion. The frontal plane is also referred to as a coronal plane. (“Corona” is Latin for “crown.”)
- The **transverse plane** is the plane that divides the body or organ horizontally into upper and lower portions. Transverse planes produce images referred to as cross sections.

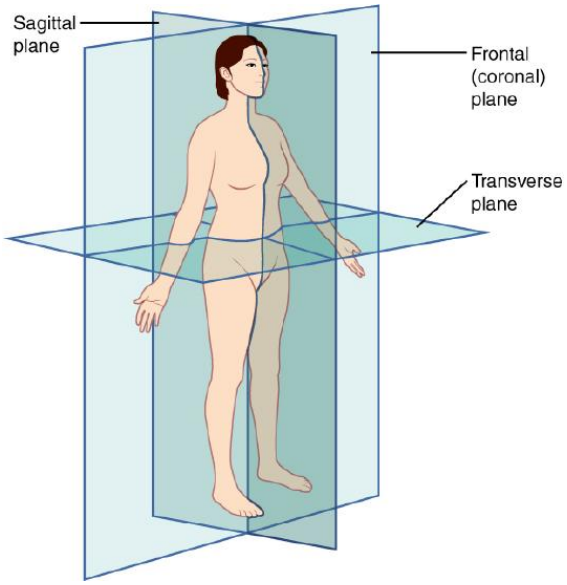

Figure $1.6.3.a$: Planes of the human body. The three planes most commonly used in anatomical and medical imaging are the sagittal, frontal (or coronal), and transverse plane. (Image credit: "Planes of Body" by OpenStax is licensed under CC BY 3.0)

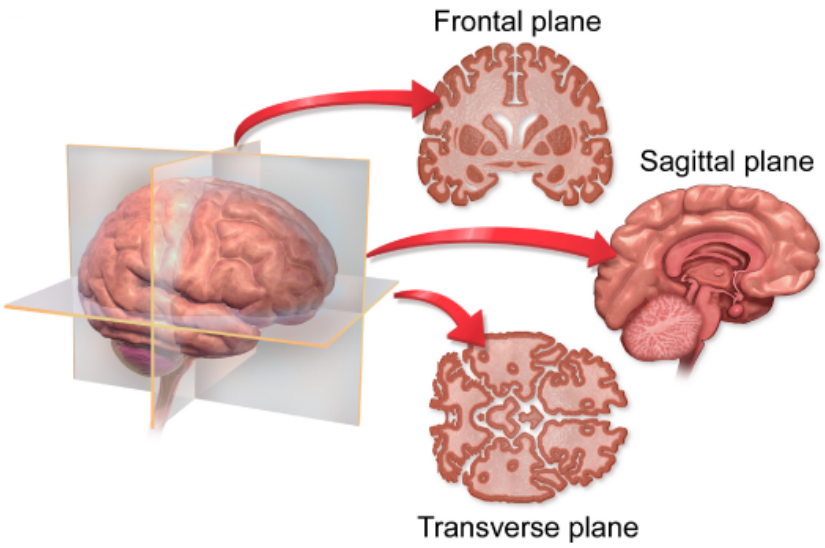

Figure 1.6.3.*b*: Planes of the human brain. The three planes most commonly used in anatomical and medical imaging are the sagittal, frontal (or coronal), and transverse plane. (Image credit: "Blausen 0104 Brain x-secs SectionalPlanes" by Blausen.com staff (2014). "Medical gallery of Blausen Medical 2014". WikiJournal of Medicine 1 (2). DOI:10.15347/wjm/2014.010. ISSN 2002-4436. is licensed under CC BY 3.0)

Body Cavities and Serous Membranes

The body maintains its internal organization by means of membranes, sheaths, and other structures that separate compartments. The **dorsal (posterior) cavity** and the **ventral (anterior) cavity** are the largest body compartments (Figure 1.6.4). These cavities contain and protect delicate internal organs, and the ventral cavity allows for significant changes in the size and shape of the organs as they perform their functions. The lungs, heart, stomach, and intestines, for example, can expand and contract without distorting other tissues or disrupting the activity of nearby organs.

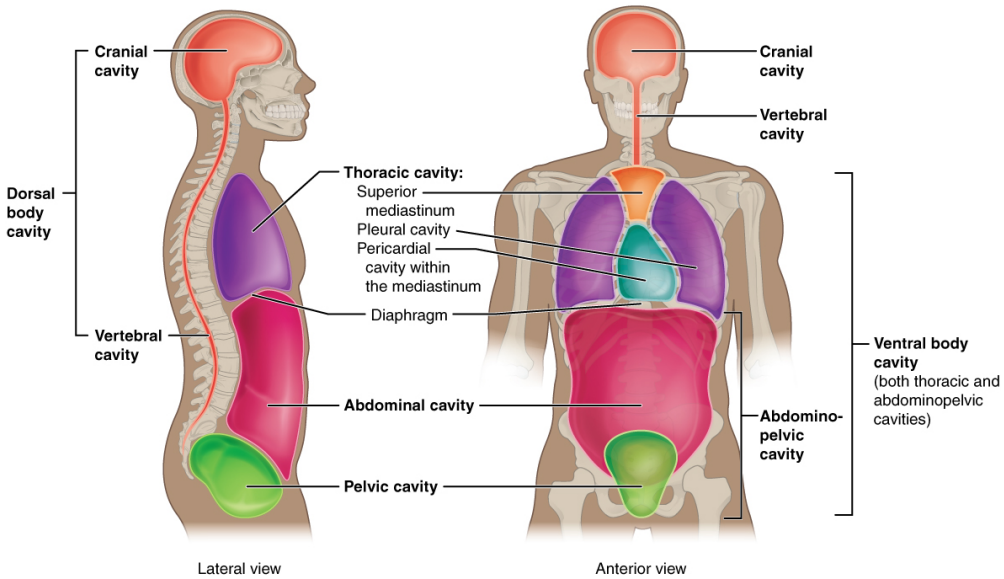

Figure 1.6.4: Dorsal and Ventral Body Cavities. The ventral cavity includes the thoracic and abdominopelvic cavities and their subdivisions. The dorsal cavity includes the cranial and spinal cavities. (Image credit: "Dorsal Ventral Body Cavities" by OpenStax is licensed under CC BY 3.0)

Subdivisions of the Posterior (Dorsal) and Anterior (Ventral) Cavities

The posterior (dorsal) and anterior (ventral) cavities are each subdivided into smaller cavities. In the posterior (dorsal) cavity, the **cranial cavity** houses the brain, and the **spinal cavity** (or vertebral cavity) encloses the spinal cord. Just as the brain and spinal

cord make up a continuous, uninterrupted structure, the cranial and spinal cavities that house them are also continuous. The brain and spinal cord are protected by the bones of the skull and vertebral column and by cerebrospinal fluid, a colorless fluid produced by the brain, which cushions the brain and spinal cord within the posterior (dorsal) cavity.

The anterior (ventral) cavity has two main subdivisions: the thoracic cavity and the abdominopelvic cavity (see Figure 1.6.4). The **thoracic cavity** is the more superior subdivision of the anterior cavity, and it is enclosed by the rib cage. It contains the pleural cavities, which house the lungs, and the mediastinum, the space between the lungs in the thoracic cavity. The mediastinum has a superior portion, which contains the trachea and esophagus, and an inferior portion containing the pericardial cavity, which surrounds the heart. The diaphragm forms the floor of the thoracic cavity and separates it from the more inferior abdominopelvic cavity. The **abdominopelvic cavity** is the largest cavity in the body. Although no membrane physically divides the abdominopelvic cavity into more specific compartments, it can be useful to distinguish between the abdominal cavity, the division that houses the digestive organs, and the pelvic cavity, the division that houses the organs of reproduction.

Abdominal Regions and Quadrants

To promote clear communication, for instance about the location of a patient's abdominal pain or a suspicious mass, health care providers typically divide up the cavity into either nine regions or four quadrants (Figure 1.6.5).

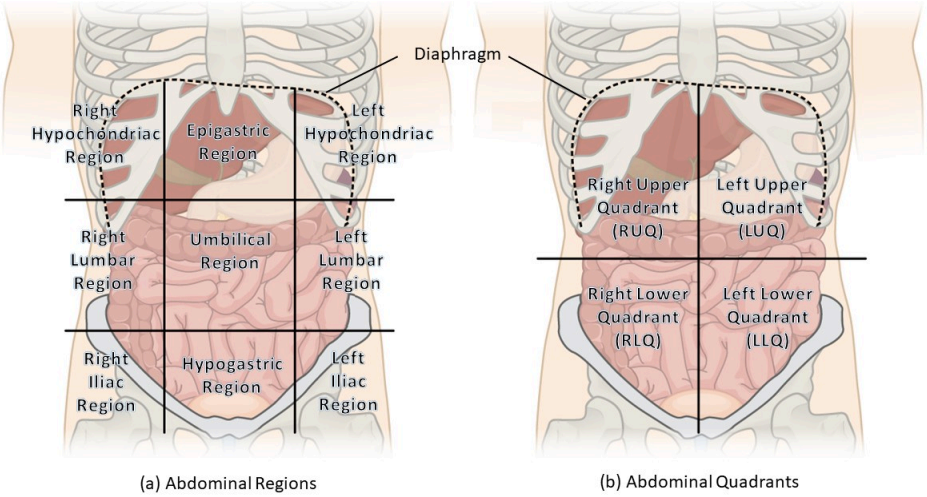

Figure 1.6.5: Regions and Quadrants of the Peritoneal Cavity. There are (a) nine abdominal regions and (b) four abdominal quadrants in the peritoneal cavity. (Image credit: "Abdominal Quadrant and Regions" by Whitney Menefee is licensed under CC BY 4.0 / A derivative from the original work)

The more detailed regional approach subdivides the cavity with one horizontal line immediately inferior to the ribs and one immediately superior to the pelvis, and two vertical lines drawn as if dropped from the midpoint of each clavicle (collarbone). There are nine resulting regions:

- Right hypochondriac region containing a portion of liver.
- Right lumbar region containing the ascending colon and a portion of the small intestine.
- Right iliac region containing the appendix, the cecum and a portion of the small intestine.
- Epigastric region containing the pancreas, gall bladder, and portions of the stomach and liver.
- Umbilical region containing the transverse colon and a portion of the small intestine.
- Hypogastric region containing a portion of the small intestine and the bladder.
- Left hypochondriac region containing the spleen and portion of the stomach
- Left lumbar region containing the descending colon and a portion of the small intestine.
- Left iliac region containing the sigmoid colon and a portion of the small intestine.

The simpler quadrants approach, which is more commonly used in medicine, subdivides the cavity with one horizontal and one vertical line that intersect at the patient's umbilicus (navel). This results in four quadrants:

- Right upper quadrant (RUQ) containing the right lobe of liver, the gall bladder, the duodenum, head of the pancreas, the right kidney and adrenal gland, portions of the colon.
- Right lower quadrant (RLQ) containing the cecum, the appendix, the ascending colon, and the right ureter.
- Left upper quadrant (LUQ) containing the stomach, the spleen, left lobe of the liver, body of the pancreas, the left kidney and adrenal gland, and portions of the colon.
- Left lower quadrant (LLQ) containing the descending colon, the sigmoid colon, portions of the small intestine, and the left ureter.

Membranes of the Anterior (Ventral) Body Cavity

A **serous membrane** (also referred to a serosa) is one of the thin membranes that cover the walls and organs in the thoracic and abdominopelvic cavities. The parietal layers of the membranes line the walls of the body cavity (pariet- refers to a cavity wall). The visceral layer of the membrane covers the organs (the viscera). Between the parietal and visceral layers is a very thin, fluid-filled serous space, or cavity (Figure 1.6.6).

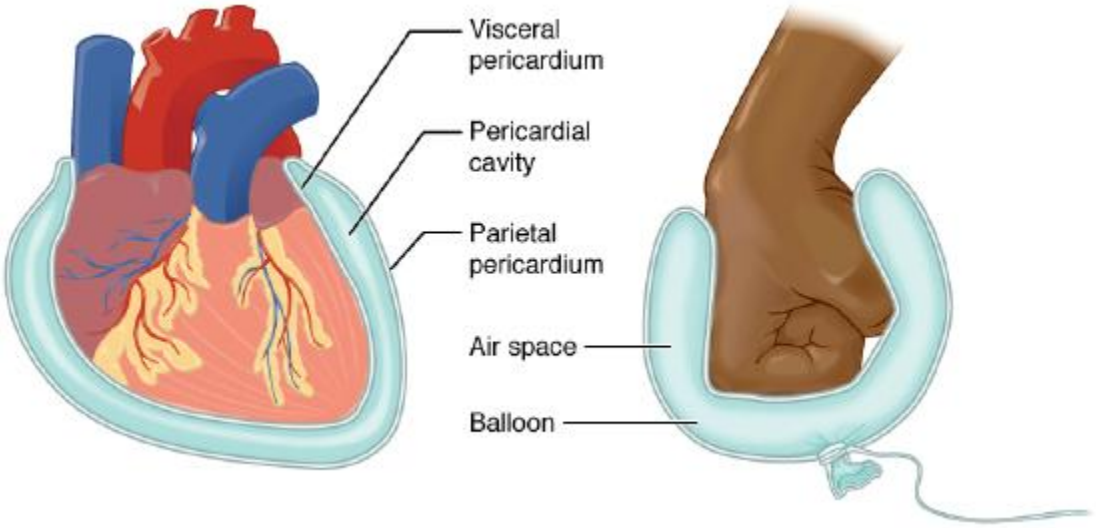

Figure 1.6.6: Serous Membrane. Serous membrane lines the pericardial cavity and reflects back to cover the heart—much the same way that an under inflated balloon would form two layers surrounding a fist. (Image credit: "Serous Membrane" by OpenStax is licensed under CC BY 3.0)

There are three serous cavities and their associated membranes. The **pleura** is the serous membrane that surrounds the lungs in the pleural cavity; the **pericardium** is the serous membrane that surrounds the heart in the pericardial cavity; and the **peritoneum** is the serous membrane that surrounds several organs in the abdominopelvic cavity. The serous fluid produced by the serous membranes reduces friction between the walls of the cavities and the internal organs when they move, such as when the lungs inflate or the heart beats. Both the parietal and visceral serosa secrete the thin, slippery serous fluid that prevents friction when an organ slides past the walls of a cavity. In the pleural cavities, pleural fluid prevents friction between the lungs and the walls of the cavity. In the pericardial sac, pericardial fluid prevents friction between the heart and the walls of the pericardial sac. And in the peritoneal cavity, peritoneal fluid prevents friction between abdominal and pelvic organs and the wall of the cavity. The serous membranes therefore provide additional protection to the viscera they enclose by reducing friction that could lead to inflammation of the organs.

Concept Review

A standard reference position for mapping the body's structures is the normal anatomical position. Regions of the body are identified using terms such as "occipital" that are more precise than common words and phrases such as "the back of the head." Directional terms such as anterior and posterior are essential for accurately describing the relative locations of body structures. Images of the body's interior commonly align along one of three planes: the sagittal, frontal, or transverse. The body's organs are organized in one of two main cavities — dorsal and ventral — which are further sub-divided according to the structures present in each area. The serous membranes have two layers — parietal and visceral — surrounding a fluid filled space. Serous membranes cover the lungs (pleural serosa), heart (pericardial serosa), and some abdominopelvic organs (peritoneal serosa).

Review Questions

Q. What is the position of the body when it is in the “normal anatomical position?”

A. The person is prone with upper limbs, including palms, touching sides and lower limbs touching at sides.

B. The person is standing facing the observer, with upper limbs extended out at a ninety-degree angle from the torso and lower limbs in a wide stance with feet pointing laterally

C. The person is supine with upper limbs, including palms, touching sides and lower limbs touching at sides.

D. None of the above

Answer

Answer: D

Q. To make a banana split, you halve a banana into two long, thin, right and left sides along the _____.

A. coronal plane

B. longitudinal plane

C. midsagittal plane

D. transverse plane

Answer

Answer: C

Q. The epigastric region is _____.

A. inferior to the hypogastric region

B. inferior to the right hypochondriac region

C. superior to the hypogastric region

D. superior to the left hypochondriac region

Answer

Answer: C

Q. The heart is within the _____.

A. cranial cavity

B. mediastinum

C. posterior (dorsal) cavity

D. All of the above

Answer

Answer: B

Critical Thinking Question

Q. If a bullet were to penetrate a lung, which three anterior thoracic body cavities would it enter, and which layer of the serous membrane would it encounter first?

Answer

A. The bullet would enter the ventral, thoracic, and pleural cavities, and it would encounter the parietal layer of serous membrane first.

Glossary

abdominopelvic cavity
division of the anterior (ventral) cavity that houses the abdominal and pelvic viscera

anatomical position
standard reference position used for describing locations and directions on the human body

anterior
describes the front or direction toward the front of the body; also referred to as ventral

anterior cavity
larger body cavity located anterior to the posterior (dorsal) body cavity; includes the serous membrane-lined pleural cavities for the lungs, pericardial cavity for the heart, and peritoneal cavity for the abdominal and pelvic organs; also referred to as ventral cavity

caudal
describes a position below or lower than another part of the body proper; near or toward the tail (in humans, the coccyx, or lowest part of the spinal column); also referred to as inferior

cranial
describes a position above or higher than another part of the body proper; also referred to as superior

cranial cavity
division of the posterior (dorsal) cavity that houses the brain

deep
describes a position farther from the surface of the body

distal
describes a position farther from the point of attachment or the trunk of the body

dorsal
describes the back or direction toward the back of the body; also referred to as posterior

dorsal cavity
posterior body cavity that houses the brain and spinal cord; also referred to the posterior body cavity

frontal plane
two-dimensional, vertical plane that divides the body or organ into anterior and posterior portions

inferior
describes a position below or lower than another part of the body proper; near or toward the tail (in humans, the coccyx, or lowest part of the spinal column); also referred to as caudal

lateral
describes the side or direction toward the side of the body

medial
describes the middle or direction toward the middle of the body

pericardium
sac that encloses the heart

peritoneum
serous membrane that lines the abdominopelvic cavity and covers the organs found there

plane
imaginary two-dimensional surface that passes through the body

pleura
serous membrane that lines the pleural cavity and covers the lungs

posterior
describes the back or direction toward the back of the body; also referred to as dorsal

posterior cavity
posterior body cavity that houses the brain and spinal cord; also referred to as dorsal cavity

prone
face down

proximal
describes a position nearer to the point of attachment or the trunk of the body

sagittal plane
two-dimensional, vertical plane that divides the body or organ into right and left sides

section
in anatomy, a single flat surface of a three-dimensional structure that has been cut through

serous membrane
membrane that covers organs and reduces friction; also referred to as serosa

serosa
membrane that covers organs and reduces friction; also referred to as serous membrane

spinal cavity
division of the dorsal cavity that houses the spinal cord; also referred to as vertebral cavity

superficial
describes a position nearer to the surface of the body

superior
describes a position above or higher than another part of the body proper; also referred to as cranial

supine
face up

thoracic cavity
division of the anterior (ventral) cavity that houses the heart, lungs, esophagus, and trachea

transverse plane
two-dimensional, horizontal plane that divides the body or organ into superior and inferior portions

ventral
describes the front or direction toward the front of the body; also referred to as anterior

ventral cavity
larger body cavity located anterior to the posterior (dorsal) body cavity; includes the serous membrane-lined pleural cavities for the lungs, pericardial cavity for the heart, and peritoneal cavity for the abdominal and pelvic organs; also referred to as anterior body cavity

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1.7: Medical Imaging

By the end of the section, you will be able to:

- Discuss the uses and drawbacks of X-ray imaging
- Identify four modern medical imaging techniques and how they are used

For thousands of years, fear of the dead and legal sanctions limited the ability of anatomists and physicians to study the internal structures of the human body. An inability to control bleeding, infection, and pain made surgeries infrequent, and those that were performed—such as wound suturing, amputations, tooth and tumor removals, skull drilling, and cesarean births—did not greatly advance knowledge about internal anatomy. Theories about the function of the body and about disease were therefore largely based on external observations and imagination. During the fourteenth and fifteenth centuries, however, the detailed anatomical drawings of Italian artist and anatomist Leonardo da Vinci and Flemish anatomist Andreas Vesalius were published, and interest in human anatomy began to increase. Medical schools began to teach anatomy using human dissection; although some resorted to grave robbing to obtain corpses. Laws were eventually passed that enabled students to dissect the corpses of criminals and those who donated their bodies for research. Still, it was not until the late nineteenth century that medical researchers discovered non-surgical methods to look inside the living body.

X-Rays

German physicist Wilhelm Röntgen (1845–1923) was experimenting with electrical current when he discovered that a mysterious and invisible “ray” would pass through his flesh but leave an outline of his bones on a screen coated with a metal compound. In 1895, Röntgen made the first durable record of the internal parts of a living human: an “X-ray” image (as it came to be called) of his wife’s hand. Scientists around the world quickly began their own experiments with X-rays, and by 1900, X-rays were widely used to detect a variety of injuries and diseases. In 1901, Röntgen was awarded the first Nobel Prize for physics for his work in this field.

The **X-ray** is a form of high energy electromagnetic radiation with a short wavelength capable of penetrating solids and ionizing gases. As they are used in medicine, X-rays are emitted from an X-ray machine and directed toward a specially treated metallic plate placed behind the patient’s body. The beam of radiation results in darkening of the X-ray plate. X-rays are slightly impeded by soft tissues, which show up as gray on the X-ray plate, whereas hard tissues, such as bone, largely block the rays, producing a light-toned “shadow.” Thus, X-rays are best used to visualize hard body structures such as teeth and bones (Figure 1.7.1). Like many forms of high energy radiation, however, X-rays are capable of damaging cells and initiating changes that can lead to cancer. This danger of excessive exposure to X-rays was not fully appreciated for many years after their widespread use.

Figure 1.7.1: X-Ray of a Hand. High energy electromagnetic radiation allows the internal structures of the body, such as bones, to be seen in X-rays like these. (Image credit:"X-Ray of Hand" by OpenStax is licensed under CC BY 3.0)

Refinements and enhancements of X-ray techniques have continued throughout the twentieth and twenty-first centuries. Although often supplanted by more sophisticated imaging techniques, the X-ray remains a “workhorse” in medical imaging, especially for viewing fractures and for dentistry. The disadvantage of irradiation to the patient and the operator is now attenuated by proper shielding and by limiting exposure.

Modern Medical Imaging

X-rays can depict a two-dimensional image of a body region, and only from a single angle. In contrast, more recent medical imaging technologies produce data that is integrated and analyzed by computers to produce three-dimensional images or images that reveal aspects of body functioning.

Computed Tomography

Tomography refers to imaging by sections. **Computed tomography (CT)** is a noninvasive imaging technique that uses computers to analyze several cross-sectional X-rays in order to reveal minute details about structures in the body (Figure 1.7.2.a). The technique was invented in the 1970s and is based on the principle that, as X-rays pass through the body, they are absorbed or reflected at different levels. In the technique, a patient lies on a motorized platform while a computerized axial tomography (CAT) scanner rotates 360 degrees around the patient, taking X-ray images. A computer combines these images into a two-dimensional view of the scanned area, or “slice.”

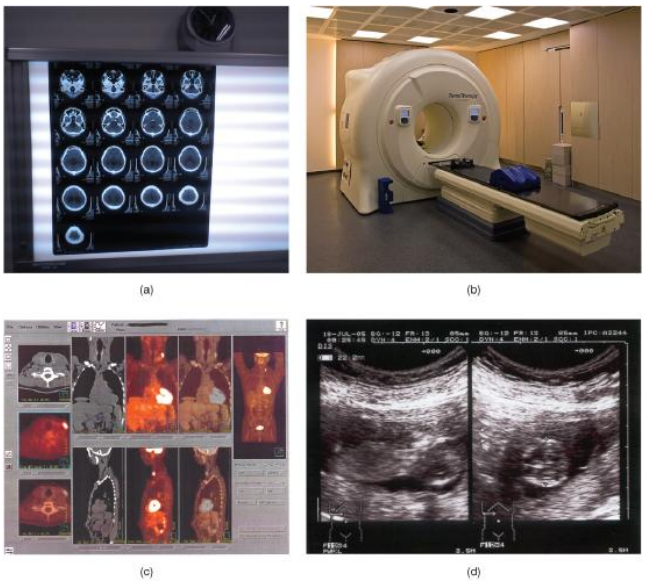

Figure 1.7.2: Medical Imaging Techniques. (a) The results of a CT scan of the head are shown as successive transverse sections. (b) An MRI machine generates a magnetic field around a patient. (c) PET scans use radiopharmaceuticals to create images of active blood flow and physiologic activity of the organ or organs being targeted. (d) Ultrasound technology is used to monitor pregnancies because it is the least invasive of imaging techniques and uses no electromagnetic radiation. (Image credit: "Medical Imaging Techniques" by OpenStax is licensed under CC BY 3.0)

Since 1970, the development of more powerful computers and more sophisticated software has made CT scanning routine for many types of diagnostic evaluations. It is especially useful for soft tissue scanning, such as of the brain and the thoracic and abdominal viscera. Its level of detail is so precise that it can allow physicians to measure the size of a mass down to a millimeter. The main disadvantage of CT scanning is that it exposes patients to a dose of radiation many times higher than that of X-rays. In fact, children who undergo CT scans are at increased risk of developing cancer, as are adults who have multiple CT scans.

Magnetic Resonance Imaging

Magnetic resonance imaging (MRI) is a noninvasive medical imaging technique based on a phenomenon of nuclear physics discovered in the 1930s, in which matter exposed to magnetic fields and radio waves was found to emit radio signals. In 1970, a physician and researcher named Raymond Damadian noticed that malignant (cancerous) tissue gave off different signals than normal body tissue. He applied for a patent for the first MRI scanning device, which was in use clinically by the early 1980s. The early MRI scanners were crude, but advances in digital computing and electronics led to their advancement over any other technique for precise imaging, especially to discover tumors. MRI also has the major advantage of not exposing patients to radiation.

Drawbacks of MRI scans include their much higher cost, and patient discomfort with the procedure. The MRI scanner subjects the patient to such powerful electromagnets that the scan room must be shielded. The patient must be enclosed in a metal tube-like device for the duration of the scan (see Figure 1.7.2.b), sometimes as long as thirty minutes, which can be uncomfortable and impractical for ill patients. The device is also so noisy that, even with earplugs, patients can become anxious or even fearful. These problems have been overcome somewhat with the development of “open” MRI scanning, which does not require the patient to be entirely enclosed in the metal tube. Patients with iron-containing metallic implants (internal sutures, some prosthetic devices, and so on) cannot undergo MRI scanning because it can dislodge these implants.

Functional MRIs (fMRIs), which detect the concentration of blood flow in certain parts of the body, are increasingly being used to study the activity in parts of the brain during various body activities. This has helped scientists learn more about the locations of different brain functions and more about brain abnormalities and diseases.

Positron Emission Tomography

Positron emission tomography (PET) is a medical imaging technique involving the use of so-called radiopharmaceuticals, substances that emit radiation that is short-lived and therefore relatively safe to administer to the body. Although the first PET scanner was introduced in 1961, it took 15 more years before radiopharmaceuticals were combined with the technique and

revolutionized its potential. The main advantage is that PET (see Figure $1.7.2.c$) can illustrate physiologic activity—including nutrient metabolism and blood flow—of the organ or organs being targeted, whereas CT and MRI scans can only show static images. PET is widely used to diagnose a multitude of conditions, such as heart disease, the spread of cancer, certain forms of infection, brain abnormalities, bone disease, and thyroid disease.

Ultrasonography

Ultrasonography is an imaging technique that uses the transmission of high-frequency sound waves into the body to generate an echo signal that is converted by a computer into a real-time image of anatomy and physiology (see Figure $1.7.2.d$). Ultrasonography is the least invasive of all imaging techniques, and it is therefore used more freely in sensitive situations such as pregnancy. The technology was first developed in the 1940s and 1950s. Ultrasonography is used to study heart function, blood flow in the neck or extremities, certain conditions such as gallbladder disease, and fetal growth and development. The main disadvantages of ultrasonography are that the image quality is heavily operator-dependent and that it is unable to penetrate bone and gas.

Concept Review

Detailed anatomical drawings of the human body first became available in the fifteenth and sixteenth centuries; however, it was not until the end of the nineteenth century, and the discovery of X-rays, that anatomists and physicians discovered non-surgical methods to look inside a living body. Since then, many other techniques, including CT scans, MRI scans, PET scans, and ultrasonography, have been developed, providing more accurate and detailed views of the form and function of the human body.

Review Questions

Q. In 1901, Wilhelm Röntgen was the first person to win the Nobel Prize for physics. For what discovery did he win?

A. nuclear physics

B. radiopharmaceuticals

C. the link between radiation and cancer

D. X-rays

Answer

Answer: D

Q. Which of the following imaging techniques would be best to use to study the uptake of nutrients by rapidly multiplying cancer cells?

A. CT

B. MRI

C. PET

D. ultrasonography

Answer

Answer: C

Q. Which of the following imaging studies can be used most safely during pregnancy?

A. CT scans

B. PET scans

C. ultrasounds

D. X-rays

Answer

Answer: C

Q. What are two major disadvantages of MRI scans?

A. release of radiation and poor quality images

B. high cost and the need for shielding from the magnetic signals

C. can only view metabolically active tissues and inadequate availability of equipment

D. release of radiation and the need for a patient to be confined to metal tube for up to 30 minutes

Answer

Answer: B

Critical Thinking Questions

Q. Which medical imaging technique is most dangerous to use repeatedly, and why?

Answer

A. CT scanning subjects patients to much higher levels of radiation than X-rays, and should not be performed repeatedly.

Q. In which direction would an MRI scanner move to produce sequential images of the body in the frontal plane, and in which direction would an MRI scanner move to produce sequential images of the body in the sagittal plane?

Answer

A. If the body were supine or prone, the MRI scanner would move from top to bottom to produce frontal sections, which would divide the body into anterior and posterior portions, as in “cutting” a deck of cards. Again, if the body were supine or prone, to produce sagittal sections, the scanner would move from left to right or from right to left to divide the body lengthwise into left and right portions.

Q. Explain why ultrasound imaging is the technique of choice for studying fetal growth and development.

Answer

A. Ultrasonography does not expose a mother or fetus to radiation, to radiopharmaceuticals, or to magnetic fields. At this time, there are no known medical risks of ultrasonography.

Glossary

computed tomography (CT)
medical imaging technique in which a computer-enhanced cross-sectional X-ray image is obtained

magnetic resonance imaging (MRI)
medical imaging technique in which a device generates a magnetic field to obtain detailed sectional images of the internal structures of the body

positron emission tomography (PET)
medical imaging technique in which radiopharmaceuticals are traced to reveal metabolic and physiological

functions in tissues

ultrasonography
application of ultrasonic waves to visualize subcutaneous body structures such as tendons and organs

X-ray
form of high energy electromagnetic radiation with a short wavelength capable of penetrating solids and ionizing gases; used in medicine as a diagnostic aid to visualize body structures such as bones

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2: CELLULAR LEVEL OF ORGANIZATION

2.1: Introduction to the Cellular Level of Organization
2.2: The Cell Membrane
2.3: The Cytoplasm and Cellular Organelles
2.4: The Nucleus
2.5: Cell Growth and Division
2.6: Cellular Differentiation

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2.1: Introduction to the Cellular Level of Organization

Chapter Learning Objectives

After studying this chapter, you will be able to:

- Describe the structure and function of the cell membrane, including its regulation of materials into and out of the cell
- Describe the functions of the various cytoplasmic organelles
- Explain the structure and contents of the nucleus
- List the stages of the cell cycle in order, including the steps of cell division in somatic cells
- Discuss how a cell differentiates and becomes more specialized

You developed from a single fertilized egg cell into the complex organism containing trillions of cells that you see when you look in a mirror. During this developmental process, early, undifferentiated cells differentiate and become specialized in their structure and function. These different cell types form specialized tissues that work in concert to perform all of the functions necessary for the living organism. Cellular and developmental biologists study how the continued division of a single cell leads to such complexity and diversity in form and function.

Consider the difference between a structural cell in the skin and a nerve cell. A structural skin cell may be shaped like a flat plate (squamous) and live only for a short time before it is shed and replaced. Packed tightly into rows and sheets, the squamous skin cells provide a protective barrier for the cells and tissues that lie beneath. A nerve cell, on the other hand, may be shaped something like a star, sending out long processes up to a meter in length and may live for the entire lifetime of the organism. With their long winding appendages, nerve cells can communicate with one another and with other types of body cells and send rapid signals that inform the organism about its environment and allow it to interact with that environment. These differences illustrate one very important theme that is consistent at all organizational levels of biology: the form of a structure is optimally suited to perform particular functions assigned to that structure. Keep this theme in mind as you tour the inside of a cell and are introduced to the various types of cells in the body.

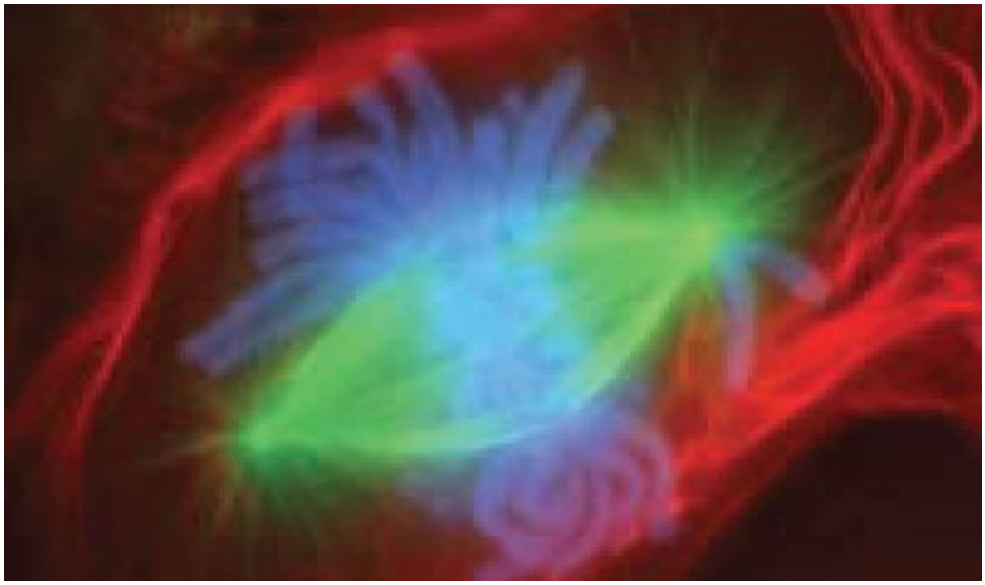

Figure 2.1.1: Fluorescence-stained Cell Undergoing Mitosis. A lung cell from a newt, commonly studied for its similarity to human lung cells, is stained with fluorescent dyes. The green stain reveals mitotic spindles, red is the cell membrane and part of the cytoplasm, and the structures that appear light blue are chromosomes. This cell is in anaphase of mitosis. (Image credit: "Flourescence Stained new" by OpenStax is licensed under CC BY 4.0)

In spite of their diversity, a primary responsibility of every cell is to contribute to homeostasis. Homeostasis is a term used in biology that refers to a dynamic state of balance within parameters that are compatible with life. For example, living cells require a water-based environment to survive in, and there are various physical (anatomical) and physiological mechanisms that keep all

of the trillions of living cells in the human body moist. This is one aspect of homeostasis. When a particular parameter, such as blood pressure or blood oxygen content, moves far enough *out* of homeostasis (generally becoming too high or too low), illness or disease—and sometimes death—inevitably results.

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2.2: The Cell Membrane

By the end of the section, you will be able to:

- Describe the molecular components that make up the cell membrane
- Explain the major features and properties of the cell membrane
- Differentiate between materials that can and cannot diffuse through the lipid bilayer
- Compare and contrast different types of passive transport with active transport, providing examples of each

Despite differences in structure and function, all living cells in multicellular organisms have a surrounding cell membrane. As the outer layer of your skin separates your body from its environment, the cell membrane (also known as the plasma membrane) separates the inner contents of a cell from its exterior environment. This cell membrane provides a protective barrier around the cell and regulates which materials can pass in or out.

Structure and Composition of the Cell Membrane

The **cell membrane** is an extremely pliable structure composed primarily of back-to-back phospholipids (a "bilayer"). Cholesterol is also present, which contributes to the fluidity of the membrane, and there are various proteins embedded within the membrane that have a variety of functions.

A single phospholipid molecule has a phosphate group on one end, called the "head," and two side-by-side chains of fatty acids that make up the lipid tails (Figure 2.2.1). The phosphate group, which includes a phosphate and glycerol, is negatively charged, making the head polar and hydrophilic—or "water loving." A **hydrophilic** molecule (or region of a molecule) is one that is attracted to water. The phosphate heads are thus attracted to the water molecules of both the extracellular and intracellular environments. The lipid tails, on the other hand, are uncharged, or nonpolar, and are hydrophobic—or "water fearing." A **hydrophobic** molecule (or region of a molecule) repels and is repelled by water. Some lipid tails consist of saturated fatty acids, which form straight tails, and some contain unsaturated fatty acids, which form kinked tails. This combination adds to the fluidity of the tails that are constantly in motion. Phospholipids are thus amphipathic molecules. An **amphipathic** molecule is one that contains both a hydrophilic and a hydrophobic region. In fact, soap works to remove oil and grease stains because it has amphipathic properties. The hydrophilic portion can dissolve in water while the hydrophobic portion can trap grease in micelles that then can be washed away.

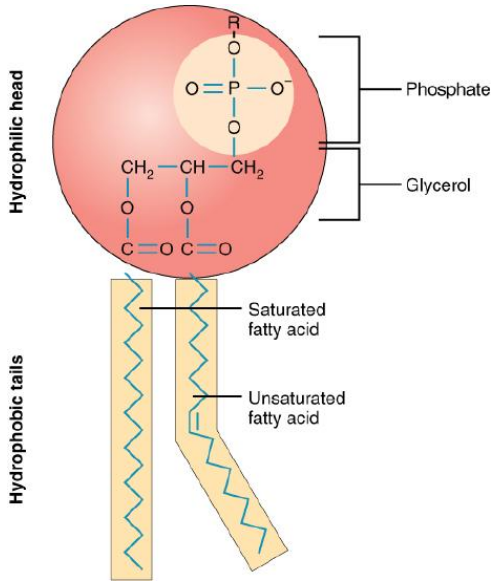

Figure 2.2.1: Phospholipid Structure. A phospholipid molecule consists of a polar phosphate "head," which is hydrophilic and a non-polar lipid "tail," which is hydrophobic. Unsaturated fatty acids result in kinks in the hydrophobic tails. (Image credit: "Phospholipid Structure" by OpenStax is licensed under CC BY 4.0)

The cell membrane consists of two adjacent layers of phospholipids. The lipid tails of one layer face the lipid tails of the other layer, meeting at the interface of the two layers. The phospholipid heads face outward, one layer exposed to the interior of the cell and one layer exposed to the exterior (Figure 2.2.2). Because the phosphate groups are polar and hydrophilic, they are attracted to water in the intracellular fluid. **Intracellular fluid (ICF)** is the fluid interior of the cell. The phosphate groups are also attracted to the extracellular fluid. **Extracellular fluid (ECF)** is the fluid environment outside the enclosure of the cell membrane. **Interstitial fluid (ISF)** is the term given to extracellular fluid not contained within blood vessels. Because the lipid tails are hydrophobic, they meet in the inner region of the membrane, excluding watery intracellular and extracellular fluid from this space. The cell membrane has many proteins, as well as other lipids (such as cholesterol), that are associated with the phospholipid bilayer. An important feature of the membrane is that it remains fluid; the lipids and proteins in the cell membrane are not rigidly locked in place.

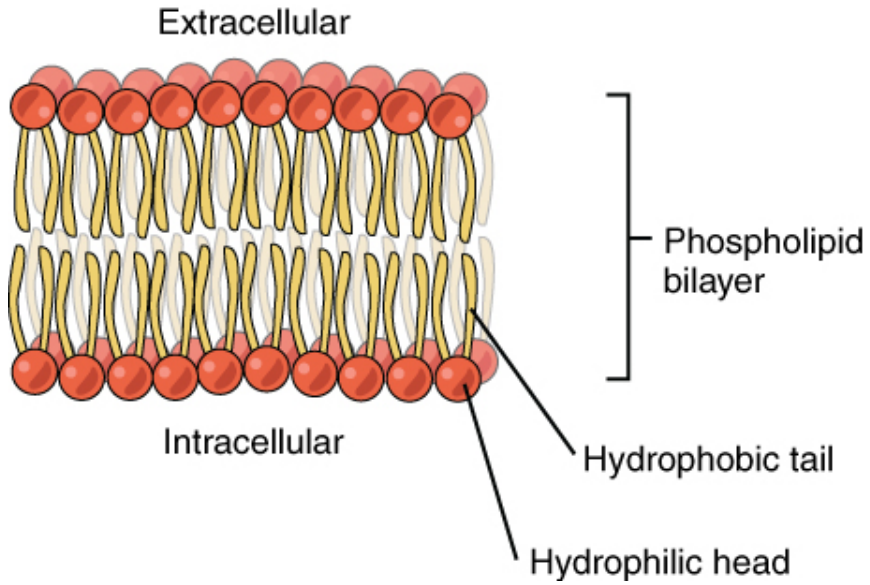

Figure 2.2.2: Phospholipid Bilayer. The phospholipid bilayer consists of two adjacent sheets of phospholipids, arranged tail to tail. The hydrophobic tails associate with one another, forming the interior of the membrane. The polar heads contact the fluid inside and outside of the cell. (Image credit: "Phospholipid Bilayer" by OpenStax is licensed under CC BY 4.0)

Membrane Proteins

The lipid bilayer forms the basis of the cell membrane, but it is peppered throughout with various proteins. Two different types of proteins that are commonly associated with the cell membrane are the integral proteins and peripheral proteins (Figure 2.2.3). As its name suggests, an **integral protein** is a protein that is embedded in the membrane. A **channel protein** is an example of an integral protein that selectively allows particular materials, such as certain ions, to pass into or out of the cell.

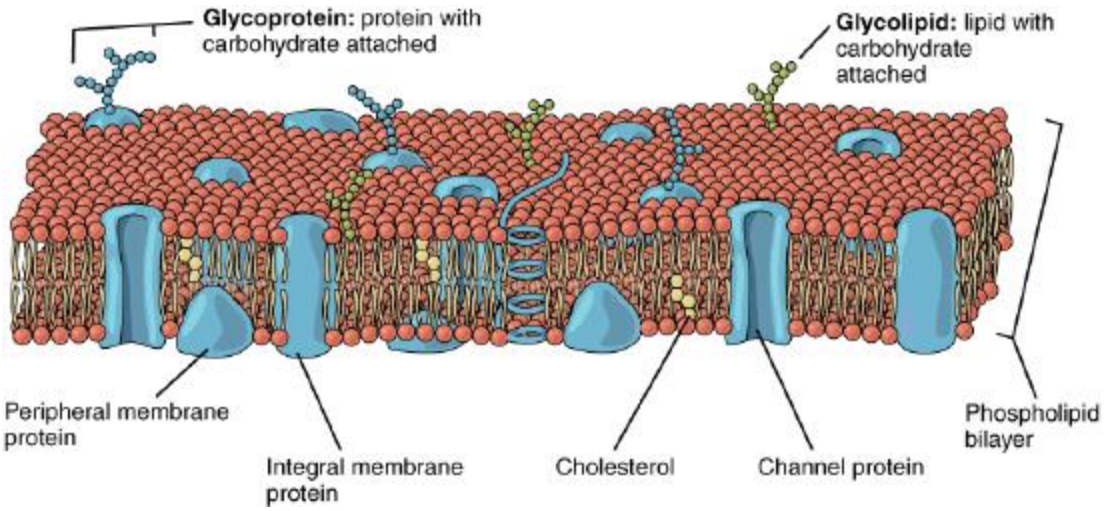

Figure 2.2.3: Cell Membrane. The cell membrane of the cell is a phospholipid bilayer containing many different molecular components, including proteins and cholesterol, some with carbohydrate groups attached. (Image credit: "Lipid Bilayer With Various Components" by OpenStax is licensed under CC BY 4.0)

Another important group of integral proteins are cell recognition proteins, which serve to mark a cell's identity so that it can be recognized by other cells. A **receptor** is a type of recognition protein that can selectively bind a specific molecule outside the cell, and this binding induces a chemical reaction within the cell. A **ligand** is the specific molecule that binds to and activates a receptor. Some integral proteins serve dual roles as both a receptor and an ion channel. One example of a receptor-ligand interaction is the receptors on nerve cells that bind neurotransmitters, such as dopamine. When a dopamine molecule binds to a dopamine receptor protein, a channel within the transmembrane protein opens to allow certain ions to flow into the cell.

Some integral membrane proteins are glycoproteins. A **glycoprotein** is a protein that has carbohydrate molecules attached, which extend into the extracellular matrix. The attached carbohydrate tags on glycoproteins aid in cell recognition. The carbohydrates that extend from membrane proteins and even from some membrane lipids collectively form the glycocalyx. The **glycocalyx** is a fuzzy-appearing coating around the cell formed from glycoproteins and other carbohydrates attached to the cell membrane. The glycocalyx can have various roles. For example, it may have molecules that allow the cell to bind to another cell, it may contain receptors for hormones, or it might have enzymes to break down nutrients. The glycocalyces found in your body are products of your genetic makeup. They give each of your trillions of cells the "identity" of belonging in your body. This identity is the primary way that your immune defense cells "know" not to attack your own body cells, but it also is the reason organs donated by another person might be rejected.

Peripheral proteins are typically found on the inner or outer surface of the lipid bilayer but can also be attached to the internal or external surface of an integral protein. These proteins typically perform a specific function for the cell. Some peripheral proteins on the surface of intestinal cells, for example, act as digestive enzymes to break down nutrients to sizes that can pass through the cells and into the bloodstream.

Extensions of the Plasma Membrane

The plasma membrane is not always just a smooth round surface. Some cells may have extensions or folds of the plasma membrane, such as microvilli, flagella, or cilia. **Microvilli** are small folds in the plasma membrane that help to increase the surface area for purpose of transport of materials. Extensions like **flagellum** and **cilia** can be used to produce movement by the cytoskeleton, which is discussed further in another section of this chapter. You can compare the structure of these three extensions in Figure 2.2.4 below.

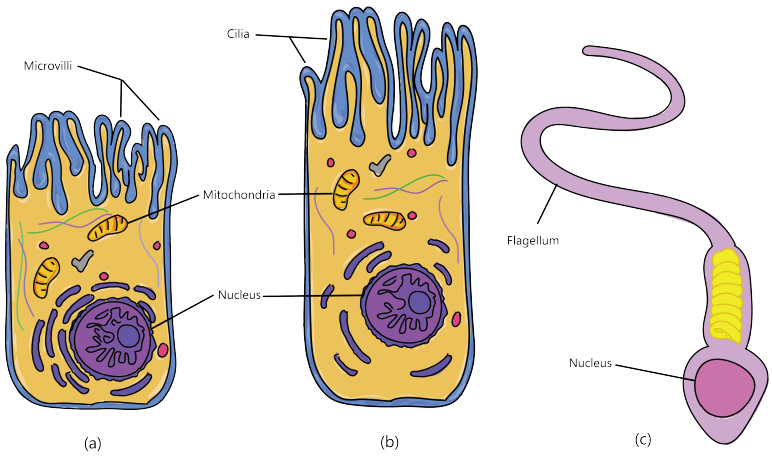

Figure 2.2.4: Extensions of the Plasma Membrane. Cells with specialized functions may have extensions of their plasma membrane including (a) microvilli (b) cilia or (c) a flagellum.(Image credit: "Extensions of the Plasma Membrane" by Whitney Menefee is a derivative from the original work of Daniel Donnelly and is licensed under CC BY 4.0)

Transport across the Cell Membrane

One of the great wonders of the cell membrane is its ability to regulate the concentration of substances inside the cell. These substances include ions such as Ca^{++}, Na^{+}, K^{+}, and Cl^{-}; nutrients including sugars, fatty acids, and amino acids; and waste products, particularly carbon dioxide (CO_2), that must leave the cell.

The membrane's lipid bilayer structure provides the first level of control. The phospholipids are tightly packed together, and the membrane has a hydrophobic interior. This structure causes the membrane to be selectively permeable. A membrane that has **selective permeability** allows only substances meeting certain criteria to pass through it unaided. In the case of the cell membrane, only relatively small, nonpolar materials can move through the lipid bilayer (remember, the lipid tails of the membrane are nonpolar). Some examples of these are other lipids, oxygen and carbon dioxide gases, and alcohol. However, water-soluble materials—like glucose, amino acids, and electrolytes—need some assistance to cross the membrane because they are repelled by the hydrophobic tails of the phospholipid bilayer. All substances that move through the membrane do so by one of two general methods, which are categorized based on whether or not energy is required. **Passive transport** is the movement of substances across the membrane without the expenditure of cellular energy. In contrast, **active transport** is the movement of substances across the membrane using energy from adenosine triphosphate (ATP).

Passive Transport

In order to understand how substances move passively across a cell membrane, it is necessary to understand concentration gradients and diffusion. A **concentration gradient** is the difference in concentration of a substance across a space. Molecules (or ions) will spread/diffuse from where they are more concentrated to where they are less concentrated until they are equally distributed in that space. (When molecules move in this way, they are said to move down their concentration gradient.) **Diffusion** is the movement of particles from an area of higher concentration to an area of lower concentration. A couple of common examples will help to illustrate this concept. Imagine being inside a closed bathroom. If a bottle of perfume were sprayed, the scent molecules would naturally diffuse from the spot where they left the bottle to all corners of the bathroom, and this diffusion would go on until no more concentration gradient remains. Another example is a spoonful of sugar placed in a cup of tea. Eventually the sugar will diffuse throughout the tea until no concentration gradient remains. In both cases, if the room is warmer or the tea hotter, diffusion occurs even faster as the molecules are bumping into each other and spreading out faster than at cooler temperatures. Having an internal body temperature around 98.6 °F thus also aids in diffusion of particles within the body.

Whenever a substance exists in greater concentration on one side of a semipermeable membrane, such as the cell membrane, any substance that can move down its concentration gradient across the membrane will do so. Consider substances that can easily diffuse through the lipid bilayer of the cell membrane, such as the gases oxygen (O_2) and CO_2. O_2 generally diffuses into

cells because it is more concentrated outside of them, and CO_2 typically diffuses out of cells because it is more concentrated inside of them. Neither of these examples requires any energy on the part of the cell, and therefore they use passive transport to move across the membrane.

Interactive Link

Diffusion

View this GIF showing the process of diffusion and how it is propelled by the kinetic energy of molecules in solution. How does temperature affect diffusion rate, and why?

Answer available at the end of this section.

Before moving on, you need to review the gases that can diffuse across a cell membrane. Because cells rapidly use up oxygen during metabolism, there is typically a lower concentration of O_2 inside the cell than outside. As a result, oxygen, a small, non-polar substance, will diffuse from the interstitial fluid directly through the lipid bilayer of the membrane and into the cytoplasm within the cell. On the other hand, because cells produce CO_2 as a byproduct of metabolism, CO_2 concentrations rise within the cytoplasm; therefore, CO_2 will move from the cell through the lipid bilayer and into the interstitial fluid, where its concentration is lower. This mechanism of molecules spreading from where they are more concentrated to where they are less concentration is a form of passive transport called simple diffusion (Figure 2.2.5).

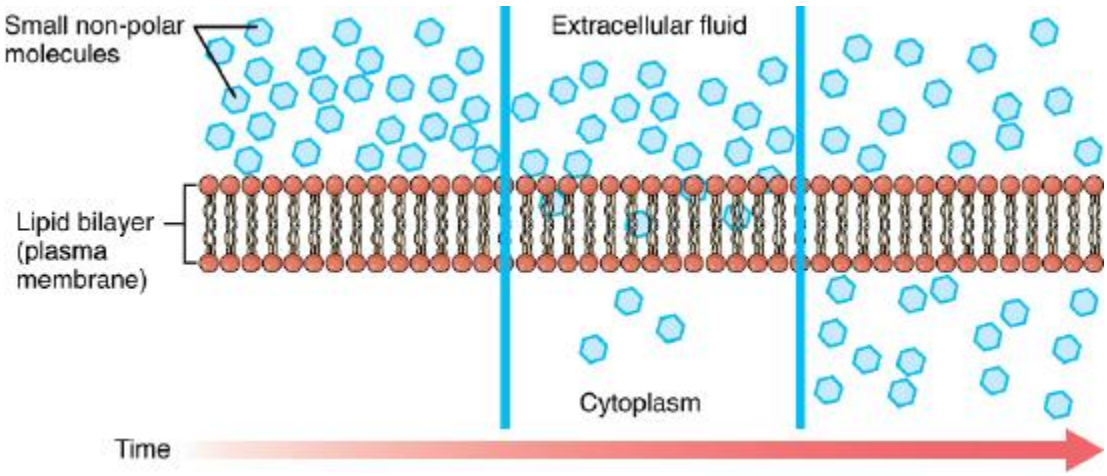

Figure 2.2.5: Simple Diffusion across the Cell (Plasma) Membrane. The structure of the lipid bilayer allows only small, non-polar substances such as oxygen and carbon dioxide to pass through the cell membrane, down their concentration gradient, by simple diffusion. (Image credit: "Simple Diffusion Across Plasma Membrane" by OpenStax is licensed under CC BY 4.0)

Solutes dissolved in water on either side of the cell membrane will tend to diffuse down their concentration gradients, but because most substances cannot pass freely through the lipid bilayer of the cell membrane, their movement is restricted to protein channels and specialized transport mechanisms in the membrane. **Facilitated diffusion** is the diffusion process used for those substances that cannot cross the lipid bilayer due to their size and/or polarity (Figure 2.2.6). A common example of facilitated diffusion is the movement of glucose into the cell, where it is used to make ATP. Although glucose can be more

concentrated outside of a cell, it cannot cross the lipid bilayer via simple diffusion because it is both large and polar. To resolve this, a specialized carrier protein called the glucose transporter will transfer glucose molecules into the cell to facilitate its inward diffusion.

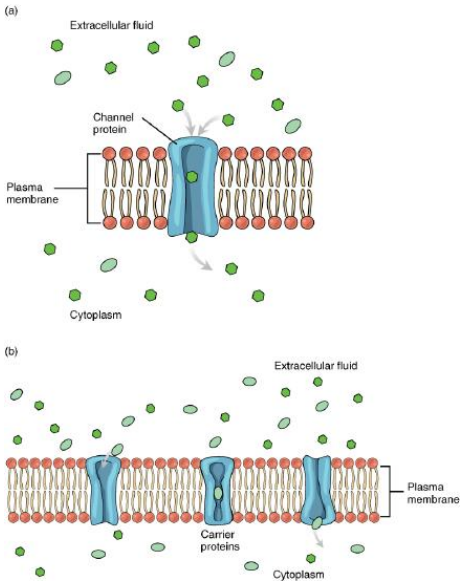

Figure 2.2.6: Facilitated Diffusion.(a) Facilitated diffusion of substances crossing the cell (plasma) membrane takes place with the help of proteins such as channel proteins and carrier proteins. Channel proteins are less selective than carrier proteins, and usually mildly discriminate between their cargo based on size and charge. (b) Carrier proteins are more selective, often only allowing one particular type of molecule to cross. (Image credit: "Facilitated Diffusion" by OpenStax is licensed under CC BY 4.0)

Facilitated diffusion is critical to the movement of charged ions such as sodium (Na^+). Even though sodium (Na^+) ions are small and highly concentrated outside of cells, these electrolytes are polarized and cannot pass through the nonpolar lipid bilayer of the membrane. Their diffusion is facilitated by membrane proteins that form sodium channels (or “pores”), so that Na^+ ions can move down their concentration gradient from outside the cells to inside the cells. There are many other solutes that must undergo facilitated diffusion to move into a cell, such as amino acids, or to move out of a cell, such as wastes. Because facilitated diffusion is a passive process, it does not require energy expenditure by the cell.

Water also can move freely across the cell membrane of all cells, either through protein channels or by slipping between the lipid tails of the membrane itself. **Osmosis** is the diffusion of water through a semipermeable membrane (Figure 2.2.7).

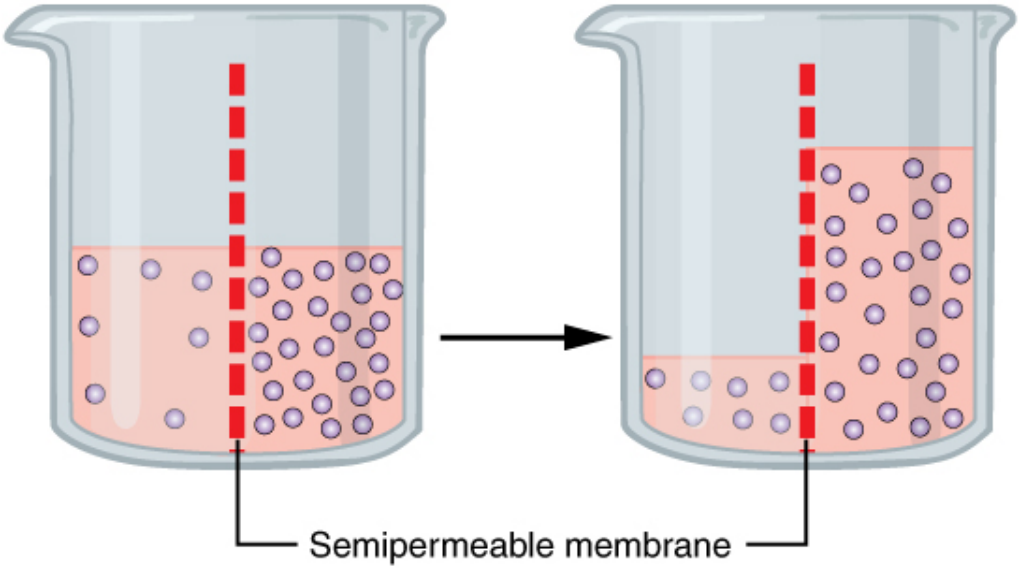

Figure 2.2.7: Osmosis. Osmosis is the diffusion of water through a semipermeable membrane down its concentration gradient. If a membrane is permeable to water, though not to a solute, water will equalize its own concentration by diffusing to the side of lower water concentration (and thus the side of higher solute concentration). In the beaker on the left, the solution on the right side of the membrane is hypertonic. (Image credit: "Osmosis" by OpenStax is licensed under CC BY 4.0)

The movement of water molecules is not itself regulated by cells, so it is important that cells are exposed to an environment in which the concentration of solutes outside of the cells (in the extracellular fluid) is equal to the concentration of solutes inside the cells (in the cytoplasm). Two solutions that have the same concentration of solutes are said to be **isotonic** (equal tension). When cells and their extracellular environments are isotonic, the concentration of water molecules is the same outside and inside the cells, and the cells maintain their normal shape (and function).

Osmosis occurs when there is an imbalance of solutes outside of a cell versus inside the cell. A solution that has a higher concentration of solutes than another solution is said to be **hypertonic**, and water molecules tend to diffuse into a hypertonic solution (Figure 2.2.8). Cells in a hypertonic solution will shrivel as water leaves the cell via osmosis. In contrast, a solution that has a lower concentration of solutes than another solution is said to be **hypotonic,** and water molecules tend to diffuse out of a hypotonic solution. Cells in a hypotonic solution will take on too much water and swell, with the risk of eventually bursting. A critical aspect of homeostasis in living things is to create an internal environment in which all of the body's cells are in an isotonic solution. Various organ systems, particularly the kidneys, work to maintain this homeostasis.

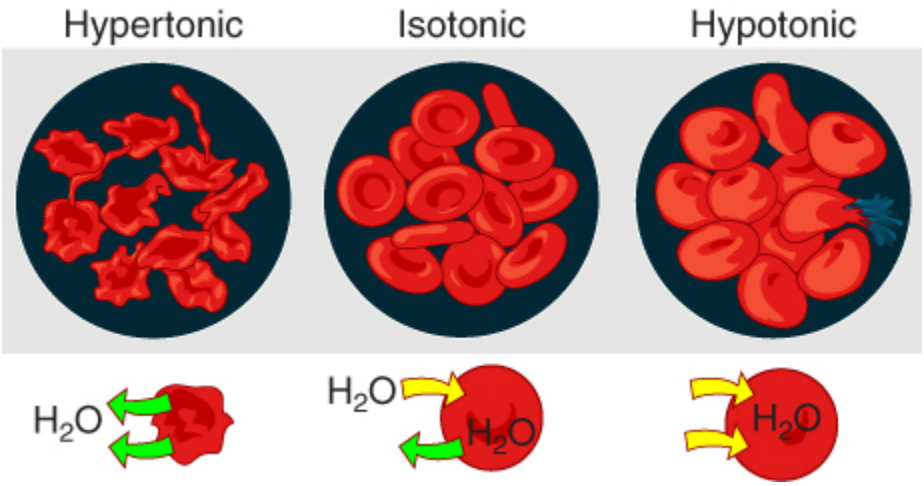

Figure 2.2.8: Concentration of Solutions. A hypertonic solution has a solute concentration higher than another solution. An isotonic solution has a solute concentration equal to another solution. A hypotonic solution has a solute concentration lower than another solution. (Image credit: "Concentration of Solutions" by OpenStax is licensed under CC BY 4.0)

Another mechanism besides diffusion to passively transport materials between compartments is filtration. Unlike diffusion of a

substance from where it is more concentrated to less concentrated, filtration uses a hydrostatic pressure gradient that pushes the fluid—and the solutes within it—from a higher pressure area to a lower pressure area. Filtration is an extremely important process in the body. For example, the circulatory system uses filtration to move plasma and substances across the endothelial lining of capillaries and into surrounding tissues, supplying cells with nutrients. Likewise, filtration pressure in the kidneys provides the mechanism to remove wastes from the bloodstream.

Active Transport

For all of the transport methods described above as passive transport, the cell expends no energy. Membrane proteins that aid in the passive transport of substances do so without the use of ATP. During active transport however, ATP is required to move a substance across a membrane. Whenever ATP is expended to actively move substances in or out of a cell, one or more membrane proteins will be involved in the transport process.

One of the most common types of active transport involves proteins that serve as pumps. The word “pump” probably conjures up thoughts of using energy to pump up the tire of a bicycle or a basketball, when energy is used to move air against a pressure gradient and inflate the tire or ball. Similarly, energy from ATP is required for these membrane proteins to transport substances—molecules or ions—across the membrane, usually against their concentration gradients (from an area of low concentration to an area of high concentration).

The **sodium-potassium pump**, which is also called Na^+/K^+ ATPase, transports sodium out of a cell while moving potassium into the cell. The Na^+/K^+ pump is an important ion pump found in the membranes of many types of cells. These pumps are particularly abundant in nerve cells, which are constantly pumping out sodium ions and pulling in potassium ions to maintain an electrical gradient across their cell membranes. An **electrical gradient** is a difference in electrical charge across a space. In the case of nerve cells, for example, the electrical gradient exists between the inside and outside of the cell, with the inside being negatively-charged (at around -70 mV) relative to the outside. The negative electrical gradient is maintained because each Na^+/K^+ pump moves three Na^+ ions out of the cell and two K^+ ions into the cell for each ATP molecule that is used (Figure 2.2.9). This process is so important for nerve cells that it accounts for the majority of their ATP usage.

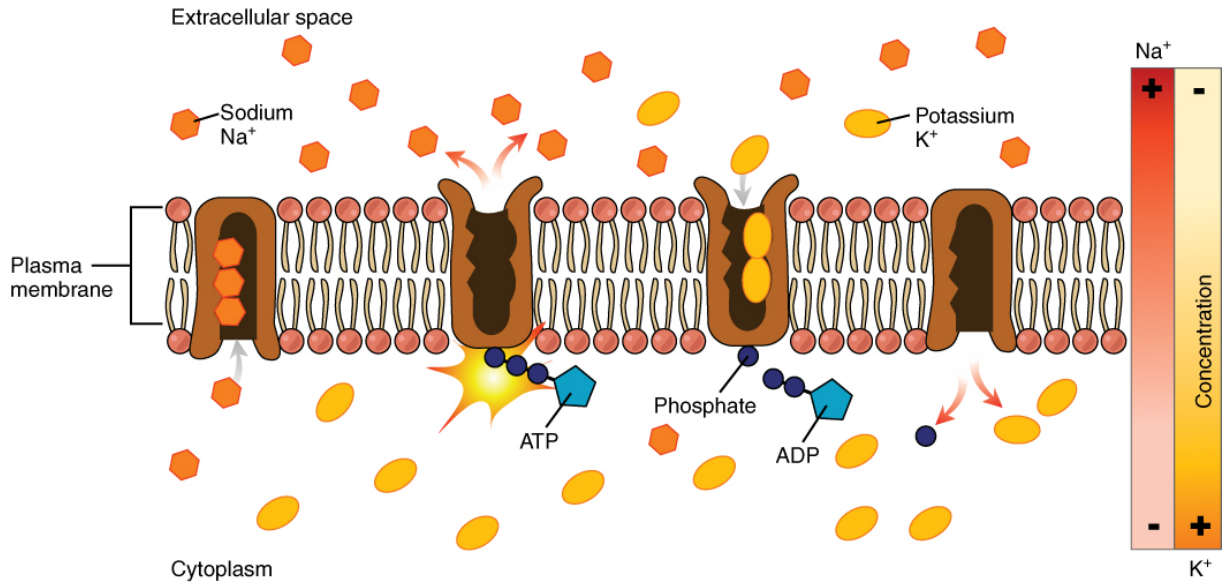

Figure 2.2.9: Sodium-Potassium Pump. The sodium-potassium pump is found in many cell (plasma) membranes. Powered by ATP, the pump moves sodium and potassium ions in opposite directions, each against its concentration gradient. In a single cycle of the pump, three sodium ions are extruded from and two potassium ions are imported into the cell. (Image credit: "Sodium Potassium Pump" by OpenStax is licensed under CC BY 4.0)

Active transport pumps can also work together with other active or passive transport systems to move substances across the membrane. For example, the sodium-potassium pump maintains a high concentration of sodium ions outside of the cell. Therefore, if the cell needs sodium ions, all it has to do is open a passive sodium channel, as the concentration gradient of the sodium ions will drive them to diffuse into the cell. In this way, the action of an active transport pump (the sodium-potassium pump) powers the passive transport of sodium ions by creating a concentration gradient. When active transport powers the

transport of another substance in this way, it is called secondary active transport.

Symporters are secondary active transporters that move two substances in the same direction. For example, the sodium-glucose symporter uses sodium ions to “pull” glucose molecules into the cell. Because cells store glucose for energy, glucose is typically at a higher concentration inside of the cell than outside. However, due to the action of the sodium-potassium pump, sodium ions will easily diffuse into the cell when the symporter is opened. The flood of sodium ions through the symporter provides the energy that allows glucose to move through the symporter and into the cell, against its concentration gradient.

Conversely, antiporters are secondary active transport systems that transport substances in opposite directions. For example, the sodium-hydrogen ion antiporter uses the energy from the inward flood of sodium ions to move hydrogen ions (H^+) out of the cell. The sodium-hydrogen antiporter is used to maintain the pH of the cell's interior.

Other forms of active transport do not involve membrane carriers. **Endocytosis** (bringing “into the cell”) is the process of a cell ingesting material by enveloping it in a portion of its cell membrane, and then pinching off that portion of membrane (Figure 2.2.10). Once pinched off, the portion of membrane and its contents becomes an independent, intracellular vesicle. A **vesicle** is a membranous sac—a spherical and hollow organelle bounded by a lipid bilayer membrane. Endocytosis often brings materials into the cell that must to be broken down or digested. **Phagocytosis** (“cell eating”) is the endocytosis of large particles. Many immune cells engage in phagocytosis of invading pathogens. Like little Pac-men, their job is to patrol body tissues for unwanted matter, such as invading bacterial cells, phagocytize them, and digest them. In contrast to phagocytosis, **pinocytosis** (“cell drinking”) brings fluid containing dissolved substances into a cell through membrane vesicles.

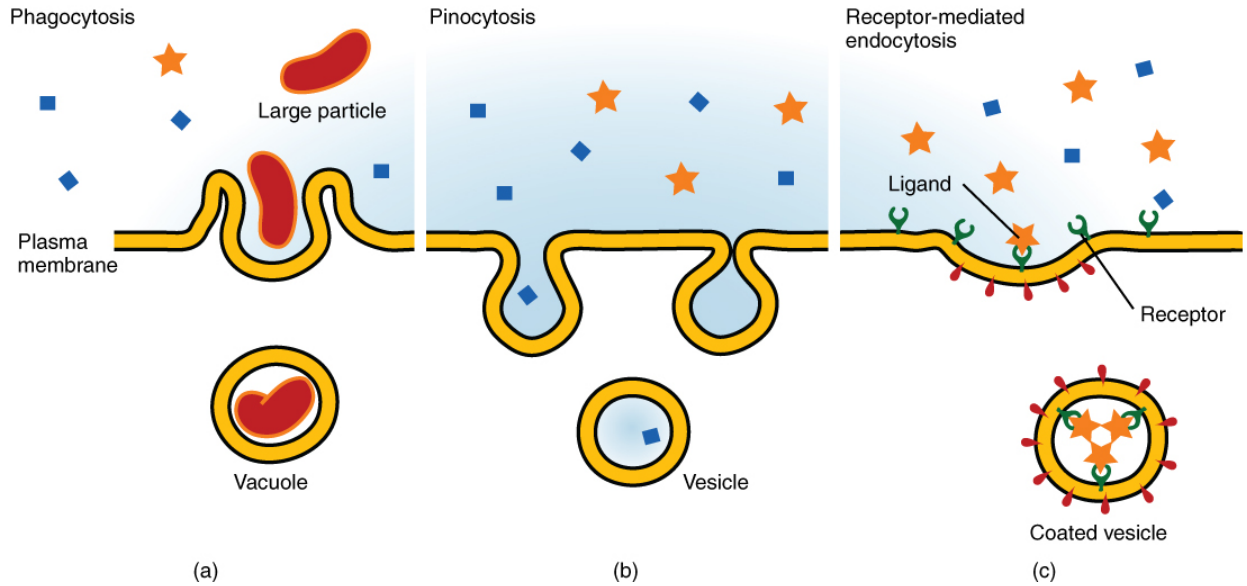

Figure 2.2.10: Three Forms of Endocytosis. Endocytosis is a form of active transport in which a cell envelopes extracellular materials using its cell membrane. (a) In phagocytosis, which is relatively nonselective, the cell takes in a large particle. (b) In pinocytosis, the cell takes in small particles in fluid. (c) In contrast, receptor-mediated endocytosis is quite selective. When external receptors bind a specific ligand, the cell responds by endocytosing the ligand. (Image credit: "Three Forms of Endocytosis" by OpenStax is licensed under CC BY 4.0)

Phagocytosis and pinocytosis take in large portions of extracellular material, and they are typically not highly selective in the substances they bring in. Cells regulate the endocytosis of specific substances via receptor-mediated endocytosis. Receptor-mediated endocytosis is endocytosis by a portion of the cell membrane that contains many receptors that are specific for a certain substance. Once the surface receptors have bound sufficient amounts of the specific substance (the receptor’s ligand), the cell will endocytose the part of the cell membrane containing the receptor-ligand complexes. Iron, a required component of hemoglobin, is endocytosed by red blood cells in this way. Iron is bound to a protein called transferrin in the blood. Specific transferrin receptors on red blood cell surfaces bind the iron-transferrin molecules, and the cell endocytoses the receptor-ligand complexes.

In contrast with endocytosis, exocytosis (taking “out of the cell”) is the process of a cell exporting material using vesicular transport (Figure 2.2.11). Many cells manufacture substances that must be secreted, like a factory manufacturing a product for export. These substances are typically packaged into membrane-bound vesicles within the cell. When the vesicle membrane fuses with the cell membrane, the vesicle releases its contents into the interstitial fluid. The vesicle membrane then becomes part of the cell membrane. Cells of the stomach and pancreas produce and secrete digestive enzymes through exocytosis (Figure 2.2.12).

Endocrine cells produce and secrete hormones that are sent throughout the body, and certain immune cells produce and secrete large amounts of histamine, a chemical important for immune responses.

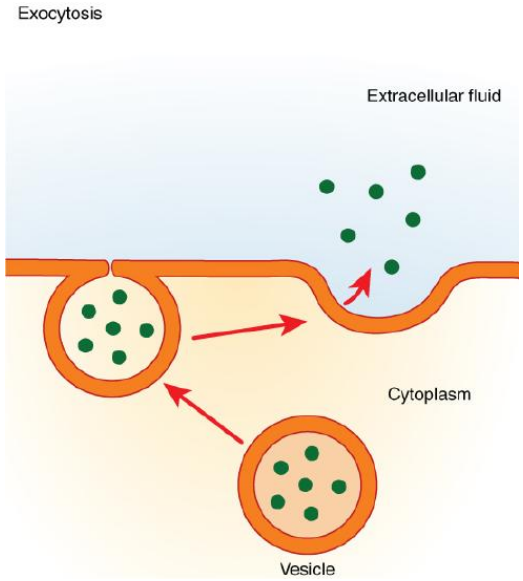

Figure 2.2.11: Exocytosis. Exocytosis is much like endocytosis in reverse. Material destined for export is packaged into a vesicle inside the cell. The membrane of the vesicle fuses with the cell membrane, and the contents are released into the extracellular space. (Image credit: "Exocytosis" by OpenStax is licensed under CC BY 4.0)

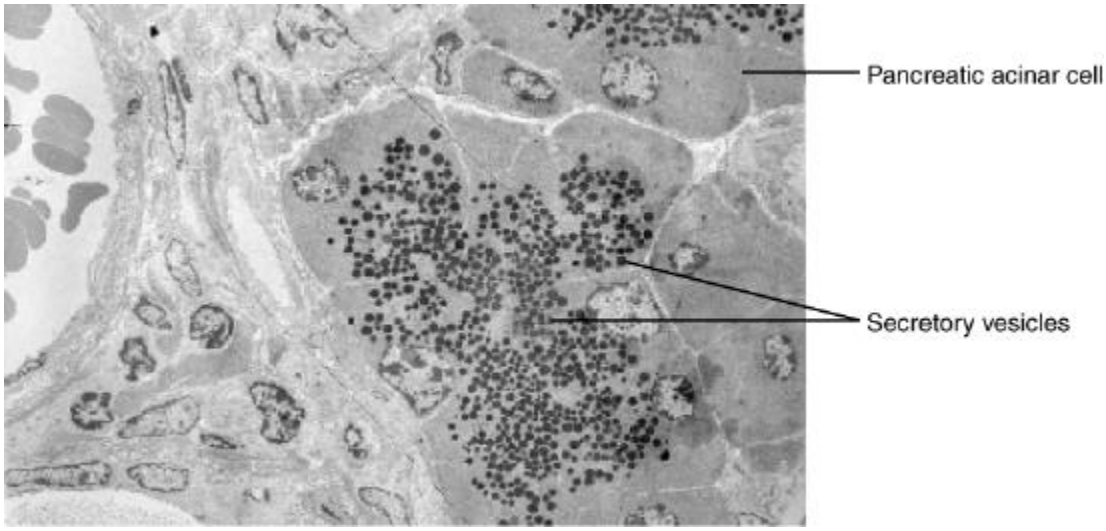

Figure 2.2.12: Pancreatic Cells' Enzyme Products. The pancreatic acinar cells produce and secrete many enzymes that digest food. The tiny black granules in this electron micrograph are secretory vesicles filled with enzymes that will be exported from the cells via exocytosis. LM × 2900. (Image credit: "Pancreatic Cells Micrograph" by OpenStax is licensed under CC BY 4.0/Micrograph provided by the Regents of University of Michigan Medical School © 2012)

DISEASES OF THE CELL: Cystic Fibrosis

Cystic fibrosis (CF) affects approximately 30,000 people in the United States, with about 1,000 new cases reported each year. The genetic disease is most well known for its damage to the lungs, causing breathing difficulties and chronic lung infections, but it also affects the liver, pancreas, and intestines. Only about 50 years ago, the prognosis for children born with CF was very grim—a life expectancy rarely over 10 years. Today, with advances in medical treatment, average life expectancy for CF patients is in the late 30s and many live much longer.

The symptoms of CF result from a malfunctioning membrane ion channel called the cystic fibrosis transmembrane conductance regulator, or CFTR. In healthy people, the CFTR protein is an integral membrane protein that transports chloride (Cl^-) ions out of the cell. In a person who has CF, the gene for the CFTR is mutated, thus, the cell manufactures a defective channel protein that typically is not incorporated into the membrane, but is instead degraded by the cell.

The CFTR requires ATP in order to function, making its Cl^- transport a form of active transport. This characteristic puzzled researchers for a long time because the Cl^- ions are actually flowing *down* their concentration gradient when transported out of cells. Active transport generally pumps ions *against* their concentration gradient, but the CFTR presents an exception to this rule.

In normal lung tissue, the movement of Cl^- out of the cell maintains a Cl^--rich, negatively charged environment immediately outside of the cell. This is particularly important in the epithelial lining of the respiratory system. Respiratory epithelial cells secrete mucus, which serves to trap dust, bacteria, and other debris. A cilium (plural = cilia) is one of the hair-like appendages found on certain cells. Cilia on the epithelial cells move the mucus and its trapped particles up the airways away from the lungs and toward the outside. In order to be effectively moved upward, the mucus cannot be too viscous; rather it must have a thin, watery consistency. The transport of Cl^- and the maintenance of an electronegative environment outside of the cell attract positive ions such as Na^+ to the extracellular space. The accumulation of both Cl^- and Na^+ ions in the extracellular space creates solute-rich mucus, which has a low concentration of water molecules. As a result, through osmosis, water moves from cells and extracellular matrix into the mucus, “thinning” it out. This is how, in a normal respiratory system, the mucus is kept sufficiently watered-down to be propelled out of the respiratory system.

If the CFTR channel is absent, Cl^- ions are not transported out of the cell in adequate numbers, thus preventing them from drawing positive ions. The absence of ions in the secreted mucus results in the lack of a normal water concentration gradient. Thus, there is no osmotic pressure pulling water into the mucus. The resulting mucus is thick and sticky, and the ciliated epithelia cannot effectively remove it from the respiratory system. Passageways in the lungs become blocked with mucus, along with the debris it carries. Bacterial infections occur more easily because bacterial cells are not effectively carried away from the lungs.

Concept Review

The cell membrane provides a barrier around the cell, separating its internal components from the extracellular environment. It is composed of a phospholipid bilayer, with hydrophobic internal lipid “tails” and hydrophilic external phosphate “heads.” Various membrane proteins are scattered throughout the bilayer, both inserted within it and attached to it peripherally. The cell membrane is selectively permeable, allowing only a limited number of materials to diffuse through its lipid bilayer. All materials that cross the membrane do so using passive (non energy-requiring) or active (energy-requiring) transport processes. During passive transport, materials move by simple diffusion or by facilitated diffusion through the membrane, down their concentration gradient. Water passes through the membrane in a diffusion process called osmosis. During active transport, energy is expended to assist material movement across the membrane. Active transport may take place with the help of protein pumps or through the use of vesicles.

Review Questions

Q. Because they are embedded within the membrane, ion channels are examples of _____.

A. receptor proteins

B. integral proteins

C. peripheral proteins

D. glycoproteins

Answer

Answer: B

Q. The diffusion of substances within a solution tends to move those substances _____ their _____ gradient.

A. up; concentration

B. up; electrochemical

C. down; pressure

D. down; concentration

Answer

Answer: D

Q. Ion pumps and phagocytosis are both examples of _____.

A. endocytosis

B. passive transport

C. active transport

D. facilitated diffusion

Answer

Answer: C

Q. Choose the answer that best completes the following analogy: Diffusion is to _____ as endocytosis is to _____.

A. filtration; phagocytosis

B. osmosis; pinocytosis

C. solutes; fluid

D. gradient; chemical energy

Answer

Answer: B

Critical Thinking Questions

Q. What materials can easily diffuse through the lipid bilayer, and why?

Answer

A. Only materials that are relatively small and nonpolar can easily diffuse through the lipid bilayer. Large particles cannot fit in between the individual phospholipids that are packed together, and polar molecules are repelled by the hydrophobic/nonpolar lipids that line the inside of the bilayer.

Q. Why is receptor-mediated endocytosis said to be more selective than phagocytosis or pinocytosis?

Answer

A. Receptor-mediated endocytosis is more selective because the substances that are brought into the cell are the specific ligands that could bind to the receptors being endocytosed. Phagocytosis or pinocytosis, on the other hand, have no such receptor-ligand specificity, and bring in whatever materials happen to be close to the membrane when it is enveloped.

Q. What do osmosis, diffusion, filtration, and the movement of ions away from like charge all have in common? In what way do they differ?

Answer

A. These four phenomena are similar in the sense that they describe the movement of substances down a particular type of gradient. Osmosis and diffusion involve the movement of water and other substances down their concentration gradients, respectively. Filtration describes the movement of particles down a pressure gradient, and the movement of ions away from like charge describes their movement down their electrical gradient.

Glossary

active transport
: form of transport across the cell membrane that requires input of cellular energy

amphipathic
: describes a molecule that exhibits a difference in polarity between its two ends, resulting in a difference in water solubility

cell membrane
: membrane surrounding all animal cells, composed of a lipid bilayer interspersed with various molecules; also known as plasma membrane

channel protein
: membrane-spanning protein that has an inner pore which allows the passage of one or more substances

cilia
: small appendage on certain cells formed by microtubules and modified for movement of materials across the cellular surface

concentration gradient
: difference in the concentration of a substance between two regions

diffusion
: movement of a substance from an area of higher concentration to one of lower concentration

electrical gradient
: difference in the electrical charge (potential) between two regions

endocytosis
: import of material into the cell by formation of a membrane-bound vesicle

exocytosis
: export of a substance out of a cell by formation of a membrane-bound vesicle

extracellular fluid (ECF)
: fluid exterior to cells; includes the interstitial fluid, blood plasma, and fluid found in other reservoirs in the body

facilitated diffusion
: diffusion of a substance with the aid of a membrane protein

flagellum
: appendage on certain cells formed by microtubules and modified for movement

glycocalyx
coating of sugar molecules that surrounds the cell membrane

glycoprotein
protein that has one or more carbohydrates attached

hydrophilic
describes a substance or structure attracted to water

hydrophobic
describes a substance or structure repelled by water

hypertonic
describes a solution concentration that is higher than a reference concentration

hypotonic
describes a solution concentration that is lower than a reference concentration

integral protein
membrane-associated protein that spans the entire width of the lipid bilayer

interstitial fluid (IF)
fluid in the small spaces between cells not contained within blood vessels

intracellular fluid (ICF)
fluid in the cytosol of cells

isotonic
describes a solution concentration that is the same as a reference concentration

ligand
molecule that binds with specificity to a specific receptor molecule

microvilli
small folds in the plasma membrane that help to increase surface area

osmosis
diffusion of molecules down their concentration across a selectively permeable membrane

passive transport
form of transport across the cell membrane that does not require input of cellular energy

peripheral protein
membrane-associated protein that does not span the width of the lipid bilayer, but is attached to the inside or outside of the membrane by way of integral proteins, membrane lipids, or other components of the membrane

phagocytosis
endocytosis of large particles

pinocytosis
endocytosis of fluid

receptor
protein molecule that contains a binding site for another specific molecule (called a ligand)

receptor-mediated endocytosis
endocytosis of ligands attached to membrane-bound receptors

selective permeability
feature of any barrier that allows certain substances to cross but excludes others

sodium-potassium pump
(also, Na^+/K^+ ATP-ase) membrane-embedded protein pump that uses ATP to move Na^+ out of a cell and K^+ into the cell

vesicle
membrane-bound structure that contains materials within or outside of the cell

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Answers

Interactive Link

Answer: Higher temperatures speed up diffusion because molecules have more kinetic energy at higher temperatures.

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2.3: The Cytoplasm and Cellular Organelles

By the end of the section, you will be able to:

- Describe the structure and function of the cellular organelles associated with the endomembrane system, including the endoplasmic reticulum, Golgi apparatus, and lysosomes
- Describe the structure and function of mitochondria and peroxisomes
- Explain the three components of the cytoskeleton, including their composition and functions

Now that you have learned that the cell membrane surrounds all cells, you can dive inside of a prototypical human cell to learn about its internal components and their functions. All living cells in multicellular organisms contain an internal cytoplasmic compartment, and a nucleus within the cytoplasm. **Cytosol**, the jelly-like substance within the cell, provides the fluid medium necessary for biochemical reactions. Eukaryotic cells, including all animal cells, also contain various cellular organelles. An **organelle** ("little organ") is one of several different types of specialized structures in the cell, each performing a unique function. Just as the various bodily organs work together in harmony to perform all of a human's functions, the many different cellular organelles work together to keep the cell healthy and performing all of its important functions. The organelles and cytosol, taken together, compose the cell's **cytoplasm**. The **nucleus** is a cell's central organelle, which contains the cell's DNA (Figure 2.3.1).

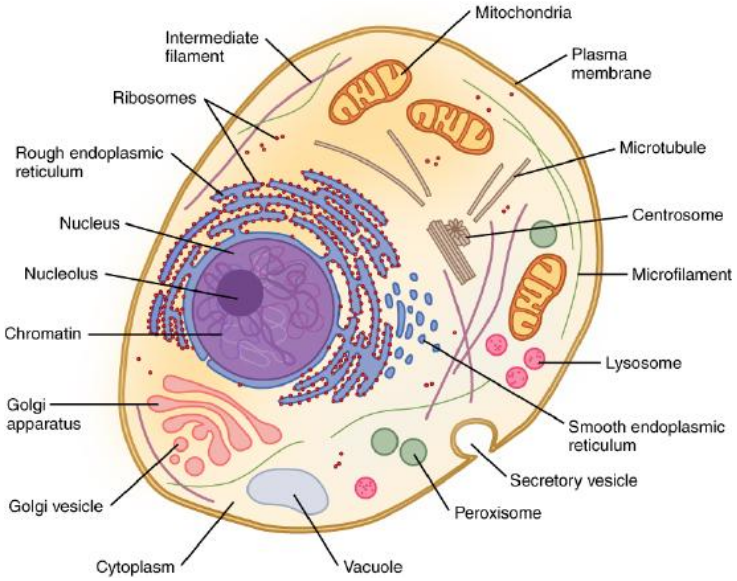

Figure 2.3.1: Prototypical Human Cell. While this image is not indicative of any one particular human cell, it is a prototypical example of a cell containing the primary organelles and internal structures. (Image credit: "Animal Cell and Components" by OpenStax is licensed under CC BY 4.0)

Organelles of the Endomembrane System

A set of three major organelles together form a system within the cell called the endomembrane system. These organelles work together to perform various cellular jobs, including the task of producing, packaging, and exporting certain cellular products. The organelles of the endomembrane system include the endoplasmic reticulum, Golgi apparatus, and vesicles.

Endoplasmic Reticulum

The **endoplasmic reticulum (ER)** is a system of channels that is continuous with the nuclear membrane (or "envelope") covering the nucleus and composed of the same lipid bilayer material. The ER can be thought of as a series of winding thoroughfares similar to the waterway canals in Venice. The ER provides passages throughout much of the cell that function in transporting, synthesizing, and storing materials. The winding structure of the ER results in a large membranous surface area that supports its

many functions (Figure 2.3.2).

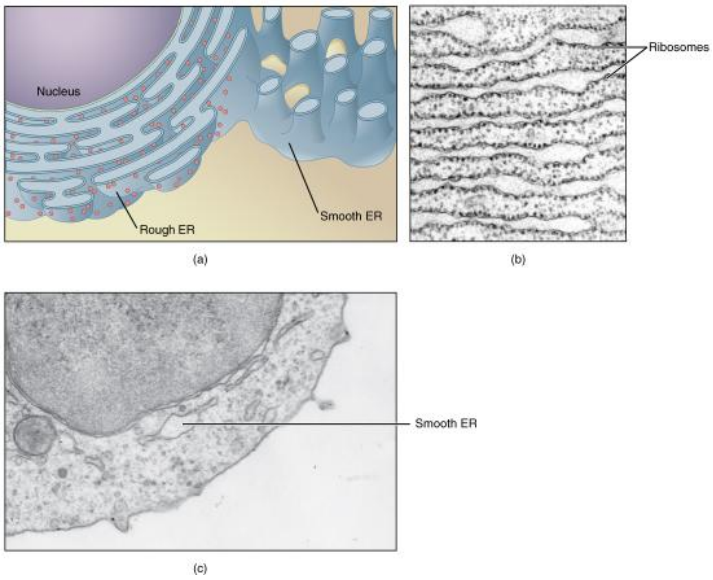

Figure 2.3.2: Endoplasmic Reticulum (ER). (a) The ER is a winding network of thin membranous sacs found in close association with the cell nucleus. The smooth and rough endoplasmic reticula are very different in appearance and function. (b) Rough ER is studded with numerous ribosomes, which are sites of protein synthesis (source: mouse tissue). EM × 110,000. (c) Smooth ER synthesizes phospholipids, steroid hormones, regulates the concentration of cellular Ca^{++},metabolizes some carbohydrates, and breaks down certain toxins (source: mouse tissue). EM × 110,510. (Image credit: "Endoplasmic Reticulum" by OpenStax is licensed under CC BY 4.0/ Micrographs provided by the Regents of University of Michigan Medical School © 2012)

Endoplasmic reticulum can exist in two forms: rough ER and smooth ER. These two types of ER perform some very different functions and can be found in very different amounts depending on the type of cell. Rough ER (RER) is so-called because its membrane is dotted with embedded granules—organelles called ribosomes, giving the RER a bumpy appearance. A **ribosome** is an organelle that serves as the site of protein synthesis. Smooth ER (SER) lacks these ribosomes.

One of the main functions of the smooth ER is in the synthesis of lipids. The smooth ER synthesizes phospholipids, the main component of biological membranes, as well as steroid hormones. For this reason, cells that produce large quantities of such hormones, such as those of the female ovaries and male testes, contain large amounts of smooth ER. In addition to lipid synthesis, the smooth ER also sequesters (i.e., stores) and regulates the concentration of cellular Ca^{++}, a function extremely important in cells of the nervous system where Ca^{++} is the trigger for neurotransmitter release. The smooth ER additionally metabolizes some carbohydrates and performs a detoxification role, breaking down certain toxins.

In contrast with the smooth ER, the primary job of the rough ER is the modification of proteins destined for the cell membrane or for export from the cell. For this protein synthesis, many ribosomes attach to the ER (giving it the studded appearance of rough ER). Typically, a protein is synthesized within the ribosome and released inside the channel of the rough ER, where sugars can be added to it (by a process called glycosylation) before it is transported within a vesicle to the next stage in the packaging and shipping process: the Golgi apparatus.

The Golgi Apparatus

The **Golgi apparatus** is responsible for sorting, modifying, and shipping off the products that come from the rough ER, much like a post-office. The Golgi apparatus looks like stacked flattened discs, almost like stacks of oddly shaped pancakes. Like the ER, these discs are membranous. The Golgi apparatus has two distinct sides, each with a different role. One side of the apparatus receives products in vesicles from the ER. These products are modified as needed and sorted as they move through the apparatus, and then they are released from the opposite side after being repackaged into new vesicles. If the product is to be exported from the cell, the vesicle migrates to the cell surface and fuses to the cell membrane, and the cargo is secreted via exocytosis (Figure 2.3.3).

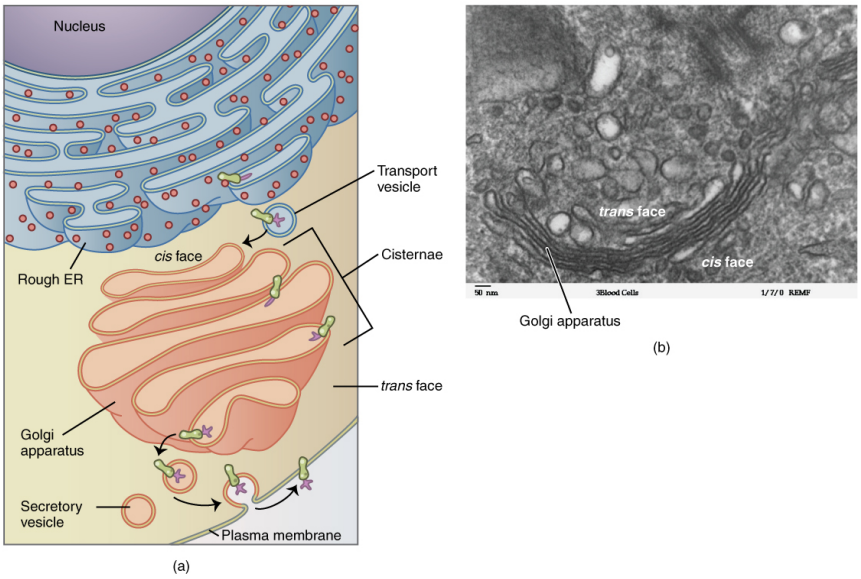

Figure 2.3.3: Golgi Apparatus. (a) Proteins and other products of the ER are sent to the Golgi apparatus, which organizes, modifies, packages, and tags them. Some of these products are transported to other areas of the cell and some are exported from the cell through exocytosis. Enzymatic proteins are packaged as new lysosomes (or packaged and sent for fusion with existing lysosomes). (b) An electron micrograph of the Golgi apparatus. (Image credit: "Golgi Apparatus" by OpenStax is licensed under CC BY 4.0)

Lysosomes

Some of the protein products packaged by the Golgi will function in a membrane-bound organelle inside the cell. For example, when the Golgi packages digestive enzymes that are meant to remain inside the cell for use in breaking down certain materials into a vesicle, that vesicle may become a new lysosome, or it may fuse with an existing lysosome. A **lysosome** is an organelle that contains enzymes that break down and digest unneeded cellular components, such as a damaged organelle. A lysosome is similar to a wrecking crew that takes down old and unsound buildings in a neighborhood. **Autophagy** ("self-eating") is the process of a cell digesting its own structures. Lysosomes are also important for breaking down foreign material. For example, when certain immune defense cells (white blood cells) phagocytize bacteria, the bacterial cell is transported into a lysosome and digested by the enzymes inside. As one might imagine, such phagocytic defense cells contain large numbers of lysosomes.

Under certain circumstances, lysosomes perform a more grand and dire function. In the case of damaged or unhealthy cells, lysosomes can be triggered to open up and release their digestive enzymes into the cytoplasm of the cell, killing the cell. This "self-destruct" mechanism is called **autolysis**, and makes the process of cell death controlled (a mechanism called "apoptosis").

Organelles for Energy Production and Detoxification

In addition to the jobs performed by the endomembrane system, the cell has many other important functions. Just as you must consume nutrients to provide yourself with energy, so must each of your cells take in nutrients, some of which convert to chemical energy that can be used to power biochemical reactions. Another important function of the cell is detoxification. Humans take in all sorts of toxins from the environment and also produce harmful chemicals as byproducts of cellular processes. Cells called hepatocytes in the liver detoxify many of these toxins.

Mitochondria

A **mitochondrion** (plural = mitochondria) is a membranous, bean-shaped organelle that is the "energy transformer" of the cell. Mitochondria consist of an outer lipid bilayer membrane as well as an additional inner lipid bilayer membrane (Figure 2.3.4). The inner membrane is highly folded into winding structures with a great deal of surface area, called cristae. It is along this inner membrane that a series of proteins, enzymes, and other molecules perform the biochemical reactions of cellular respiration. These reactions convert energy stored in nutrient molecules (such as glucose) into adenosine triphosphate (ATP), which provides usable cellular energy to the cell. Cells use ATP constantly, and so the mitochondria are constantly at work. Oxygen molecules are required during cellular respiration, which is why you must constantly breathe it in. One of the organ systems in the body that has high demands for ATP is the muscular system because ATP is required to sustain muscle contraction. As a result, muscle cells

are packed full of mitochondria. Nerve cells also need large quantities of ATP to run their sodium-potassium pumps. Therefore, an individual neuron will be loaded with over a thousand mitochondria. On the other hand, a bone cell, which is not nearly as metabolically-active, might only have a couple hundred mitochondria.

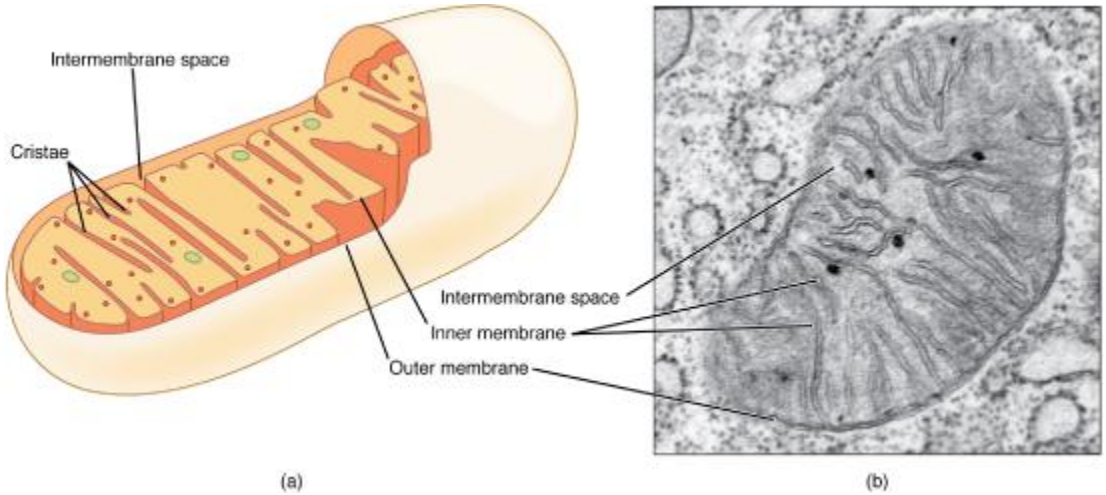

Figure 2.3.4: Mitochondrion. The mitochondria are the energy-conversion factories of the cell. (a) A mitochondrion is composed of two separate lipid bilayer membranes. Along the inner membrane are various molecules that work together to produce ATP, the cell's major energy currency. (b) An electron micrograph of mitochondria. EM × 236,000. (Image credit: "Mitochondrion" by OpenStax is licensed under CC BY 4.0/ Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Peroxisomes

Like a lysosome, a **peroxisome** is a membrane-bound cellular organelle that contains mostly enzymes (Figure 2.3.5). Peroxisomes perform a couple of different functions, including lipid metabolism and chemical detoxification. In contrast to the digestive enzymes found in lysosomes, the enzymes within peroxisomes serve to transfer hydrogen atoms from various molecules to oxygen, producing hydrogen peroxide (H_2O_2). In this way, peroxisomes neutralize free radicals that are produced during many normal cellular processes. Free radicals are reactive because they contain free unpaired electrons typically associated with oxygen (so they are also called reactive oxygen species). Free radicals can easily oxidize other molecules throughout the cell, causing cellular damage and even cell death.

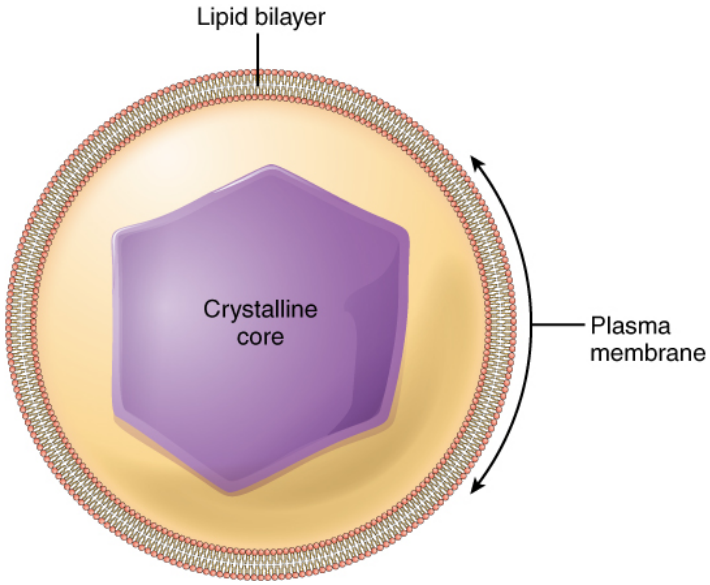

Figure 2.3.5: Peroxisome. Peroxisomes are membrane-bound organelles that contain an abundance of enzymes for detoxifying harmful substances and lipid metabolism. (Image credit: "Peroxisome" by OpenStax is licensed under CC BY 4.0)

AGING AND THE CELL: The Free Radical Theory

The free radical theory on aging was originally proposed in the 1950s, and still remains under debate. Generally speaking, the free radical theory of aging suggests that accumulated cellular damage from oxidative stress contributes to the physiological and anatomical effects of aging. There are two significantly different versions of this theory: one states that the aging process itself is a result of oxidative damage, and the other states that oxidative damage causes age-related disease and disorders. The latter version of the theory is more widely accepted than the former. However, many lines of evidence suggest that oxidative damage does contribute to the aging process. Research has shown that reducing oxidative damage can result in a longer lifespan in certain organisms such as yeast, worms, and fruit flies. Conversely, increasing oxidative damage can shorten the lifespan of mice and worms. Interestingly, a manipulation called calorie-restriction (moderately restricting the caloric intake) has been shown to increase life span in some laboratory animals. It is believed that this increase is at least in part due to a reduction of oxidative stress. However, a long-term study of primates with calorie-restriction showed no increase in their lifespan. A great deal of additional research will be required to better understand the link between reactive oxygen species and aging.

The Cytoskeleton

Much like the bony skeleton structurally supports the human body, the cytoskeleton helps the cells to maintain their structural integrity. The **cytoskeleton** is a group of fibrous proteins that provide structural support for cells, but this is only one of the functions of the cytoskeleton. Cytoskeletal components are also critical for cell motility, cell reproduction, and transportation of substances within the cell.

The cytoskeleton forms a complex thread-like network throughout the cell consisting of three different kinds of protein-based filaments: microfilaments, intermediate filaments, and microtubules (Figure 2.3.6). The thickest of the three is the **microtubule**, a structural filament composed of subunits of a protein called tubulin. Microtubules maintain cell shape and structure, help resist compression of the cell, and play a role in positioning the organelles within the cell. Microtubules also make up two types of cellular appendages important for motion: cilia and flagella (seen previously in this chapter). **Cilia** are found on many cells of the body, including the epithelial cells that line the airways of the respiratory system. Cilia move rhythmically; they beat constantly, moving waste materials such as dust, mucus, and bacteria upward through the airways, away from the lungs and toward the mouth. Beating cilia on cells lining the female fallopian tubes move egg cells from the ovary towards the uterus. A **flagellum** (plural = flagella) is an appendage larger than a cilium and specialized for cell locomotion. The only flagellated cell in humans is the sperm cell that must propel itself towards female egg cells.

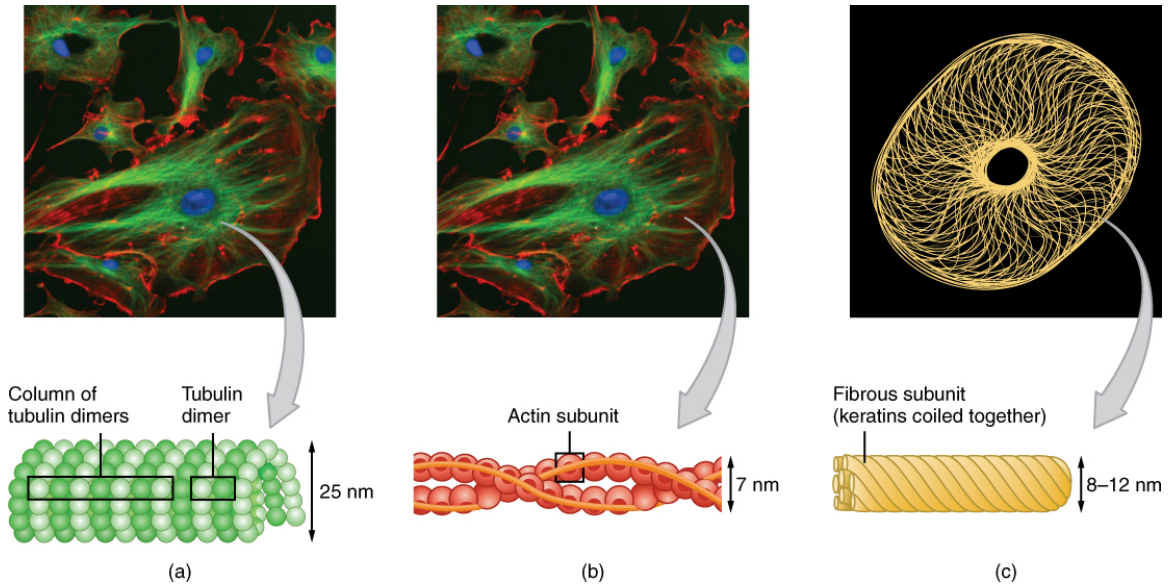

Figure 2.3.6: The Three Components of the Cytoskeleton. The cytoskeleton consists of (a) microtubules, (b) microfilaments, and (c) intermediate filaments. The cytoskeleton plays an important role in maintaining cell shape and structure, promoting cellular movement, and aiding cell division. (Image credit: "Cytoskeleton Components" by OpenStax is licensed under CC BY 4.0)

A very important function of microtubules is to set the paths (somewhat like railroad tracks) along which the genetic material can be pulled (a process requiring ATP) during cell division, so that each new daughter cell receives the appropriate set of chromosomes. Two short, identical microtubule structures called centrioles are found near the nucleus of cells. A **centriole** can serve as the cellular origin point for microtubules extending outward as cilia or flagella or can assist with the separation of DNA during cell division. Microtubules grow out from the centrioles by adding more tubulin subunits, like adding additional links to a chain.

In contrast with microtubules, the **microfilament** is a thinner type of cytoskeletal filament (see Figure $2.3.6.b$). Actin, a protein that forms chains, is the primary component of these microfilaments. Actin fibers, twisted chains of actin filaments, constitute a large component of muscle tissue and, along with the protein myosin, are responsible for muscle contraction. Like microtubules, actin filaments are long chains of single subunits (called actin subunits). In muscle cells, these long actin strands, called thin filaments, are “pulled” by thick filaments of the myosin protein to contract the cell.

Actin also has an important role during cell division. When a cell is about to split in half during cell division, actin filaments work with myosin to create a cleavage furrow that eventually splits the cell down the middle, forming two new cells from the original cell.

The final cytoskeletal filament is the intermediate filament. As its name would suggest, an **intermediate filament** is a filament intermediate in thickness between the microtubules and microfilaments (see Figure $2.3.6.c$). Intermediate filaments are made up of long fibrous subunits of a protein called keratin that are wound together like the threads that compose a rope. Intermediate filaments, in concert with the microtubules, are important for maintaining cell shape and structure. Unlike the microtubules, which resist compression, intermediate filaments resist tension—the forces that pull apart cells. There are many cases in which cells are prone to tension, such as when epithelial cells of the skin are compressed, tugging them in different directions. Intermediate filaments help anchor organelles together within a cell and also link cells to other cells by forming special cell-to-cell junctions.

Concept Review

The internal environmental of a living cell is made up of a fluid, jelly-like substance called cytosol, which consists mainly of water, but also contains various dissolved nutrients and other molecules. The cell contains an array of cellular organelles, each one performing a unique function and helping to maintain the health and activity of the cell. The cytosol and organelles together compose the cell’s cytoplasm. Most organelles are surrounded by a lipid membrane similar to the cell membrane of the cell. The endoplasmic reticulum (ER), Golgi apparatus, and lysosomes share a functional connectivity and are collectively referred to as the endomembrane system. There are two types of ER: smooth and rough. While the smooth ER performs many functions, including lipid synthesis and ion storage, the rough ER is mainly responsible for protein synthesis using its associated ribosomes. The rough ER sends newly made proteins to the Golgi apparatus where they are modified and packaged for delivery to various locations within or outside of the cell. Some of these protein products are enzymes destined to break down unwanted material and are packaged as lysosomes for use inside the cell.

Cells also contain mitochondria and peroxisomes, which are the organelles responsible for producing the cell’s energy supply and detoxifying certain chemicals, respectively. Biochemical reactions within mitochondria transform energy-carrying molecules into the usable form of cellular energy known as ATP. Peroxisomes contain enzymes that transform harmful substances such as free radicals into oxygen and water. Cells also contain a miniaturized “skeleton” of protein filaments that extend throughout its interior. Three different kinds of filaments compose this cytoskeleton (in order of increasing thickness): microfilaments, intermediate filaments, and microtubules. Each cytoskeletal component performs unique functions as well as provides a supportive framework for the cell.

Review Questions

Q. Choose the term that best completes the following analogy: Cytoplasm is to cytosol as a swimming pool containing chlorine and flotation toys is to _____.

A. the walls of the pool

B. the chlorine

C. the flotation toys

D. the water

Answer

Answer: D

Q. The rough ER has its name due to what associated structures?

A. Golgi apparatus

B. ribosomes

C. lysosomes

D. proteins

Answer

Answer: B

Q. Which of the following is a function of the rough ER?

A. production of proteins

B. detoxification of certain substances

C. synthesis of steroid hormones

D. regulation of intracellular calcium concentration

Answer

Answer: A

Q. Which of the following is a feature common to all three components of the cytoskeleton?

A. They all serve to scaffold the organelles within the cell.

B. They are all characterized by roughly the same diameter.

C. They are all polymers of protein subunits.

D. They all help the cell resist compression and tension.

Answer

Answer: C

Q. Which of the following organelles produces large quantities of ATP when both glucose and oxygen are available to the cell?

A. mitochondria

B. peroxisomes

C. lysosomes

D. ER

Answer

Answer: A

Critical Thinking Questions

Q. Explain why the structure of the ER, mitochondria, and Golgi apparatus assist their respective functions.

Answer

A. The structure of the Golgi apparatus is suited to its function because it is a series of flattened membranous discs; substances are modified and packaged in sequential steps as they travel from one disc to the next. The structure of Golgi apparatus also involves a receiving face and a sending face, which organize cellular products as they enter and leave the Golgi apparatus. The ER and the mitochondria both have structural specializations that increase their surface area. In the mitochondria, the inner membrane is extensively folded, which increases surface area for ATP production. Likewise, the ER is elaborately wound throughout the cell, increasing its surface area for functions like lipid synthesis, Ca^{++} storage, and protein synthesis.

Q. Compare and contrast lysosomes with peroxisomes: name at least two similarities and one difference.

Answer

A. Peroxisomes and lysosomes are both cellular organelles bound by lipid bilayer membranes, and they both contain many enzymes. However, peroxisomes contain enzymes that detoxify substances by transferring hydrogen atoms and producing H_2O_2, whereas the enzymes in lysosomes function to break down and digest various unwanted materials.

Glossary

autolysis
breakdown of cells by their own enzymatic action

autophagy
lysosomal breakdown of a cell's own components

centriole
small, self-replicating organelle that provides the origin for microtubule growth and moves DNA during cell division

cilia
small appendage on certain cells formed by microtubules and modified for movement of materials across the cellular surface

cytoplasm
internal material between the cell membrane and nucleus of a cell, mainly consisting of a water-based fluid called cytosol, within which are all the other organelles and cellular solute and suspended materials

cytoskeleton
"skeleton" of a cell; formed by rod-like proteins that support the cell's shape and provide, among other functions, locomotive abilities

cytosol
clear, semi-fluid medium of the cytoplasm, made up mostly of water

endoplasmic reticulum (ER)
cellular organelle that consists of interconnected membrane-bound tubules, which may or may not be associated with ribosomes (rough type or smooth type, respectively)

flagellum
appendage on certain cells formed by microtubules and modified for movement

Golgi apparatus
cellular organelle formed by a series of flattened, membrane-bound sacs that functions in protein modification, tagging, packaging, and transport

intermediate filament
: type of cytoskeletal filament made of keratin, characterized by an intermediate thickness, and playing a role in resisting cellular tension

lysosome
: membrane-bound cellular organelle originating from the Golgi apparatus and containing digestive enzymes

microfilament
: the thinnest of the cytoskeletal filaments; composed of actin subunits that function in muscle contraction and cellular structural support

microtubule
: the thickest of the cytoskeletal filaments, composed of tubulin subunits that function in cellular movement and structural support

mitochondrion
: one of the cellular organelles bound by a double lipid bilayer that function primarily in the production of cellular energy (ATP)

mutation
: change in the nucleotide sequence in a gene within a cell's DNA

nucleus
: cell's central organelle; contains the cell's DNA

organelle
: any of several different types of membrane-enclosed specialized structures in the cell that perform specific functions for the cell

peroxisome
: membrane-bound organelle that contains enzymes primarily responsible for detoxifying harmful substances

reactive oxygen species (ROS)
: a group of extremely reactive peroxides and oxygen-containing radicals that may contribute to cellular damage

ribosome
: cellular organelle that functions in protein synthesis

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2.4: The Nucleus

By the end of the section, you will be able to:

- Describe the structure and features of the nuclear membrane
- List the contents of the nucleus
- Explain the organization of the DNA molecule within the nucleus

The nucleus is the largest and most prominent of a cell's organelles (Figure 2.4.1). The nucleus is generally considered the control center of the cell because it stores all of the genetic instructions for manufacturing proteins. Interestingly, some cells in the body, such as muscle cells, contain more than one nucleus (Figure 2.4.2), so they are referred to as multinucleated cells. Other cells, such as mammalian red blood cells (RBCs), do not contain nuclei at all. RBCs eject their nuclei as they mature, making space for the large numbers of hemoglobin molecules that carry oxygen throughout the body (Figure 2.4.3). Without nuclei, the life span of RBCs is short, and so the body must produce new ones constantly.

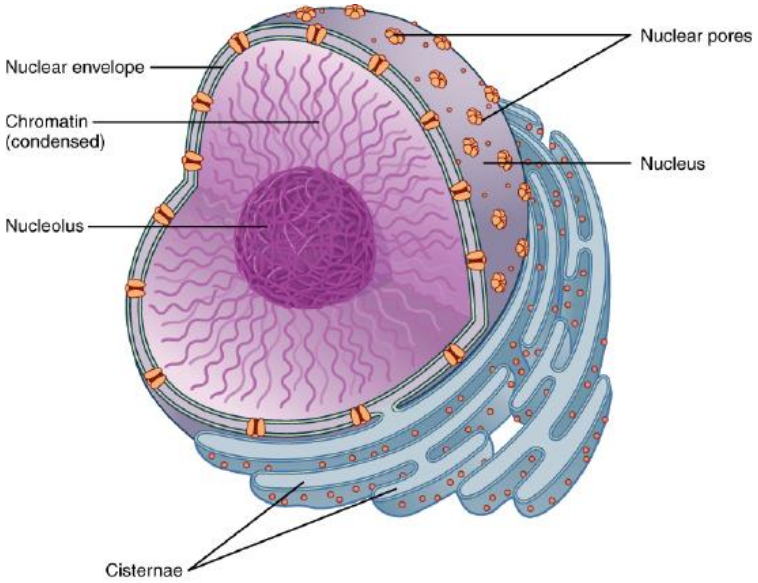

Figure 2.4.1: The Nucleus. The nucleus is the control center of the cell. The nucleus of living cells contains the genetic material that determines the entire structure and function of that cell. (Image credit: "Nucleus" by OpenStax is licensed under CC BY 4.0)

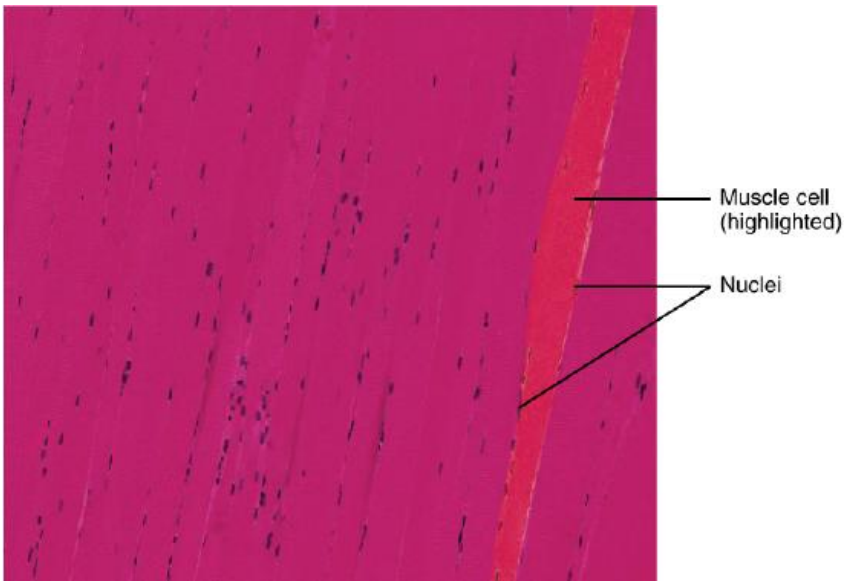

Figure 2.4.2: Multinucleate Muscle Cell. Unlike cardiac muscle cells and smooth muscle cells, which have a single nucleus, a skeletal muscle cell contains many nuclei, and is referred to as “multinucleated.” These muscle cells are long and fibrous (often referred to as muscle fibers). During development, many smaller cells fuse to form a mature muscle fiber. The nuclei of the fused cells are conserved in the mature cell, thus imparting a multinucleate characteristic to mature muscle cells. LM × 1004.3. (Image credit: "Multinucleate Muscle Tissue Micrograph" by OpenStax is licensed under CC BY 4.0/ Micrograph provided by the Regents of University of Michigan Medical School © 2012)

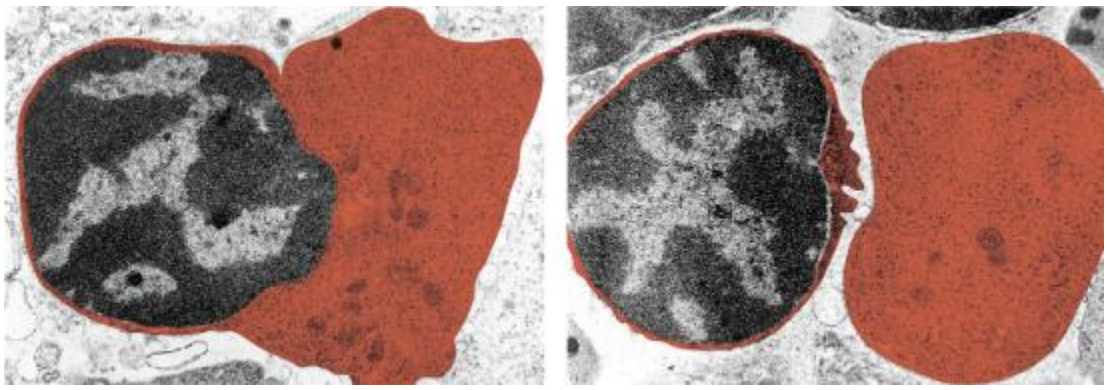

Figure 2.4.3: Red Blood Cell Extruding Its Nucleus. Mature red blood cells lack a nucleus. As they mature, erythroblasts extrude their nucleus, making room for more hemoglobin. The two panels here show an erythroblast before and after ejecting its nucleus, respectively. (Image credit: "RBC Extruding Nucleus Micrograph" by OpenStax is licensed under CC BY 4.0/ Modification of micrograph provided by the Regents of University of Michigan Medical School © 2012)

Inside the nucleus lies the blueprint that dictates everything a cell will do and all of the products it will make. This information is stored within DNA, deoxyribonucleic acid. The nucleus sends “commands” to the cell via molecular messengers that translate the information from DNA. Each nucleated cell in your body (with the exception of germ cells, also known as eggs and sperm) contains the complete set of your DNA. When a cell divides, the DNA must be duplicated so that the each new cell receives a full complement of DNA.

Organization of the Nucleus and Its DNA

Like most other cellular organelles, the nucleus is surrounded by a membrane. The membrane surrounding the nucleus, called the **nuclear envelope,** consists of two adjacent lipid bilayers with a thin fluid space in between them. Spanning these two bilayers are nuclear pores. A **nuclear pore** is a tiny passageway for the passage of proteins, RNA (ribonucleic acid), and solutes between the nucleus and the cytoplasm. Proteins called pore complexes lining the nuclear pores regulate the passage of materials into and out of the nucleus.

Inside the nuclear envelope is a gel-like nucleoplasm with solutes that include the building blocks of nucleic acids. There also can be a dark-staining mass often visible under a simple light microscope, called a **nucleolus** (plural = nucleoli). The nucleolus is a region of the nucleus that is responsible for manufacturing the RNA necessary for construction of ribosomes. Once

synthesized, newly made ribosomal subunits exit the cell's nucleus through the nuclear pores.

The genetic instructions that are used to build and maintain an organism are arranged in an orderly manner in strands of DNA. Within the nucleus are threads of **chromatin** composed of DNA and associated proteins (Figure 2.4.4). Along the chromatin threads, the DNA is wrapped around a set of **histone** proteins. A **nucleosome** is a single, wrapped DNA-histone complex. Multiple nucleosomes along the entire molecule of DNA appear like a beaded necklace, in which the string is the DNA and the beads are the associated histones. When a cell is in the process of division, the chromatin condenses into chromosomes, so that the DNA can be safely transported to the "daughter cells." The **chromosome** is composed of DNA and proteins; it is the condensed form of chromatin. It is estimated that humans have almost 22,000 genes distributed on 46 chromosomes.

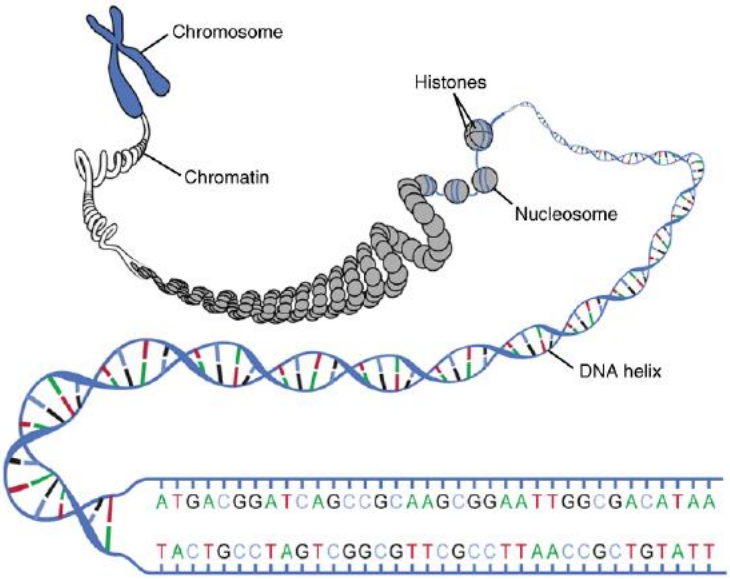

Figure 2.4.4: DNA Macrostructure. Strands of DNA are wrapped around supporting histones. These proteins are increasingly bundled and condensed into chromatin, which is packed tightly into chromosomes when the cell is ready to divide. (Image credit: "DNA Macrostructure" by OpenStax is licensed under CC BY 4.0)

Concept Review

The nucleus is the command center of the cell, containing the genetic instructions for all of the materials a cell will make (and thus all of its functions it can perform). The nucleus is encased within a membrane of two interconnected lipid bilayers, side-by-side. This nuclear envelope is studded with protein-lined pores that allow materials to be trafficked into and out of the nucleus. The nucleus contains one or more nucleoli, which serve as sites for ribosome synthesis. The nucleus houses the genetic material of the cell: DNA. DNA is normally found as a loosely contained structure called chromatin within the nucleus, where it is wound up and associated with a variety of histone proteins. When a cell is about to divide, the chromatin coils tightly and condenses to form chromosomes.

Review Questions

Q. The nucleolus specifically functions in the formation of which of the following structures?

A. chromatin

B. histones

C. ribosomal subunits

D. nucleosomes

Answer

Answer: C

Q. Place the following structures in order from least to most complex organization: chromatin, nucleosome, DNA, chromosome

A. DNA, nucleosome, chromatin, chromosome

B. nucleosome, DNA, chromosome, chromatin

C. DNA, chromatin, nucleosome, chromosome

D. nucleosome, chromatin, DNA, chromosome

Answer

Answer: A

Glossary

chromatin
substance consisting of DNA and associated proteins

chromosome
condensed version of chromatin

histone
family of proteins that associate with DNA in the nucleus to form chromatin

nuclear envelope
membrane that surrounds the nucleus; consisting of a double lipid-bilayer

nuclear pore
one of the small, protein-lined openings found scattered throughout the nuclear envelope

nucleolus
small region of the nucleus that functions in ribosome synthesis

nucleosome
unit of chromatin consisting of a DNA strand wrapped around histone proteins

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2.5: Cell Growth and Division

By the end of the section, you will be able to:

- Describe, in order, the stages of the cell cycle
- Discuss how the cell cycle is regulated
- Describe the implications of losing control over the cell cycle
- Describe the stages of mitosis and cytokinesis, in order

So far in this chapter, you have read numerous times of the importance and prevalence of cell division. While there are a few cells in the body that do not undergo cell division (such as gametes, red blood cells, most neurons, and some muscle cells), most somatic cells divide regularly. A **somatic cell** is a general term for a body cell, and all human cells, except for the cells that produce eggs and sperm (which are referred to as germ cells), are somatic cells. Somatic cells contain two copies of each of their chromosomes (one copy received from each parent). Each **homologous pair** of chromosomes includes the two copies of a single chromosome found in each somatic cell. The human is a **diploid** organism, having 23 homologous pairs of chromosomes in each of the somatic cells. The condition of having pairs of chromosomes is known as diploidy.

Cells in the body replace themselves over the lifetime of a person. For example, the cells lining the gastrointestinal tract must be frequently replaced when constantly "worn off" by the movement of food through the gut. But what triggers a cell to divide, and how does it prepare for and complete cell division? The **cell cycle** is the sequence of events in the life of the cell from the moment it is created at the end of a previous cycle of cell division until it then divides itself, generating two new cells.

The Cell Cycle

One "turn" or cycle of the cell cycle consists of two general phases: interphase, followed by mitosis and cytokinesis. **Interphase** is the period of the cell cycle during which the cell is not dividing. The majority of cells are in interphase most of the time. **Mitosis** is the division of genetic material, during which the cell nucleus breaks down and two new, fully functional, nuclei are formed. **Cytokinesis** divides the cytoplasm into two distinctive cells.

Interphase

A cell grows and carries out all normal metabolic functions and processes in a period called G_1 (Figure 2.5.1). **G_1 phase** (gap 1 phase) is the first gap, or growth phase in the cell cycle. For cells that will divide again, G_1 is followed by replication of the DNA, during the S phase. The **S phase** (synthesis phase) is period during which a cell replicates its DNA.

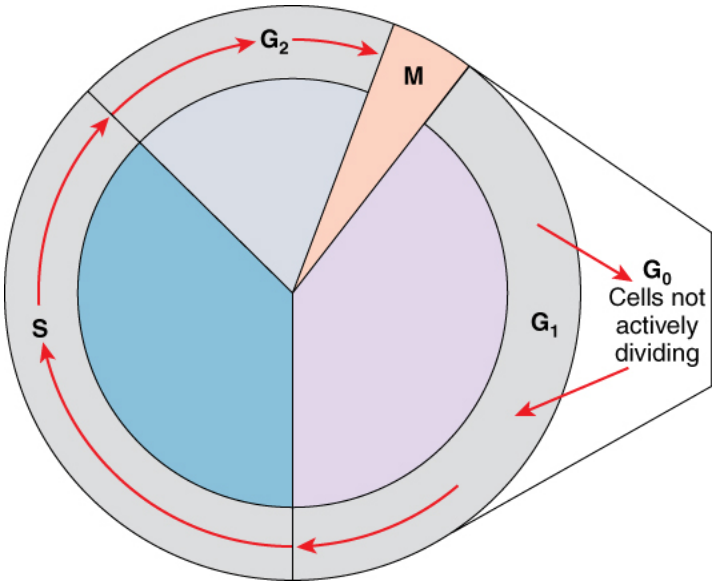

Figure 2.5.1: Cell Cycle. The two major phases of the cell cycle include mitosis (cell division), and interphase, when the cell grows and performs all of its normal functions. Interphase is further subdivided into G_1, S, and G_2 phases. (Image credit: "Cell Cycle" by OpenStax is licensed under CC BY 4.0)

After the synthesis phase, the cell proceeds through the G_2 phase. The **G_2 phase** is a second gap phase, during which the cell continues to grow and makes the necessary preparations for mitosis. Between G_1, S, and G_2 phases, cells will vary the most in their duration of the G1 phase. It is here that a cell might spend a couple of hours, or many days. The S phase typically lasts between 8-10 hours and the G_2 phase approximately 5 hours. In contrast to these phases, the **G_0 phase** is a resting phase of the cell cycle. Cells that have temporarily stopped dividing and are resting (a common condition) and cells that have permanently ceased dividing (like nerve cells) are said to be in G_0.

The Structure of Chromosomes

Billions of cells in the human body divide every day. During the synthesis phase (S, for DNA synthesis) of interphase, the amount of DNA within the cell precisely doubles. Therefore, after DNA replication but before cell division, each cell actually contains *two* copies of each chromosome. Each copy of the chromosome is referred to as a **sister chromatid** and is physically bound to the other copy. The **centromere** is the structure that attaches one sister chromatid to another. Because a human cell has 46 chromosomes, during this phase, there are 92 chromatids (46 × 2) in the cell. Make sure not to confuse the concept of a pair of chromatids (one chromosome and its exact copy attached during mitosis) and a homologous pair of chromosomes (two paired chromosomes which were inherited separately, one from each parent) (Figure 2.5.2).

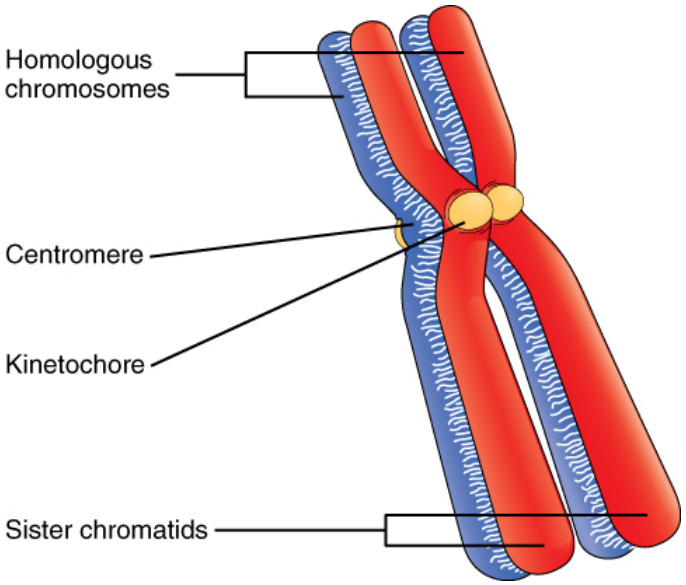

Figure 2.5.2: A Homologous Pair of Chromosomes with their Attached Sister Chromatids. The red and blue colors correspond to a homologous pair of chromosomes. Each member of the pair was separately inherited from one parent. Each chromosome in the homologous pair is also bound to an identical sister chromatid, which is produced by DNA replication, and results in the familiar "X" shape. ("Homologous Pair of Chromosomes" by OpenStax is licensed under CC BY 4.0)

Mitosis and Cytokinesis

The **mitotic phase** of the cell typically takes between 1 and 2 hours. During this phase, a cell undergoes two major processes. First, it completes mitosis, during which the contents of the nucleus are equitably pulled apart and distributed between its two halves. Cytokinesis then occurs, dividing the cytoplasm and cell body into two new cells. Mitosis is divided into four major stages that take place after interphase (Figure 2.5.3) and in the following order: prophase, metaphase, anaphase, and telophase. The process is then followed by cytokinesis.

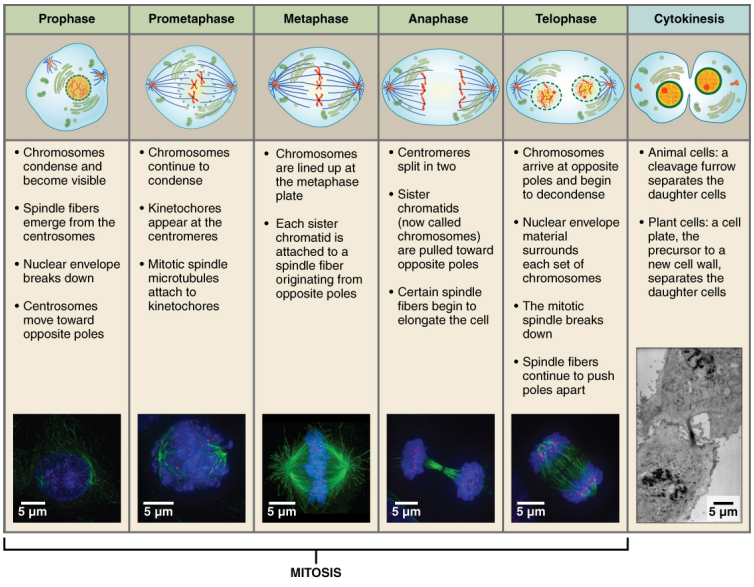

Figure 2.5.3: Cell Division: Mitosis Followed by Cytokinesis. The stages of cell division oversee the separation of identical genetic material into two new nuclei, followed by the division of the cytoplasm. (Image credit: "Stages of Mitosis and Cytokinesis" by OpenStax is licensed under CC BY 4.0)

Prophase is the first phase of mitosis, during which the loosely packed chromatin coils and condenses into visible chromosomes. During prophase, each chromosome becomes visible with its identical partner attached, forming the familiar X-shape of sister chromatids. The nucleolus disappears early during this phase, and the nuclear envelope also disintegrates.

A major occurrence during prophase concerns a very important structure that contains the origin site for microtubule growth. Recall the cellular structures called centrioles that serve as origin points from which microtubules extend. These tiny structures also play a very important role during mitosis. A **centrosome** is a pair of centrioles together. The cell contains two centrosomes side-by-side, which begin to move apart during prophase. As the centrosomes migrate to two different sides of the cell, microtubules begin to extend from each like long fingers from two hands extending toward each other. The **mitotic spindle** is the structure composed of the centrosomes and their emerging microtubules.

Near the end of prophase there is an invasion of the nuclear area by microtubules from the mitotic spindle. The nuclear membrane has disintegrated, and the microtubules attach themselves to the centromeres that adjoin pairs of sister chromatids. The **kinetochore** is a protein structure on the centromere that is the point of attachment between the mitotic spindle and the sister chromatids. This stage is referred to as late prophase or "prometaphase" to indicate the transition between prophase and metaphase.

Metaphase is the second stage of mitosis. During this stage, the sister chromatids, with their attached microtubules, line up along a linear plane in the middle of the cell. A metaphase plate forms between the centrosomes that are now located at either end of the cell. The **metaphase plate** is the name for the plane through the center of the spindle on which the sister chromatids are positioned. The microtubules are now poised to pull apart the sister chromatids and bring one from each pair to each side of the cell.

Anaphase is the third stage of mitosis. Anaphase takes place over a few minutes, when the pairs of sister chromatids are separated from one another, forming individual chromosomes once again. These chromosomes are pulled to opposite ends of the cell by their kinetochores, as the microtubules shorten. Each end of the cell receives one partner from each pair of sister chromatids, ensuring that the two new daughter cells will contain identical genetic material.

Telophase is the final stage of mitosis. Telophase is characterized by the formation of two new daughter nuclei at either end of the dividing cell. These newly formed nuclei surround the genetic material, which uncoils such that the chromosomes return to loosely packed chromatin. Nucleoli also reappear within the new nuclei, and the mitotic spindle breaks apart, each new cell receiving its own complement of DNA, organelles, membranes, and centrioles. At this point, the cell is already beginning to split in half as cytokinesis begins.

The **cleavage furrow** is a contractile band made up of microfilaments that forms around the midline of the cell during cytokinesis. (Recall that microfilaments consist of actin.) This contractile band squeezes the two cells apart until they finally separate. Two new cells are now formed. One of these cells (the "stem cell") enters its own cell cycle; able to grow and divide again at some future time. The other cell transforms into the functional cell of the tissue, typically replacing an "old" cell there.

Imagine a cell that completed mitosis but never underwent cytokinesis. In some cases, a cell may divide its genetic material and grow in size, but fail to undergo cytokinesis. This results in larger cells with more than one nucleus. Usually this is an unwanted aberration and can be a sign of cancerous cells.

Cell Cycle Control

A very elaborate and precise system of regulation controls direct the way cells proceed from one phase to the next in the cell cycle and begin mitosis. The control system involves molecules within the cell as well as external triggers. These internal and external control triggers provide "stop" and "advance" signals for the cell. Precise regulation of the cell cycle is critical for maintaining the health of an organism, and loss of cell cycle control can lead to cancer.

Mechanisms of Cell Cycle Control

As the cell proceeds through its cycle, each phase involves certain processes that must be completed before the cell should advance to the next phase. A **checkpoint** is a point in the cell cycle at which the cycle can be signaled to move forward or stopped. At each of these checkpoints, different varieties of molecules provide the stop or go signals, depending on certain conditions within the cell. A **cyclin** is one of the primary classes of cell cycle control molecules. A **cyclin-dependent kinase (CDK)** is one of a group of molecules that work together with cyclins to determine progression past cell checkpoints. Major cyclin-CDK complexes involved in regulating the cell cycle include Cyclin D - CDK4, Cyclin E - CDK2, Cyclin A - CDK2, and Cyclin B - CDK1 (Figure 2.5.4). By interacting with many additional molecules, these triggers push the cell cycle forward unless prevented from doing so by "stop" signals, if for some reason the cell is not ready. At the G_1 checkpoint, the cell must be ready for DNA synthesis to occur. At the G_2 checkpoint the cell must be fully prepared for mitosis. Even during mitosis, a crucial stop and go checkpoint in metaphase

ensures that the cell is fully prepared to complete cell division. The metaphase checkpoint ensures that all sister chromatids are properly attached to their respective microtubules and lined up at the metaphase plate before the signal is given to separate them during anaphase.

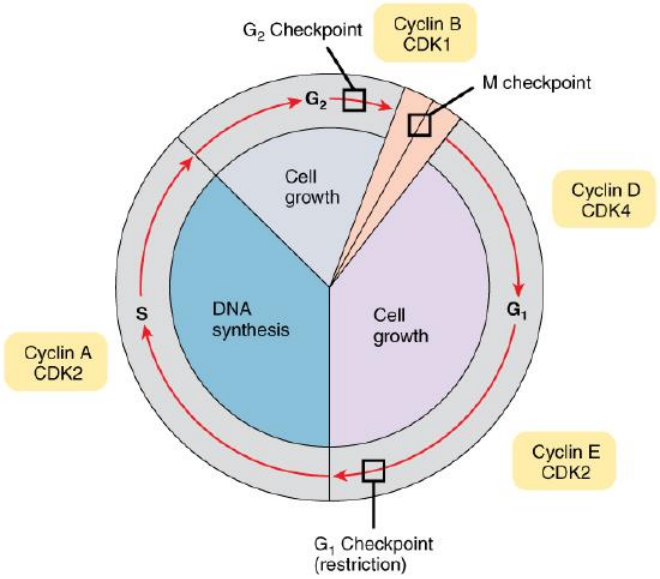

Figure 2.5.4: Control of the Cell Cycle. Cells proceed through the cell cycle under the control of a variety of molecules, such as cyclins and cyclin-dependent kinases. These control molecules determine whether or not the cell is prepared to move into the following stage. (Image credit: "Cell Cycle With Cyclins and Checkpoints" by OpenStax is licensed under CC BY 4.0)

The Cell Cycle Out of Control: Implications

Most people understand that cancer or tumors are caused by abnormal cells that multiply continuously. If the abnormal cells continue to divide unstopped, they can damage the tissues around them, spread to other parts of the body, and eventually result in death. In healthy cells, the tight regulation mechanisms of the cell cycle prevent this from happening, while failures of cell cycle control can cause unwanted and excessive cell division. Failures of control may be caused by inherited genetic abnormalities that compromise the function of certain “stop” and “go” signals. Environmental insult that damages DNA can also cause dysfunction in those signals. Often, a combination of both genetic predisposition and environmental factors lead to cancer.

The process of a cell escaping its normal control system and becoming cancerous may actually happen throughout the body quite frequently. Fortunately, certain cells of the immune system are capable of recognizing cells that have become cancerous and destroying them. However, in certain cases the cancerous cells remain undetected and continue to proliferate. If the resulting tumor does not pose a threat to surrounding tissues, it is said to be benign and can usually be easily removed. If capable of damage, the tumor is considered malignant and the patient is diagnosed with cancer.

HOMEOSTATIC IMBALANCES

Cancer Arises from Homeostatic Imbalances

Cancer is an extremely complex condition, capable of arising from a wide variety of genetic and environmental causes. Typically, mutations or aberrations in a cell’s DNA that compromise normal cell cycle control systems lead to cancerous tumors. Cell cycle control is an example of a homeostatic mechanism that maintains proper cell function and health. While progressing through the phases of the cell cycle, a large variety of intracellular molecules provide stop and go signals to regulate movement forward to the next phase. These signals are maintained in an intricate balance so that the cell only proceeds to the next phase when it is ready. This homeostatic control of the cell cycle can be thought of like a car’s cruise control. Cruise control will continually apply just the right amount of acceleration to maintain a desired speed, unless the driver hits the brakes, in which case the car will slow down. Similarly, the cell includes molecular messengers, such as cyclins, that push the cell forward in its cycle.

In addition to cyclins, a class of proteins that are encoded by genes called proto-oncogenes provide important signals that regulate the cell cycle and move it forward. Examples of proto-oncogene products include cell-surface receptors for growth factors, or cell-signaling molecules, two classes of molecules that can promote DNA replication and cell division. In contrast, a second class of genes known as tumor suppressor genes sends stop signals during a cell cycle. For example, certain protein products of tumor suppressor genes signal potential problems with the DNA and thus stop the cell from dividing, while other proteins signal the cell to die if it is damaged beyond repair. Some tumor suppressor proteins also signal a sufficient surrounding cellular density, which indicates that the cell need not presently divide. The latter function is uniquely important in preventing tumor growth: normal cells exhibit a phenomenon called “contact inhibition;” thus, extensive cellular contact with neighboring cells causes a signal that stops further cell division.

These two contrasting classes of genes, proto-oncogenes and tumor suppressor genes, are like the accelerator and brake pedal of the cell’s own “cruise control system,” respectively. Under normal conditions, these stop and go signals are maintained in a homeostatic balance. Generally speaking, there are two ways that the cell’s cruise control can lose control: a malfunctioning (overactive) accelerator, or a malfunctioning (underactive) brake. When compromised through a mutation, or otherwise altered, proto-oncogenes can be converted to oncogenes, which produce oncoproteins that push a cell forward in its cycle and stimulate cell division even when it is undesirable to do so. For example, a cell that should be programmed to self-destruct (a process called apoptosis) due to extensive DNA damage might instead be triggered to proliferate by an oncoprotein. On the other hand, a dysfunctional tumor suppressor gene may fail to provide the cell with a necessary stop signal, also resulting in unwanted cell division and proliferation.

A delicate homeostatic balance between the many proto-oncogenes and tumor suppressor genes delicately controls the cell cycle and ensures that only healthy cells replicate. Therefore, a disruption of this homeostatic balance can cause aberrant cell division and cancerous growths.

Concept Review

The life of cell consists of stages that make up the cell cycle. After a cell is born, it passes through an interphase before it is ready to replicate itself and produce daughter cells. This interphase includes two gap phases (G_1 and G_2), as well as an S phase, during which its DNA is replicated in preparation for cell division. The cell cycle is under precise regulation by chemical messengers both inside and outside the cell that provide “stop” and “go” signals for movement from one phase to the next. Failures of these signals can result in cells that continue to divide uncontrollably, which can lead to cancer.

Once a cell has completed interphase and is ready for cell division, it proceeds through four separate stages of mitosis (prophase, metaphase, anaphase, and telophase). Telophase is followed by the division of the cytoplasm (cytokinesis), which generates two daughter cells. This process takes place in all normally dividing cells of the body except for the germ cells that produce eggs and sperm.

Review Questions

Q. Which of the following phases is characterized by preparation for DNA synthesis?

A. G_0

B. G_1

C. G_2

D. S

Answer

Answer: B

Q. A mutation in the gene for a cyclin protein might result in which of the following?

A. a cell with additional genetic material than normal

B. cancer

C. a cell with less genetic material than normal

D. any of the above

Answer

Answer: D

Q. What is a primary function of tumor suppressor genes?

A. stop all cells from dividing

B. stop certain cells from dividing

C. help oncogenes produce oncoproteins

D. allow the cell to skip certain phases of the cell cycle

Answer

Answer: B

Critical Thinking Questions

Q. What would happen if anaphase proceeded even though the sister chromatids were not properly attached to their respective microtubules and lined up at the metaphase plate?

Answer

Answer: One or both of the new daughter cells would accidently receive duplicate chromosomes and/or would be missing certain chromosomes.

Q. What are cyclins and cyclin-dependent kinases, and how do they interact?

Answer

Answer: A cyclin is one of the primary classes of cell cycle control molecules, while a cyclin-dependent kinase is one of a group of molecules that work together with cyclins to determine progression past cell checkpoints. By interacting with many additional molecules, these triggers push the cell cycle forward unless prevented from doing so by “stop” signals, if for some reason the cell is not ready.

Glossary

anaphase
third stage of mitosis (and meiosis), during which sister chromatids separate into two new nuclear regions of a dividing cell

cell cycle
life cycle of a single cell, from its birth until its division into two new daughter cells

centromere
region of attachment for two sister chromatids

centrosome
cellular structure that organizes microtubules during cell division

checkpoint
progress point in the cell cycle during which certain conditions must be met in order for the cell to proceed to a subsequence phase

cleavage furrow
contractile ring that forms around a cell during cytokinesis that pinches the cell into two halves

cyclin
one of a group of proteins that function in the progression of the cell cycle

cyclin-dependent kinase (CDK)
one of a group of enzymes associated with cyclins that help them perform their functions

cytokinesis
final stage in cell division, where the cytoplasm divides to form two separate daughter cells

diploid
condition marked by the presence of a double complement of genetic material (two sets of chromosomes, one set inherited from each of two parents)

G_0 phase
phase of the cell cycle, usually entered from the G_1 phase; characterized by long or permanent periods where the cell does not move forward into the DNA synthesis phase

G_1 phase
first phase of the cell cycle, after a new cell is born

G_2 phase
third phase of the cell cycle, after the DNA synthesis phase

homologous pair
describes two copies of the same chromosome (not identical), one inherited from each parent

interphase
entire life cycle of a cell, excluding mitosis

kinetochore
region of a centromere where microtubules attach to a pair of sister chromatids

metaphase
second stage of mitosis (and meiosis), characterized by the linear alignment of sister chromatids in the center of the cell

metaphase plate
linear alignment of sister chromatids in the center of the cell, which takes place during metaphase

mitosis
division of genetic material, during which the cell nucleus breaks down and two new, fully functional, nuclei are formed

mitotic phase
phase of the cell cycle in which a cell undergoes mitosis

mitotic spindle
network of microtubules, originating from centrioles, that arranges and pulls apart chromosomes during mitosis

prophase
first stage of mitosis (and meiosis), characterized by breakdown of the nuclear envelope and condensing of the chromatin to form chromosomes

S phase
stage of the cell cycle during which DNA replication occurs

sister chromatid
one of a pair of identical chromosomes, formed during DNA replication

somatic cell
all cells of the body excluding gamete cells

telophase
final stage of mitosis (and meiosis), preceding cytokinesis, characterized by the formation of two new daughter nuclei

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2.6: Cellular Differentiation

By the end of the section, you will be able to:

- Discuss how the generalized cells of a developing embryo or the stem cells of an adult organism become differentiated into specialized cells
- Distinguish between the categories of stem cells

How does a complex organism such as a human develop from a single cell—a fertilized egg—into the vast array of cell types such as nerve cells, muscle cells, and epithelial cells that characterize the adult? Throughout development and adulthood, the process of cellular differentiation leads cells to assume their final morphology and physiology. Differentiation is the process by which unspecialized cells become specialized to carry out distinct functions.

Stem Cells

A **stem cell** is an unspecialized cell that can divide without limit as needed and can, under specific conditions, differentiate into specialized cells. Stem cells are divided into several categories according to their potential to differentiate.

The first embryonic cells that arise from the division of the zygote are the ultimate stem cells; these stems cells are described as **totipotent** because they have the potential to differentiate into any of the cells needed to enable an organism to grow and develop.

The embryonic cells that develop from totipotent stem cells and are precursors to the fundamental tissue layers of the embryo are classified as pluripotent. A **pluripotent** stem cell is one that has the potential to differentiate into any type of human tissue but cannot support the full development of an organism. These cells then become slightly more specialized, and are referred to as multipotent cells.

A **multipotent** stem cell has the potential to differentiate into different types of cells within a given cell lineage or small number of lineages, such as a red blood cell or white blood cell.

Finally, multipotent cells can become further specialized oligopotent cells. An **oligopotent** stem cell is limited to becoming one of a few different cell types. In contrast, a **unipotent** cell is fully specialized and can only reproduce to generate more of its own specific cell type.

Stem cells are unique in that they can also continually divide and regenerate new stem cells instead of further specializing. There are different stem cells present at different stages of a human's life. They include the embryonic stem cells of the embryo, fetal stem cells of the fetus, and adult stem cells in the adult. One type of adult stem cell is the epithelial stem cell, which gives rise to the keratinocytes in the multiple layers of epithelial cells in the epidermis of skin. Adult bone marrow has three distinct types of stem cells: hematopoietic stem cells, which give rise to red blood cells, white blood cells, and platelets (Figure $2.6.1$); endothelial stem cells, which give rise to the endothelial cell types that line blood and lymph vessels; and mesenchymal stem cells, which give rise to the different types of muscle cells.

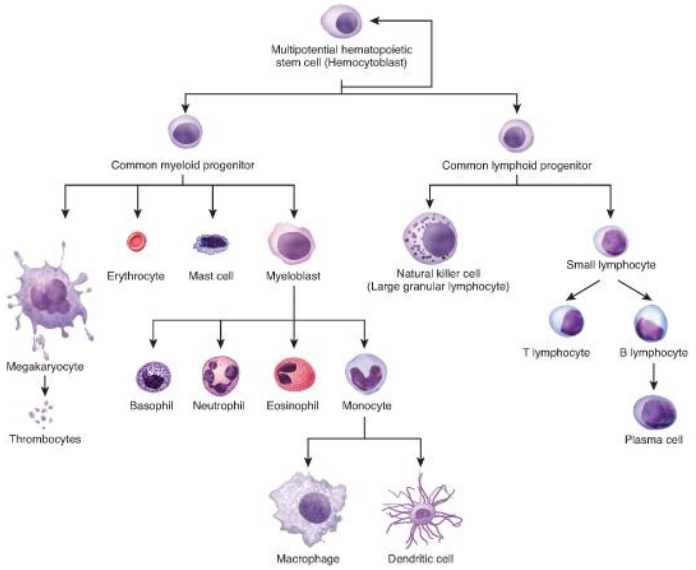

Figure 2.6.1: Hematopoiesis. The process of hematopoiesis involves the differentiation of multipotent cells into blood and immune cells. The multipotent hematopoietic stem cells give rise to many different cell types, including the cells of the immune system and red blood cells. (Image credit: "Hematopoiesis new" by OpenStax is licensed under CC BY 4.0)

Differentiation

When a cell differentiates (becomes more specialized), it may undertake major changes in its size, shape, metabolic activity, and overall function. Because all cells in the body, beginning with the fertilized egg, contain the same DNA, how do the different cell types come to be so different? The answer is analogous to a movie script. The different actors in a movie all read from the same script, however, they are each only reading their own part of the script. Similarly, all cells contain the same full complement of DNA, but each type of cell only "reads" the portions of DNA that are relevant to its own function. In biology, this is referred to as the unique genetic expression of each cell.

In order for a cell to differentiate into its specialized form and function, it need only manipulate those genes (and thus those proteins) that will be expressed, and not those that will remain silent. The primary mechanism by which genes are turned "on" or "off" is through transcription factors. A **transcription factor** is one of a class of proteins that bind to specific genes on the DNA molecule and either promote or inhibit their transcription (Figure 2.6.2).

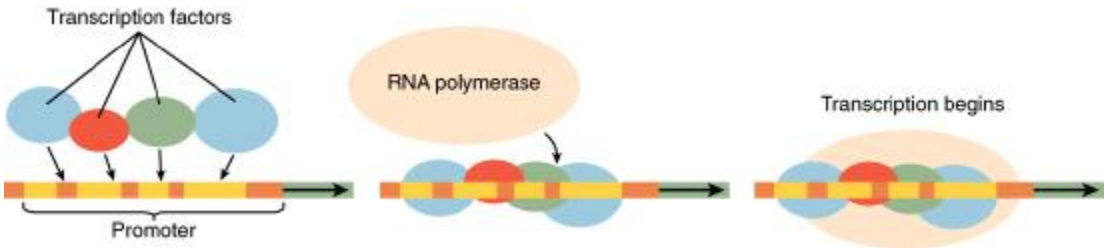

Figure 2.6.2: Transcription Factors Regulate Gene Expression. While each body cell contains the organism's entire genome, different cells regulate gene expression with the use of various transcription factors. Transcription factors are proteins that affect the binding of RNA polymerase to a particular gene on the DNA molecule. (Image credit: "RNA Polymerase Binding" by OpenStax is licensed under CC BY 4.0)

EVERYDAY CONNECTION

Stem Cell Research

Stem cell research aims to find ways to use stem cells to regenerate and repair cellular damage. Over time, most adult cells undergo the wear and tear of aging and lose their ability to divide and repair themselves. Stem cells do not display a particular morphology or function. Adult stem cells, which exist as a small subset of cells in most tissues, keep dividing and can differentiate into a number of specialized cells generally formed by that tissue. These cells enable the body to renew and repair body tissues.

The mechanisms that induce a non-differentiated cell to become a specialized cell are poorly understood. In a laboratory setting, it is possible to induce stem cells to differentiate into specialized cells by changing the physical and chemical conditions of growth. Several sources of stem cells are used experimentally and are classified according to their origin and potential for differentiation. Human embryonic stem cells (hESCs) are extracted from embryos and are pluripotent. The adult stem cells that are present in many organs and differentiated tissues, such as bone marrow and skin, are multipotent, being limited in differentiation to the types of cells found in those tissues. The stem cells isolated from umbilical cord blood are also multipotent, as are cells from deciduous teeth (baby teeth). Researchers have recently developed induced pluripotent stem cells (iPSCs) from mouse and human adult stem cells. These cells are genetically reprogrammed multipotent adult cells that function like embryonic stem cells; they are capable of generating cells characteristic of all three germ layers.

Because of their capacity to divide and differentiate into specialized cells, stem cells offer a potential treatment for diseases such as diabetes and heart disease (Figure 2.6.3). Cell-based therapy refers to treatment in which stem cells induced to differentiate in a growth dish are injected into a patient to repair damaged or destroyed cells or tissues. Many obstacles must be overcome for the application of cell-based therapy. Although embryonic stem cells have a nearly unlimited range of differentiation potential, they are seen as foreign by the patient's immune system and may trigger rejection. Also, the destruction of embryos to isolate embryonic stem cells raises considerable ethical and legal questions.

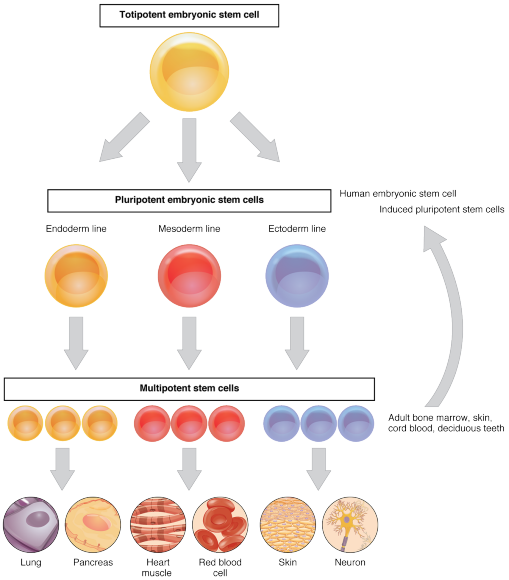

Figure 2.6.3: Stem Cells. The capacity of stem cells to differentiate into specialized cells make them potentially valuable in therapeutic applications designed to replace damaged cells of different body tissues. (Image credit: "Stem Cell" by OpenStax is licensed under CC BY 4.0)

In contrast, adult stem cells isolated from a patient are not seen as foreign by the body, but they have a limited range of differentiation. Some individuals bank the cord blood or deciduous teeth of their child, storing away those sources of stem cells for future use, should their child need it. Induced pluripotent stem cells are considered a promising advance in the field because using them avoids the legal, ethical, and immunological pitfalls of embryonic stem cells.

Concept Review

One of the major areas of research in biology is that of how cells specialize to assume their unique structures and functions, since all cells essentially originate from a single fertilized egg. Cell differentiation is the process of cells becoming specialized as they body develops. A stem cell is an unspecialized cell that can divide without limit as needed and can, under specific conditions,

differentiate into specialized cells. Stem cells are divided into several categories according to their potential to differentiate. While all somatic cells contain the exact same genome, different cell types only express some of those genes at any given time. These differences in gene expression ultimately dictate a cell's unique morphological and physiological characteristics. The primary mechanism that determines which genes will be expressed and which ones will not is through the use of different transcription factor proteins, which bind to DNA and promote or hinder the transcription of different genes. Through the action of these transcription factors, cells specialize into one of hundreds of different cell types in the human body.

Review Questions

Q. Arrange the following terms in order of increasing specialization: oligopotency, pleuripotency, unipotency, multipotency.

A. multipotency, pleuripotency, oligopotency, unipotency

B. pleuripotency, oligopotency, multipotency unipotency

C. oligopotency, pleuripotency, unipotency, multipotency

D. pleuripotency, multipotency, oligopotency, unipotency

Answer

Answer: D

Q. Which type of stem cell gives rise to red and white blood cells?

A. endothelial

B. epithelial

C. hematopoietic

D. mesenchymal

Answer

Answer: C

Q. What multipotent stem cells from children sometimes banked by parents?

A. fetal stem cells

B. embryonic stem cells

C. cells from the umbilical cord and from baby teeth

D. hematopoietic stem cells from red and white blood cells

Answer

Answer: C

Critical Thinking Questions

Q. Explain how a transcription factor ultimately determines whether or not a protein will be present in a given cell?

Answer

A. Transcription factors bind to DNA and either promote or inhibit the transcription of a gene. If they promote the transcription of a particular gene, then that gene will be transcribed and the mRNA subsequently translated

into protein. If gene transcription is inhibited, then there will be no way of synthesizing the gene's corresponding protein.

Q. Discuss two reasons why the therapeutic use of embryonic stem cells can present a problem.

Answer

A. Embryonic stem cells derive from human embryos, which are destroyed to obtain the cells. The destruction of human embryos is an ethical problem. And, the DNA in an embryonic stem cell would differ from the DNA of the person being treated, which could result in immune problems or rejected of tissue.

Glossary

multipotent
describes the condition of being able to differentiate into different types of cells within a given cell lineage or small number of lineages, such as a red blood cell or white blood cell

oligopotent
describes the condition of being more specialized than multipotency; the condition of being able to differentiate into one of a few possible cell types

pluripotent
describes the condition of being able to differentiate into a large variety of cell types

stem cell
cell that is oligo-, multi-, or pleuripotent that has the ability to produce additional stem cells rather than becoming further specialized

totipotent
embryonic cells that have the ability to differentiate into any type of cell and organ in the body

transcription factor
one of the proteins that regulate the transcription of genes

unipotent
describes the condition of being committed to a single specialized cell type

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3: TISSUE LEVEL OF ORGANIZATION

3.1: Introduction to the Tissue Level of Organization
3.2: Types of Tissues
3.3: Epithelial Tissue
3.4: Connective Tissue
3.5: Muscle Tissue
3.6: Nervous Tissue
3.7: Tissue Injury and Aging

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3.1: Introduction to the Tissue Level of Organization

Chapter Objectives:

After studying this chapter, you will be able to:

- Identify the main tissue types and discuss their roles in the human body
- Identify the four types of tissue membranes and the characteristics of each that make them functional
- Explain the functions of various epithelial tissues and how their forms enable their functions
- Explain the functions of various connective tissues and how their forms enable their functions
- Describe the characteristics of muscle tissue and how these enable function
- Discuss the characteristics of nervous tissue and how these enable information processing and control of muscular and glandular activities

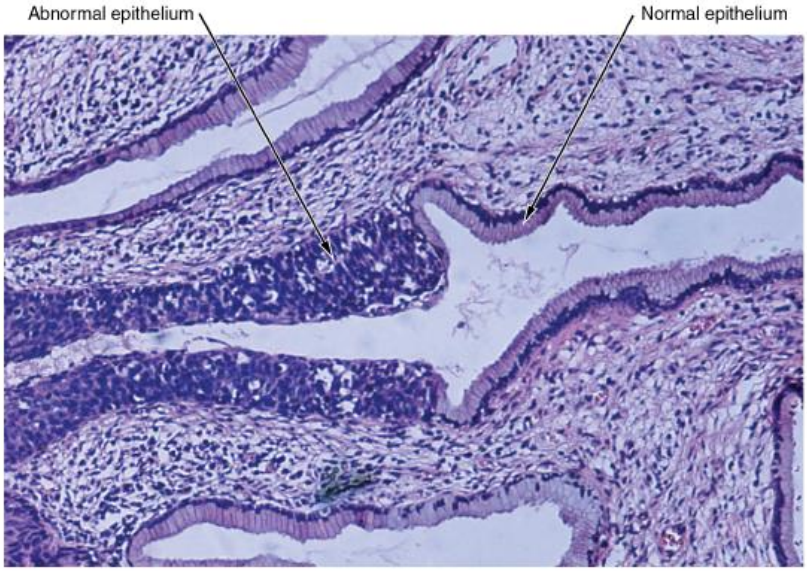

Figure 3.1.1: Micrograph of Cervical Tissue. This figure is a view of the regular architecture of normal tissue contrasted with the irregular arrangement of cancerous cells. (Image credit: "Micrograph of Cervical Tissue updated" by OpenStax is licensed under CC BY 4.0)

The body contains at least 200 distinct cell types. These cells contain essentially the same internal structures yet they vary enormously in shape and function. The different types of cells are not randomly distributed throughout the body; rather they occur in organized layers, a level of organization referred to as tissue. The micrograph that opens this chapter (Figure 3.1.1) shows the high degree of organization among different types of cells in the tissue of the cervix. You can also see how that organization breaks down when cancer takes over the regular mitotic functioning of a cell.

Among cells, the variety in shape reflects the many different roles that cells fulfill in your body. The human body starts as a single cell at fertilization. As this fertilized egg divides, it gives rise to trillions of cells, each built from the same blueprint, but organizing into tissues and becoming irreversibly committed to a developmental pathway.

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3.2: Types of Tissues

By the end of the section, you will be able to:

- Identify the four main tissue types
- Discuss the general functions of each tissue type
- Discuss the embryonic origin of tissue
- Identify the three major germ layers
- Identify the main types of tissue membranes

The term **tissue** is used to describe a group of cells found together in the body. The cells within a tissue share a common embryonic origin. Microscopic observation reveals that the cells in a tissue share morphological features and are arranged in an orderly pattern that achieves the tissue's functions. From the evolutionary perspective, tissues appear in more complex organisms. For example, multicellular protists, ancient eukaryotes, do not have cells organized into tissues.

Although there are many types of cells in the human body, they are organized into four broad categories of tissues: epithelial, connective, muscle, and nervous. Each of these categories is characterized by specific functions that contribute to the overall health and maintenance of the body. A disruption of the structure is a sign of injury or disease. Such changes can be detected through histology, the microscopic study of tissue appearance, organization, and function.

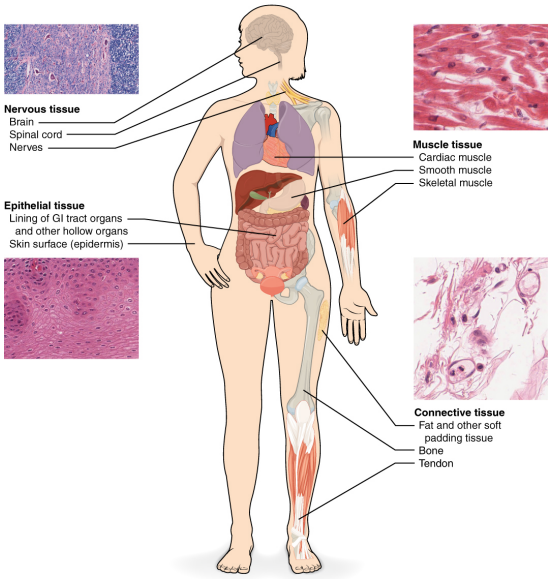

Figure 3.2.1: Four Types of Tissue: Body. The four types of tissues are exemplified in nervous tissue, stratified squamous epithelial tissue, cardiac muscle tissue, and connective tissue in small intestine. Clockwise from nervous tissue, LM × 872, LM × 282, LM × 460, LM × 800. (Image credit: "Types of Tissue" by OpenStax is licensed under CC BY-NC 3.0/ Micrographs provided by the Regents of University of Michigan Medical School © 2012)

The Four Types of Tissues

Epithelial tissue, also referred to as epithelium, refers to the sheets of cells that cover exterior surfaces of the body (e.g. the skin surface, or epidermis), lines internal cavities and passageways (such as the lining of the GI tract organs and other hollow organs), and forms certain glands. **Connective tissue**, as its name implies, binds the cells and organs of the body together and functions in the protection, support, and integration of all parts of the body. Some examples include fat and other soft padding tissue, bones, and tendons. **Muscle tissue** is excitable, responding to stimulation and contracting to provide movement, and occurs as three major types: skeletal (voluntary) muscle, smooth muscle, and cardiac muscle in the heart. **Nervous tissue,** which can be found in the brain, spinal cord, and nerves**,** is also excitable, allowing the propagation of electrochemical signals in the form of nerve impulses that communicate between different regions of the body (Figure 3.2.1).

The next level of organization is the organ, where several types of tissues come together to form a working unit. Just as knowing the structure and function of cells helps you in your study of tissues, knowledge of tissues will help you understand how organs function.

Embryonic Origin of Tissues

The zygote, or fertilized egg, is a single cell formed by the fusion of an egg and sperm. After fertilization the zygote gives rise to rapid mitotic cycles, generating many cells to form the embryo. The first embryonic cells generated have the ability to differentiate into any type of cell in the body and, as such, are called **totipotent**, meaning each has the capacity to divide, differentiate, and develop into a new organism. As cell proliferation progresses, three major cell lineages are established within the embryo. Each of these lineages of embryonic cells forms the distinct germ layers from which all the tissues and organs of the human body eventually form. Each germ layer is identified by its relative position: **ectoderm** (ecto- = "outer"), **mesoderm** (meso- = "middle"), and **endoderm** (endo- = "inner").

Figure 3.2.2 shows the types of tissues and organs associated with the each of the three germ layers. The ectoderm gives rise to the epidermis, glands on the skin, some cranial bones, the pituitary gland and adrenal medulla, the nervous system, the mouth between cheek and gums, and the anus. The mesoderm gives rise to connective tissues proper, bone, cartilage, blood, endothelium of blood vessels, muscle, synovial membranes, serous membranes lining body cavities, kidneys, and the lining of the gonads. The endoderm gives rise to the lining of the airways and digestive system, (except the mouth and distal portion (rectum and anal canal)), and some glands including digestive glands, endocrine glands, and the adrenal cortex. Note that epithelial tissue originates in all three layers, whereas nervous tissue derives primarily from the ectoderm and muscle tissue from mesoderm.

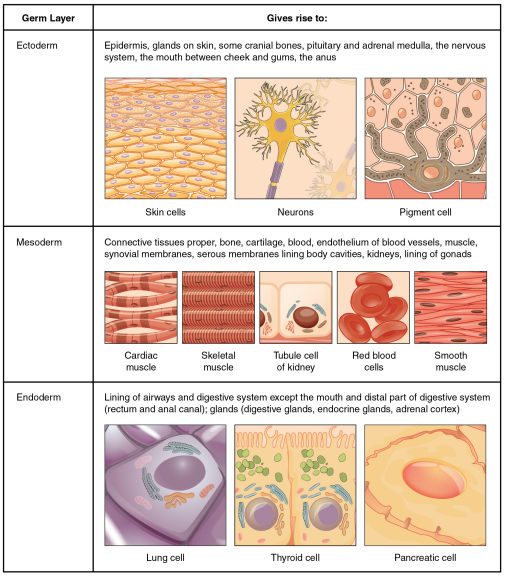

Figure 3.2.2: Embryonic Origin of Tissues and Major Organs. Tissues and organs are derived from three distinct germ layers, the ectoderm, mesoderm, and endoderm. (Image credit: "419 420 421 Table 04 01 updated" by OpenStax is licensed under CC BY-NC 3.0)

Interactive Link

Stem Cells

QR Code representing a URL

View this slideshow video to learn more about stem cells. How do somatic stem cells differ from embryonic stem cells?

Answer available at the end of this section.

Tissue Membranes

A tissue membrane is a thin layer or sheet of cells that covers the outside of the body (for example, skin), the organs (for example, pericardium), internal passageways that lead to the exterior of the body (for example, the digestive tract), and the lining of the moveable joint cavities. There are two basic types of tissue membranes: epithelial membranes and connective tissue membranes (Figure 3.2.3).

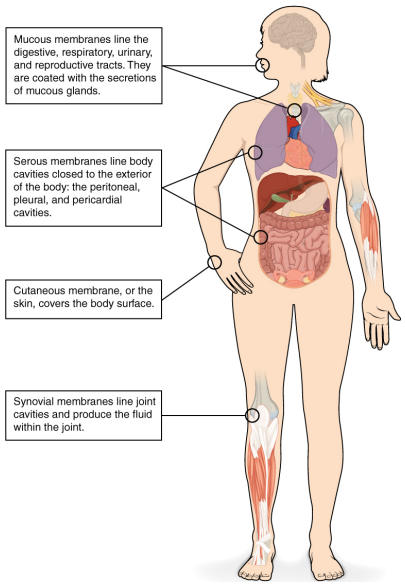

Figure 3.2.3: Tissue Membranes. The two broad categories of tissue membranes in the body are (1) epithelial membranes, which include mucous membranes, serous membranes, and the cutaneous membrane, in other words, the skin, and (2) connective tissue membranes, which include synovial membranes. (Image credit: "Types of Membranes" by OpenStax is licensed under CC BY-NC 3.0)

Epithelial Membranes

The **epithelial membrane** is composed of epithelium attached to a layer of connective tissue, for example, your skin. The **mucous membrane** is also a composite of connective and epithelial tissues. Sometimes called mucosae (singular mucosa), these epithelial membranes line the body cavities and hollow passageways that open to the external environment, and include the digestive, respiratory, urinary, and reproductive tracts. Mucous, produced by the epithelial exocrine glands, covers the epithelial layer and protects it in a variety of specific ways. The underlying connective tissue, called the **lamina propria** (literally “own layer”), help support the fragile epithelial layer.

A **serous membrane** is an epithelial membrane composed of mesodermally derived epithelium called the mesothelium that is supported by connective tissue. These membranes line the coelomic cavities of the body, that is, those cavities that do not open to the outside, and they cover the organs located within those cavities. They are essentially membranous bags, with mesothelium lining the inside and connective tissue on the outside. Serous fluid secreted by the cells of the thin squamous mesothelium lubricates the membrane and reduces abrasion and friction between organs. Serous membranes are identified according to location. Three serous membranes line the thoracic cavity: the two pleura that cover the lungs and the pericardium that covers the heart. A fourth, the peritoneum, is the serous membrane in the abdominal cavity that covers abdominal organs and forms double sheets of mesenteries that suspend many of the digestive organs.

The skin is an epithelial membrane also called the **cutaneous membrane**. It is a stratified squamous epithelial membrane resting on top of connective tissue. The apical surface of this membrane is exposed to the external environment and is covered with dead, keratinized cells that help protect the body from desiccation (drying out) and pathogens.

Connective Tissue Membranes

The **connective tissue membrane** is formed solely from connective tissue. These membranes encapsulate organs, such as the kidneys, and line our movable joints, so each is typically referred to as a capsule. A **synovial membrane** is a type of connective tissue membrane that lines the cavity of a freely movable joint. For example, synovial membranes surround the joints of the

shoulder, elbow, and knee. Fibroblasts in the inner layer of the synovial membrane release hyaluronan into the joint cavity. The hyaluronan effectively traps available water to form the synovial fluid, a natural lubricant that enables the bones of a joint to move freely against one another without much friction. This synovial fluid readily exchanges water and nutrients with blood, as do all body fluids.

Concept Review

The human body contains more than 200 types of cells that can all be classified into four types of tissues: epithelial, connective, muscle, and nervous. Epithelial tissues act as coverings. Connective tissue integrates the various parts of the body and provides support and protection to organs. Muscle tissue allows the body to move. Nervous tissues propagate information.

The study of the shape and arrangement of cells in tissue is called histology. All cells and tissues in the body derive from three germ layers in the embryo: the ectoderm, mesoderm, and endoderm.

Different types of tissues form membranes that enclose organs, provide a friction-free interaction between organs, and keep organs together. Synovial membranes are connective tissue membranes that protect and line the joints. Epithelial membranes are formed from epithelial tissue attached to a layer of connective tissue. There are three types of epithelial membranes: mucous, which contain glands; serous, which secrete fluid; and cutaneous which makes up the skin.

Review Questions

Q. Which of the following is not a type of tissue?

A. muscle

B. nervous

C. synovial

D. epithelial

Answer

Answer: C

Q. The process by which a less specialized cell matures into a more specialized cell is called _____.

A. differentiation

B. maturation

C. modification

D. specialization

Answer

Answer: A

Q. Differentiated cells in a developing embryo derive from _____.

A. endothelium, mesothelium, and epithelium

B. ectoderm, mesoderm, and endoderm

C. connective tissue, epithelial tissue, and muscle tissue

D. epidermis, mesoderm, and endothelium

Answer

Answer: B

Q. Which of the following lines the body cavities exposed to the external environment?

A. mesothelium

B. lamina propria

C. mesenteries

D. mucosa

Answer

Answer: D

Critical Thinking Questions

Q. Identify the four types of tissue in the body, and describe the major functions of each tissue.

Answer

A. The four types of tissue in the body are epithelial, connective, muscle, and nervous. Epithelial tissue is made of layers of cells that cover the surfaces of the body that come into contact with the exterior world, line internal cavities, and form glands. Connective tissue binds the cells and organs of the body together and performs many functions, especially in the protection, support, and integration of the body. Muscle tissue, which responds to stimulation and contracts to provide movement, is divided into three major types: skeletal (voluntary) muscles, smooth muscles, and the cardiac muscle in the heart. Nervous tissue allows the body to receive signals and transmit information as electric impulses from one region of the body to another.

Q. The zygote is described as totipotent because it ultimately gives rise to all the cells in your body including the highly specialized cells of your nervous system. Describe this transition, discussing the steps and processes that lead to these specialized cells.

Answer

A. The zygote divides into many cells. As these cells become specialized, they lose their ability to differentiate into all tissues. At first they form the three primary germ layers. Following the cells of the ectodermal germ layer, they too become more restricted in what they can form. Ultimately, some of these ectodermal cells become further restricted and differentiate in to nerve cells.

Q. What is the function of synovial membranes?

Answer

A. Synovial membranes are a type of connective tissue membrane that supports mobility in joints. The membrane lines the joint cavity and contains fibroblasts that produce hyaluronan, which leads to the production of synovial fluid, a natural lubricant that enables the bones of a joint to move freely against one another.

Glossary

connective tissue
type of tissue that serves to hold in place, connect, and integrate the body's organs and systems

connective tissue membrane
connective tissue that encapsulates organs and lines movable joints

cutaneous membrane
skin; epithelial tissue made up of a stratified squamous epithelial cells that cover the outside of the body

ectoderm
outermost embryonic germ layer from which the epidermis and the nervous tissue derive

endoderm
innermost embryonic germ layer from which most of the digestive system and lower respiratory system derive

epithelial membrane
epithelium attached to a layer of connective tissue

epithelial tissue
type of tissue that serves primarily as a covering or lining of body parts, protecting the body; it also functions in absorption, transport, and secretion

histology
microscopic study of tissue architecture, organization, and function

lamina propria
areolar connective tissue underlying a mucous membrane

mesoderm
middle embryonic germ layer from which connective tissue, muscle tissue, and some epithelial tissue derive

mucous membrane
tissue membrane that is covered by protective mucous and lines tissue exposed to the outside environment

muscle tissue
type of tissue that is capable of contracting and generating tension in response to stimulation; produces movement.

nervous tissue
type of tissue that is capable of sending and receiving impulses through electrochemical signals.

serous membrane
type of tissue membrane that lines body cavities and lubricates them with serous fluid

synovial membrane
connective tissue membrane that lines the cavities of freely movable joints, producing synovial fluid for lubrication

tissue
group of cells that are similar in form and perform related functions

tissue membrane
thin layer or sheet of cells that covers the outside of the body, organs, and internal cavities

totipotent
embryonic cells that have the ability to differentiate into any type of cell and organ in the body

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Answers

Interactive Link

Answer: Most somatic stem cells give rise to only a few cell types.

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3.3: Epithelial Tissue

By the end of the section, you will be able to:

- Explain the structure and function of epithelial tissue
- Distinguish between tight junctions, anchoring junctions, and gap junctions
- Distinguish between simple epithelia and stratified epithelia, as well as between squamous, cuboidal, and columnar epithelia
- Describe the structure and function of endocrine and exocrine glands and their respective secretions

Most epithelial tissues are essentially large sheets of cells covering all the surfaces of the body exposed to the outside world and lining the outside of organs. Epithelium also forms much of the glandular tissue of the body. Skin is not the only area of the body exposed to the outside. Other areas include the airways, the digestive tract, as well as the urinary and reproductive systems, all of which are lined by an epithelium. Hollow organs and body cavities that do not connect to the exterior of the body, which includes, blood vessels and the heart, are lined by endothelium (plural = endothelia), which is a type of epithelium.

Epithelial cells derive from all three major embryonic layers. The epithelia lining the skin, parts of the mouth and nose, and the anus develop from the ectoderm. Cells lining the airways and most of the digestive system originate in the endoderm. The epithelium that lines vessels in the lymphatic and cardiovascular system derives from the mesoderm and is called an endothelium.

All epithelia share some important structural and functional features. This tissue is highly cellular, with little or no extracellular material present between cells. Adjoining cells form a specialized intercellular connection between their cell membranes called a **cell junction**. The epithelial cells exhibit polarity with differences in structure and function between the exposed or apical facing surface of the cell and the basal surface close to the underlying body structures. The **basal lamina**, a mixture of glycoproteins and collagen, provides an attachment site for the epithelium, separating it from underlying connective tissue. The basal lamina attaches to a **reticular lamina**, which is secreted by the underlying connective tissue, forming a **basement membrane** that helps hold it all together.

Epithelial tissues are nearly completely avascular. For instance, no blood vessels cross the basement membrane to enter the tissue, and nutrients must come by diffusion or absorption from underlying tissues or the surface. Many epithelial tissues are capable of rapidly replacing damaged and dead cells. Sloughing off of damaged or dead cells is a characteristic of surface epithelium and allows our airways and digestive tracts to rapidly replace damaged cells with new cells.

Generalized Functions of Epithelial Tissue

Epithelial tissues provide the body's first line of protection from physical, chemical, and biological wear and tear. The cells of an epithelium act as gatekeepers of the body controlling permeability and allowing selective transfer of materials across a physical barrier. All substances that enter the body must cross an epithelium. Some epithelia often include structural features that allow the selective transport of molecules and ions across their cell membranes.

Many epithelial cells are capable of secretion and release mucous and specific chemical compounds onto their apical surfaces. The epithelium of the small intestine releases digestive enzymes, for example. Cells lining the respiratory tract secrete mucous that traps incoming microorganisms and particles. A glandular epithelium contains many secretory cells.

Some epithelial tissues also provide sensation. Nerve supply to epithelial tissues can alert the body to pressure, pain, and temperature from external or internal stimuli. This can help the body to maintain homeostasis or avoid harmful situations in the environment.

The Epithelial Cell

Epithelial cells are typically characterized by the polarized distribution of organelles and membrane-bound proteins between their basal and apical surfaces. Particular structures found in some epithelial cells are an adaptation to specific functions. Certain organelles are segregated to the basal sides, whereas other organelles and extensions, such as cilia, when present, are on the

apical surface.

Cilia are microscopic extensions of the apical cell membrane that are supported by microtubules. They beat in unison and move fluids as well as trapped particles. Ciliated epithelium lines the ventricles of the brain where it helps circulate the cerebrospinal fluid. The ciliated epithelium of your airway forms a mucociliary escalator that sweeps particles of dust and pathogens trapped in the secreted mucous toward the throat. It is called an escalator because it continuously pushes mucous with trapped particles upward. In contrast, nasal cilia sweep the mucous blanket down towards your throat. In both cases, the transported materials are usually swallowed, and end up in the acidic environment of your stomach.

Cell to Cell Junctions

Cells of epithelia are closely connected and are not separated by intracellular material. Three basic types of connections allow varying degrees of interaction between the cells: tight junctions, anchoring junctions, and gap junctions (Figure 3.3.1).

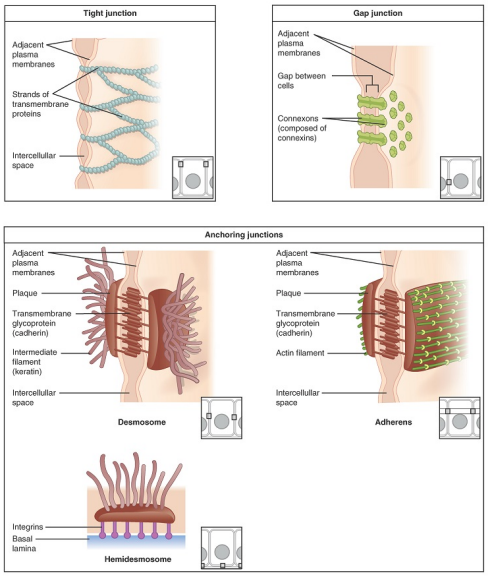


Figure 3.3.1: Types of Cell Junctions. The three basic types of cell-to-cell junctions are tight junctions, gap junctions, and anchoring junctions. (Image credit: "Types of Cell Junctions" by OpenStax is licensed under CC BY 3.0)

At one end of the spectrum is the **tight junction**, which separates the cells into apical and basal compartments. Tight junctions essentially "stitch" adjacent cell together, forming an impermeable barrier. An **anchoring junction** includes several types of cell junctions that help stabilize epithelial tissues. Anchoring junctions are common on the lateral and basal surfaces of cells where they provide strong and flexible connections. There are three types of anchoring junctions: desmosomes, hemidesmosomes, and adherens. Desmosomes occur in patches on the membranes of cells. The patches are structural proteins on the inner surface of the cell's membrane. The adhesion molecule, cadherin, is embedded in these patches and projects through the cell membrane to link with the cadherin molecules of adjacent cells. These connections are especially important in holding cells together. Hemidesmosomes, which look like half a desmosome, link cells to the extracellular matrix, for example, the basal lamina. While similar in appearance to desmosomes, they include the adhesion proteins called integrins rather than cadherins. Adherens junctions use either cadherins or integrins depending on whether they are linking to other cells or matrix. The junctions are characterized by the presence of the contractile protein actin located on the cytoplasmic surface of the cell membrane. The actin can connect isolated patches or form a belt-like structure inside the cell. These junctions influence the shape and folding of the epithelial tissue.

In contrast with the tight and anchoring junctions, a **gap junction** forms an intercellular passageway between the membranes of adjacent cells to facilitate the movement of small molecules and ions between the cytoplasm of adjacent cells. These junctions allow electrical and metabolic coupling of adjacent cells, which coordinates function in large groups of cells.

Classification of Epithelial Tissues

Epithelial tissues are classified according to the shape of the cells and number of the cell layers formed (Figure 3.3.2). Cell shapes

can be squamous (flattened and thin), cuboidal (boxy, as wide as it is tall), or columnar (rectangular, taller than it is wide). Similarly, the number of cell layers in the tissue can be one—where every cell rests on the basal lamina—which is a simple epithelium, or more than one, which is a stratified epithelium and only the basal layer of cells rests on the basal lamina. Pseudostratified (pseudo- = "false") describes tissue with a single layer of irregularly shaped cells that give the appearance of more than one layer. Transitional describes a form of specialized stratified epithelium in which the shape of the cells can vary.

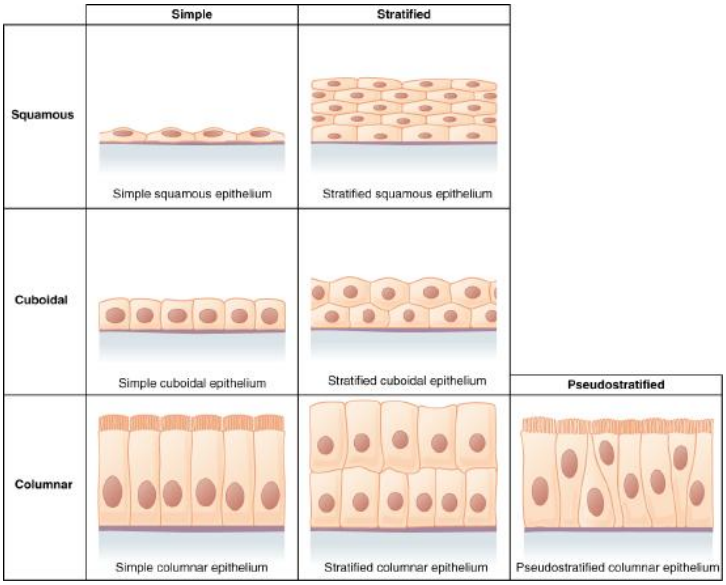


Figure 3.3.2: Epithelial Tissues. Simple epithelial tissue is organized as a single layer of cells and stratified epithelial tissue is formed by several layers of cells. (Image credit: "Epithelial Tissue" by OpenStax is licensed under CC BY 3.0)

Simple Epithelia

The shape of the cells in the single cell layer of simple epithelium reflects the functioning of those cells. The cells in **simple squamous epithelium** (Figure 3.3.3) have the appearance of thin scales. Squamous cell nuclei tend to be flat, horizontal, and elliptical, mirroring the form of the cell. The **endothelium** is the epithelial tissue that lines vessels of the lymphatic and cardiovascular system, and it is made up of a single layer of squamous cells. Simple squamous epithelium, because of the thinness of the cell, is present where rapid passage of chemical compounds is observed. The alveoli of lungs where gases diffuse, segments of kidney tubules, and the lining of capillaries are also made of simple squamous epithelial tissue. The **mesothelium** is a simple squamous epithelium that forms the surface layer of the serous membrane that lines body cavities and internal organs. Its primary function is to provide a smooth and protective surface. Mesothelial cells are squamous epithelial cells that secrete a fluid that lubricates the mesothelium.

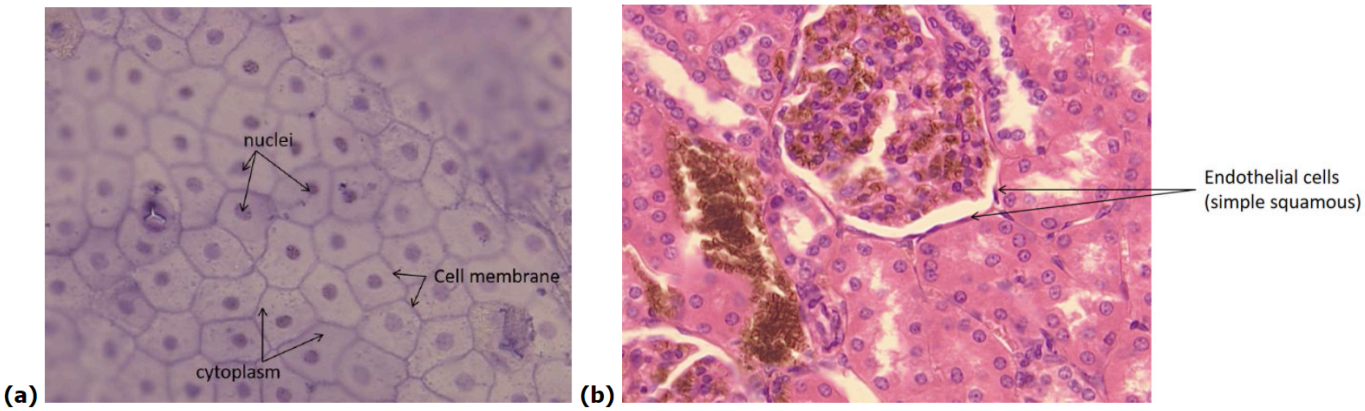


Figure 3.3.3: Simple Squamous Epithelium. (a) Simple squamous cells are packed tightly together in a thin sheet. (b) An endothelium, made of simple squamous cells, forming a glomerular capsule in the kidney. (Image credit:"Simple Squamous Epithelium" by Jennifer MacDonald, Histotechnology Program, Mt. San Antonio College is licensed under CC BY-NC 4.0)

In **simple cuboidal epithelium** (Figure 3.3.4), the nucleus of the box-like cells appears round and is generally located near the center of the cell. These epithelia are active in the secretion and absorption of molecules. Simple cuboidal epithelia are observed in the lining of the kidney tubules and in the ducts of glands.

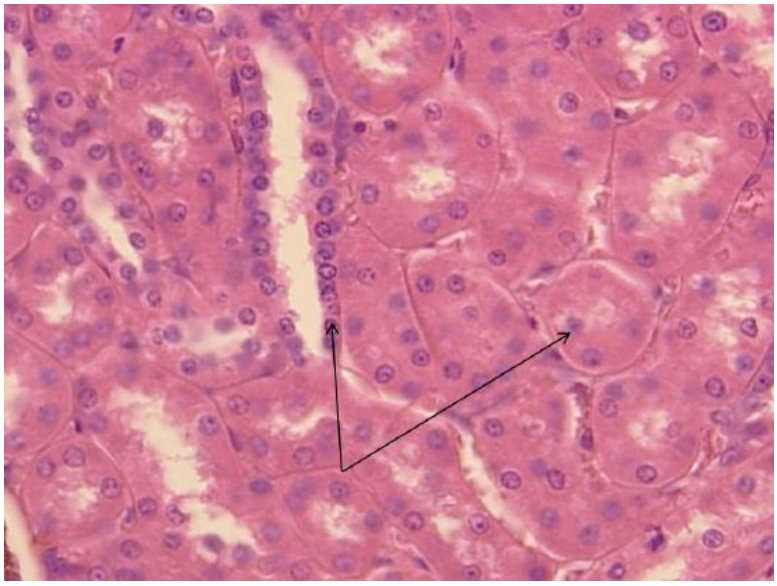


Figure 3.3.4: Simple Cuboidal Epithelium. Arrows indicate simple cuboidal epithelium lining kidney tubules. (Image credit: “Simple Cuboidal Epithelium" by Jennifer MacDonald, Histotechnology Program, Mt. San Antonio College is licensed under CC BY-NC 4.0)

In **simple columnar epithelium** (Figure 3.3.5), the nucleus of the tall column-like cells tends to be elongated and located in the basal end of the cells. Like the cuboidal epithelia, this epithelium is active in the absorption and secretion of molecules. Simple columnar epithelium forms the lining of some sections of the digestive system and parts of the female reproductive tract. Ciliated columnar epithelium is composed of simple columnar epithelial cells with cilia on their apical surfaces. These epithelial cells are found in the lining of the Fallopian tubes and parts of the respiratory system, where the beating of the cilia helps remove particulate matter.

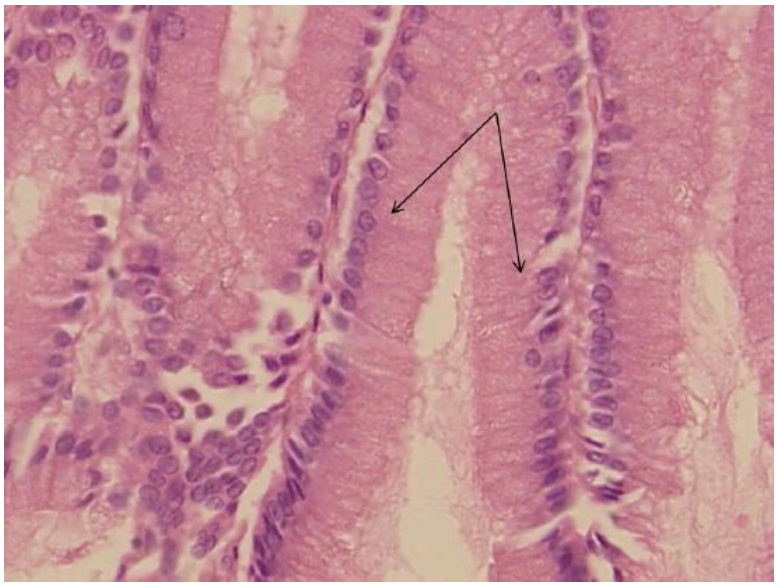


Figure 3.3.5: Simple Columnar Epithelium. Arrows indicate simple columnar epithelium. (Image credit: “Simple Columnar Epithelium" by Jennifer MacDonald, Histotechnology Program, Mt. San Antonio College is licensed under CC BY-NC 4.0)

Pseudostratified columnar epithelium (Figure 3.3.6) is a type of epithelium that appears to be stratified but instead consists of a single layer of irregularly shaped and differently sized columnar cells. In pseudostratified epithelium, nuclei of neighboring cells appear at different levels rather than clustered in the basal end. The arrangement gives the appearance of stratification; but in fact all the cells are in contact with the basal lamina, although some do not reach the apical surface. Pseudostratified columnar

epithelium is found in the respiratory tract, where some of these cells have cilia.

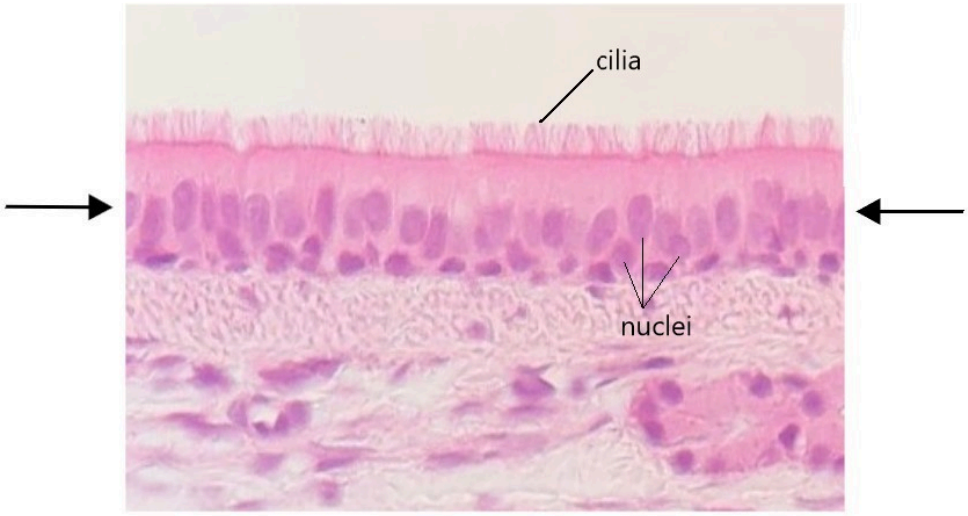


Figure 3.3.6: Pseudostratifed Columnar Epithelium. Arrows indicate the layer of pseudostratified columnar epithelium. (Image credit: "Pseudostratifed Columnar Epithelium" by Whitney Menefee is licensed under CC BY 4.0).

Both simple and pseudostratified columnar epithelia are heterogeneous epithelia because they include additional types of cells interspersed among the epithelial cells. For example, a **goblet cell** is a mucous-secreting unicellular "gland" interspersed between the columnar epithelial cells of mucous membranes (Figure 3.3.7).

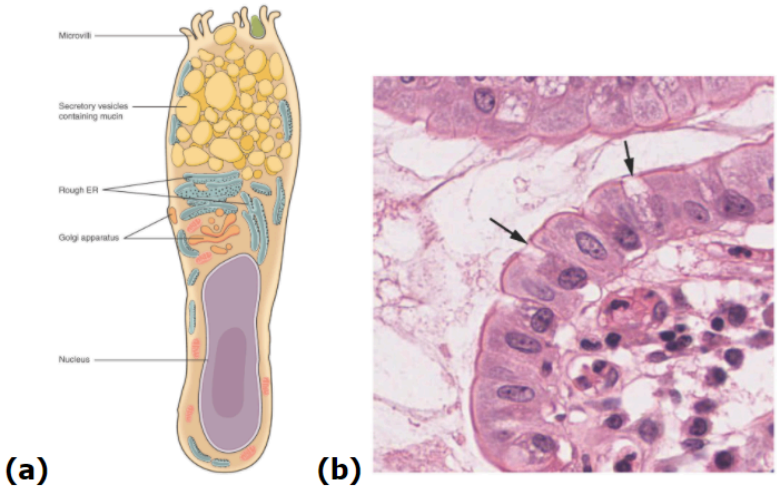


Figure 3.3.7: Goblet Cell. (a) In the lining of the small intestine, columnar epithelium cells are interspersed with goblet cells. (b) The arrows in this micrograph point to the mucous-secreting goblet cells. LM × 1600. (Image credit: "Goblet Cell" by OpenStax is licensed under CC BY 3.0/ Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Stratified Epithelia

A stratified epithelium consists of several stacked layers of cells. This epithelium protects against physical and chemical wear and tear. The stratified epithelium is named by the shape of the most apical layer of cells, closest to the free space. **Stratified squamous epithelium** (Figure 3.3.8) is the most common type of stratified epithelium in the human body. The apical cells are squamous, whereas the basal layer contains either columnar or cuboidal cells. The top layer may be covered with dead cells filled with keratin. The epidermis of mammalian skin is an example of this dry, keratinized, stratified squamous epithelium. The

lining of the oral cavity is an example of an non-keratinized, stratified squamous epithelium. **Stratified cuboidal epithelium** and **stratified columnar epithelium** (Figure 3.3.8) can also be found in certain glands and ducts, but are uncommon in the human body.

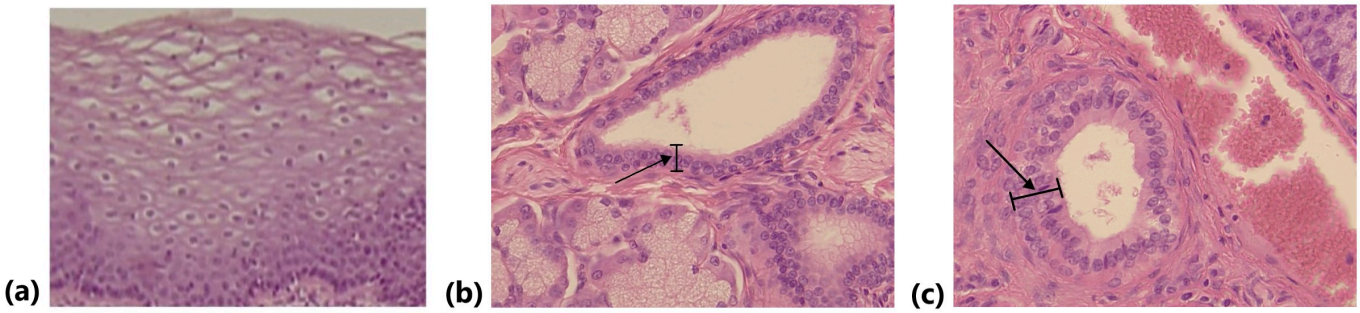


Figure 3.3.8: Stratified Epithelial Tissues. (a) Stratified Squamous Epithelium. (b) Stratified Cuboidal Epithelium indicated by arrow. (c) Stratified Columnar Epithelium indicated by arrow. (Image credit:"Stratified Epithelial Tissues" by Jennifer MacDonald, Histotechnology Program, Mt. San Antonio College is licensed under CC BY-NC 4.0).

Another kind of stratified epithelium is **transitional epithelium** (Figure 3.3.9), so-called because of the gradual changes in the shapes of the apical cells as the bladder fills with urine. It is found only in the urinary system, specifically the ureters and urinary bladder. When the bladder is empty, this epithelium is convoluted and has cuboidal apical cells with convex, umbrella shaped, apical surfaces. As the bladder fills with urine, this epithelium loses its convolutions and the apical cells transition from cuboidal to squamous. It appears thicker and more multi-layered when the bladder is empty, and more stretched out and less stratified when the bladder is full and distended.

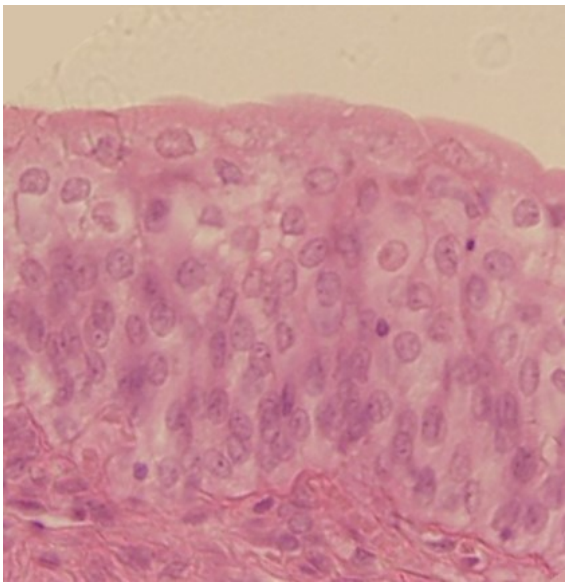
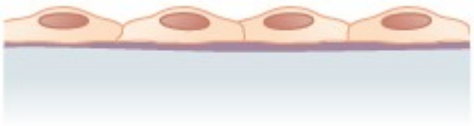
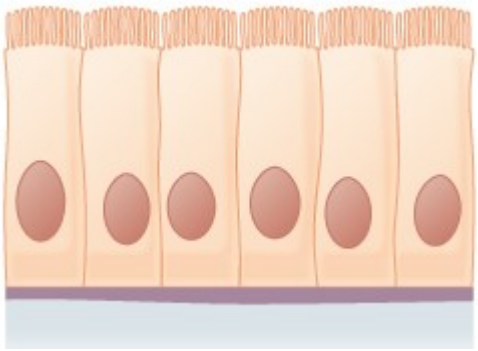
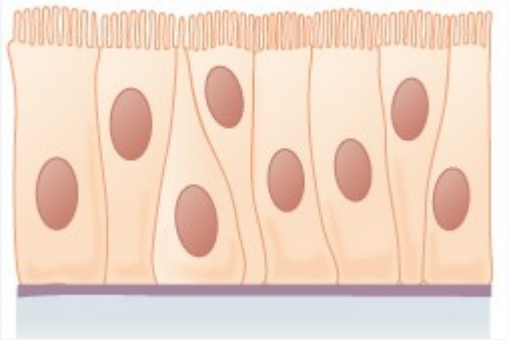
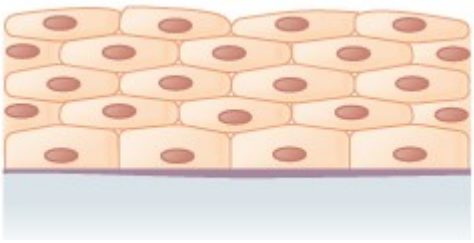
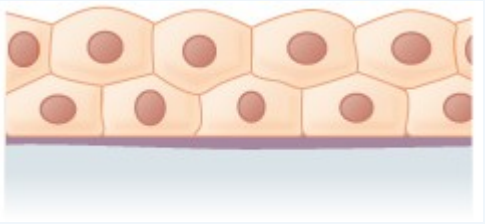
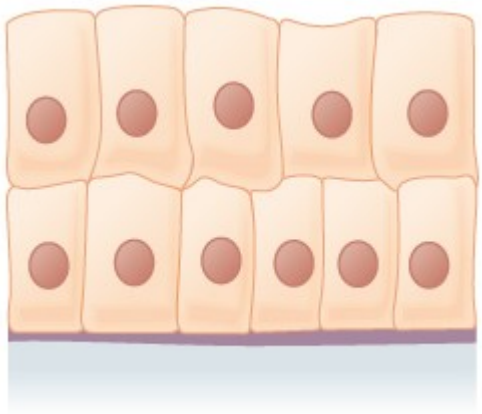
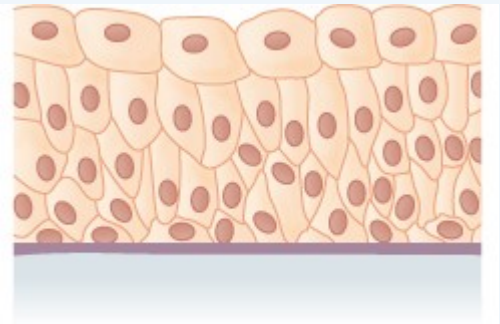


Figure 3.3.9: Transitional Epithelium. Transitional epithelium is found lining organs of the urinary system, allowing them to stretch. (Image credit: "Transitional Epithelium" by Jennifer MacDonald, Histotechnology Program, Mt. San Antonio College is licensed under CC BY-NC 4.0).

Table 3.3.1: Summary of Epithelial Tissues. The cell shape and number of layers determines an epithelial tissue's location and function.

Tissue	Location	Function
Simple Squamous Epithelium 	Air sacs of lungs and lining of the heart, blood vessels, and lymphatic vessels.	Allows material to pass through by diffusion and filtration, and secretes lubricating substance
Simple Cuboidal Epithelium	In ducts and secretory portions of small glands and in the kidney tubules	Secretes and absorbs
Simple Columnar Epithelium 	Ciliated tissues are in bronchi, uterine tubes, and uterus; smooth (nonciliated tissues) are in the digestive tract, bladder	Absorbs; it also secretes mucous and enzymes
Psuedostratified Columnar Epithelium 	Ciliated tissue lines the trachea and much of the upper respiratory tract	Secretes mucus, ciliated tissue moves mucus

Tissue	Location	Function
Stratified Squamous Epithelium 	Lines the esophagus, mouth, and vagina	Protects against abrasion
Stratified Cuboidal Epithelium 	Sweat glands, salivary glands, and the mammary glands	Protective tissue
Stratified Columnar Epithelium 	The male urethra and the ducts of some glands	Secretes and protects

Tissue	Location	Function
Transitional Epithelium 	Lines the bladder, urethra, and the ureters	Allows the urinary organs to expand and stretch

Glandular Epithelium

A gland is a structure made up of one or more cells modified to synthesize and secrete chemical substances. Most glands consist of groups of epithelial cells. A gland can be classified as an **endocrine gland**, a ductless gland that releases secretions directly into surrounding tissues and fluids (endo- = “inside”), or an **exocrine gland** whose secretions leave through a duct that opens directly, or indirectly, to the external environment (exo- = “outside”).

Endocrine Glands

The secretions of endocrine glands are called hormones. Hormones are released into the interstitial fluid, diffused into the bloodstream, and delivered to targets, in other words, cells that have receptors to bind the hormones. The endocrine system is part of a major regulatory system coordinating the regulation and integration of body responses. A few examples of endocrine glands include the anterior pituitary, thymus, adrenal cortex, and gonads (ovaries and testes).

Exocrine Glands

Exocrine glands release their contents through a duct that leads to the epithelial surface. Mucous, sweat, saliva, and breast milk are all examples of secretions from exocrine glands. They are all discharged through tubular ducts. Secretions into the lumen of the gastrointestinal tract, technically outside of the body, are of the exocrine category.

Glandular Structure

Exocrine glands are classified as either unicellular or multicellular. The unicellular glands are scattered single cells, such as goblet cells, found in the mucous membranes of the small and large intestine.

The multicellular exocrine glands known as serous glands develop from simple epithelium to form a secretory surface that secretes directly into an inner cavity. These glands line the internal cavities of the abdomen and chest and release their secretions directly into the cavities. Other multicellular exocrine glands release their contents through a tubular duct. The duct is single in a simple gland but in compound glands is divided into one or more branches (Figure 3.3.10). In tubular glands, the ducts can be straight or coiled. Examples of tubular glands include simple tubular (e.g. intestinal glands), simple coiled tubular (e.g. merocrine sweat glands), simple branched tubular (e.g. gastric glands, and mucous glands of the esophagus, tongue, and duodenum), and compound tubular (e.g. mucous gland of the mouth, and bulbourethral glands and the seminiferous tubules of the testes, both of which are found in the male reproductive system). Glands that contain a duct that form pockets are alveolar (acinar), such as the exocrine portion of the pancreas. An example of an alveolar (acinar) gland includes simple alveolar, which are only found in the early stages of development as precursors to simple branched glands. Other examples include simple branched alveolar (e.g. sebaceous (oil) glands), and compound alveolar (e.g. mammary glands). Combinations of tubes and pockets are known as tubuloalveolar (tubuloacinar) compound glands. In a branched gland, a duct is connected to more than one secretory group of cells.

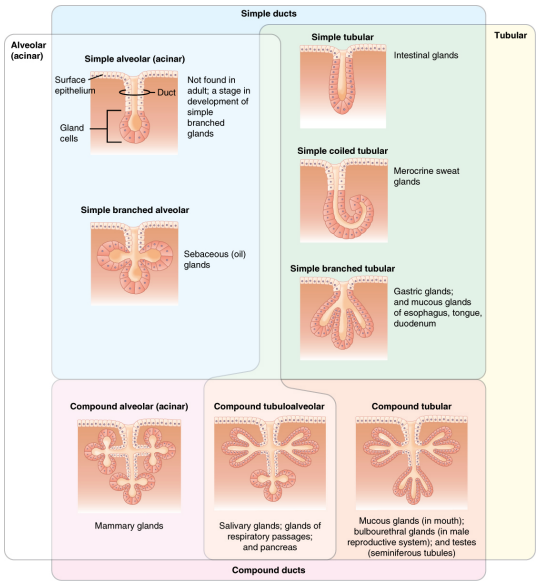


Figure 3.3.10: Types of Exocrine Glands. Exocrine glands are classified by their structure. (Image credit: "Types of Glands" by OpenStax is licensed under CC BY 3.0)

Methods and Types of Secretion

Exocrine glands can be classified by their mode of secretion and the nature of the substances released, as well as by the structure of the glands and shape of ducts (Figure 3.3.11). **Merocrine secretion** is the most common type of exocrine secretion. The secretions are enclosed in vesicles that move to the apical surface of the cell where the contents are released by exocytosis. For example, watery mucous containing the glycoprotein mucin, a lubricant that offers some pathogen protection is a merocrine secretion. The eccrine glands that produce and secrete sweat are another example.

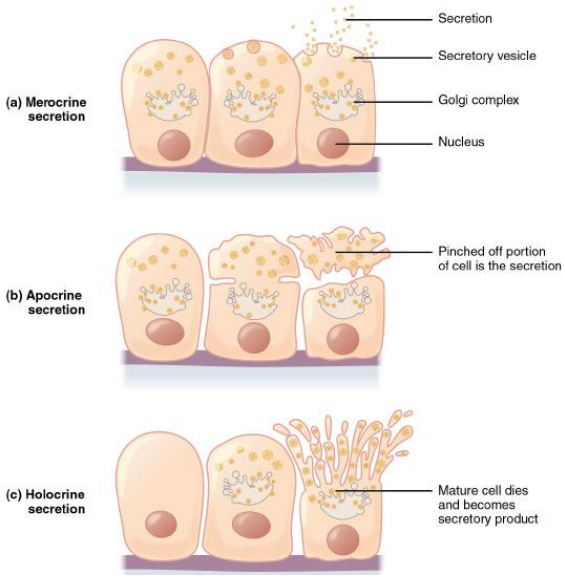


Figure 3.3.11: Modes of Glandular Secretion. (a) In merocrine secretion, the cell remains intact. (b) In apocrine secretion, the apical portion of the cell is released, as well. (c) In holocrine secretion, the cell is destroyed as it releases its product and the cell itself becomes part of the secretion. (Image credit: "Modes of Secretion by Glands" by OpenStax is licensed under CC BY 3.0)

Apocrine secretion accumulates near the apical portion of the cell. That portion of the cell and its secretory contents pinch off from the cell and are released. Some sweat glands of the axilla region are classified as apocrine glands. Both merocrine and apocrine glands continue to produce and secrete their contents with little damage caused to the cell because the nucleus and golgi regions remain intact after secretion.

In contrast, the process of **holocrine secretion** involves the rupture and destruction of the entire gland cell. The cell accumulates its secretory products and releases them only when it bursts. New gland cells differentiate from cells in the surrounding tissue to replace those lost by secretion. The sebaceous glands that produce the oils on the skin and hair are holocrine glands/cells (Figure 3.3.12).

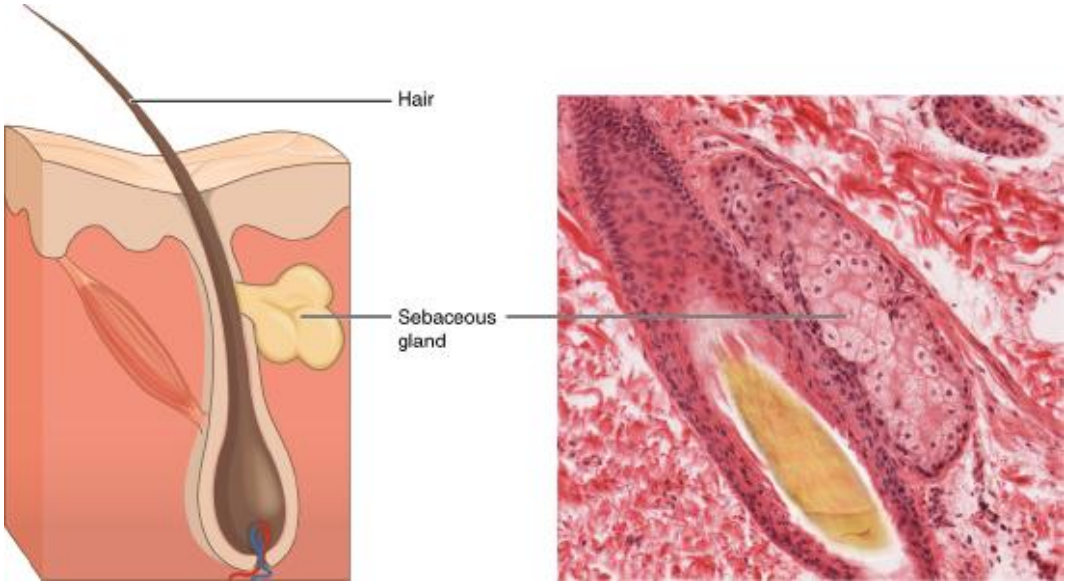


Figure 3.3.12: Sebaceous Glands. These glands secrete oils that lubricate and protect the skin. They are holocrine glands and they are destroyed after releasing their contents. New glandular cells form to replace the cells that are lost. LM × 400. (Image credit: "Sebaceous Glands" by OpenStax is licensed under CC BY 3.0/ Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Glands are also named after the products they produce. The **serous gland** produces watery, blood-plasma-like secretions rich in enzymes such as alpha amylase, whereas the **mucous gland** releases watery to viscous products rich in the glycoprotein mucin. Both serous and mucous glands are common in the salivary glands of the mouth. Mixed exocrine glands contain both serous and mucous glands and release both types of secretions.

Concept Review

In epithelial tissue, cells are closely packed with little or no extracellular matrix except for the basal lamina that separates the epithelium from underlying tissue. The main functions of epithelia are protection from the environment, coverage, secretion and excretion, absorption, and filtration. Cells are bound together by tight junctions that form an impermeable barrier. They can also be connected by gap junctions, which allow free exchange of soluble molecules between cells, and anchoring junctions, which attach cell to cell or cell to matrix. The different types of epithelial tissues are characterized by their cellular shapes and arrangements: squamous, cuboidal, or columnar epithelia. Single cell layers form simple epithelia, whereas stacked cells form stratified epithelia. Very few capillaries penetrate these tissues.

Glands are secretory tissues and organs that are derived from epithelial tissues. Exocrine glands release their products through ducts. Endocrine glands secrete hormones directly into the interstitial fluid and blood stream. Glands are classified both according to the type of secretion and by their structure. Merocrine glands secrete products as they are synthesized. Apocrine glands release secretions by pinching off the apical portion of the cell, whereas holocrine gland cells store their secretions until they rupture and release their contents. In this case, the cell becomes part of the secretion.

Review Questions

Q. In observing epithelial cells under a microscope, the cells are arranged in a single layer and look tall and narrow, and the nucleus is located close to the basal side of the cell. The specimen is what type of epithelial tissue?

A. columnar

B. stratified

C. squamous

D. transitional

Answer

Answer: A

Q. Which of the following is the epithelial tissue that lines the interior of blood vessels?

A. columnar

B. pseudostratified

C. simple squamous

D. transitional

Answer

Answer: C

Q. Which type of epithelial tissue specializes in moving particles across its surface and is found in airways?

A. transitional

B. stratified columnar

C. pseudostratified ciliated columnar

D. stratified squamous

Answer

Answer: C

Q. The _____ exocrine gland stores its secretion until the glandular cell ruptures, whereas the _____ gland releases its apical region and reforms.

A. holocrine; apocrine

B. eccrine; endocrine

C. apocrine; holocrine

D. eccrine; apocrine

Answer

Answer: A

Critical Thinking Questions

Q. The structure of a tissue usually is optimized for its function. Describe how the structure of individual cells and tissue arrangement of the intestine lining matches its main function, to absorb nutrients.

Answer

A. Columnar epithelia, which form the lining of the digestive tract, can be either simple or stratified. The cells are long and narrow, which provide protection while still allowing for secretion and absorption.

Glossary

anchoring junction
: mechanically attaches adjacent cells to each other or to the basement membrane

apical
: that part of a cell or tissue which, in general, faces an open space

apocrine secretion
: release of a substance along with the apical portion of the cell

basal lamina
: thin extracellular layer that lies underneath epithelial cells and separates them from other tissues

basement membrane
: in epithelial tissue, a thin layer of fibrous material that anchors the epithelial tissue to the underlying connective tissue; made up of the basal lamina and reticular lamina

cell junction
: point of cell-to-cell contact that connects one cell to another in a tissue

endocrine gland
: groups of cells that release chemical signals into the intercellular fluid to be picked up and transported to their target organs by blood

endothelium
: tissue that lines vessels of the lymphatic and cardiovascular system, made up of a simple squamous epithelium

exocrine gland
: group of epithelial cells that secrete substances through ducts that open to the skin or to internal body surfaces that lead to the exterior of the body

gap junction
: allows cytoplasmic communications to occur between cells

goblet cell
: unicellular gland found in columnar epithelium that secretes mucous

holocrine secretion
: release of a substance caused by the rupture of a gland cell, which becomes part of the secretion

merocrine secretion
: release of a substance from a gland via exocytosis

mesothelium
: simple squamous epithelial tissue which covers the major body cavities and is the epithelial portion of serous membranes

mucous gland
: group of cells that secrete mucous, a thick, slippery substance that keeps tissues moist and acts as a lubricant

pseudostratified columnar epithelium
: tissue that consists of a single layer of irregularly shaped and sized cells that give the appearance of multiple layers; found in ducts of certain glands and the upper respiratory tract

reticular lamina
: matrix containing collagen and elastin secreted by connective tissue; a component of the basement membrane

serous gland
: group of cells within the serous membrane that secrete a lubricating substance onto the surface

simple columnar epithelium
: tissue that consists of a single layer of column-like cells; promotes secretion and absorption in tissues and organs

simple cuboidal epithelium
: tissue that consists of a single layer of cube-shaped cells; promotes secretion and absorption in ducts and tubules

simple squamous epithelium
: tissue that consists of a single layer of flat scale-like cells; promotes diffusion and filtration across surface

stratified columnar epithelium
: tissue that consists of two or more layers of column-like cells, contains glands and is found in some ducts

stratified cuboidal epithelium
: tissue that consists of two or more layers of cube-shaped cells, found in some ducts

stratified squamous epithelium
: tissue that consists of multiple layers of cells with the most apical being flat scale-like cells; protects surfaces from abrasion

tight junction
: forms an impermeable barrier between cells

transitional epithelium
: form of stratified epithelium found in the urinary tract, characterized by an apical layer of cells that change shape in response to the presence of urine

Contributors and Attributions

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3.4: Connective Tissue

By the end of the section, you will be able to:

- Identify and distinguish between the types of connective tissue: proper, supportive, and fluid
- Explain the functions of connective tissues

As may be obvious from its name, one of the major functions of connective tissue is to connect tissues and organs. Unlike epithelial tissue, which is composed of cells closely packed with little or no extracellular space in between, connective tissue cells are dispersed in a **matrix**. The matrix usually includes a large amount of extracellular material produced by the connective tissue cells that are embedded within it. The matrix plays a major role in the functioning of this tissue. The major component of the matrix is a **ground substance** often crisscrossed by protein fibers. This ground substance is usually a fluid, but it can also be mineralized and solid, as in bones. Connective tissues come in a vast variety of forms, yet they typically have in common three characteristic components: cells, large amounts of amorphous ground substance, and protein fibers. The amount and structure of each component correlates with the function of the tissue, from the rigid ground substance in bones supporting the body to the inclusion of specialized cells; for example, phagocytic cells that engulf pathogens and also rid tissue of cellular debris are common in many connective tissues.

Functions of Connective Tissues

Connective tissues perform many functions in the body, but most importantly, they support and connect other tissues; from the connective tissue sheath that surrounds muscle cells, to the tendons that attach muscles to bones, and to the skeleton that supports the positions of the body. Protection is another major function of connective tissue, in the form of fibrous capsules and bones that protect delicate organs and, of course, the skeletal system. Specialized cells in connective tissue defend the body from microorganisms that enter the body. Transport of fluid, nutrients, waste, and chemical messengers is ensured by specialized fluid connective tissues, such as blood and lymph. Adipose cells store surplus energy in the form of fat and contribute to the thermal insulation of the body.

Embryonic Connective Tissue

All connective tissues derive from the mesodermal layer of the embryo. The first connective tissue to develop in the embryo is **mesenchyme**, the stem cell line from which all connective tissues are later derived. Clusters of mesenchymal cells are scattered throughout adult tissue and supply the cells needed for replacement and repair after a connective tissue injury. A second type of embryonic connective tissue forms in the umbilical cord, called **mucous connective tissue** or Wharton's jelly. This tissue is no longer present after birth, leaving only scattered mesenchymal cells throughout the body.

Classification of Connective Tissues

The three broad categories of connective tissue are classified according to the characteristics of their ground substance and the types of fibers found within the matrix (Table 3.4.1). **Connective tissue proper** includes **loose connective tissue** and **dense connective tissue**. Both tissues have a variety of cell types and protein fibers suspended in a viscous ground substance. Dense connective tissue is reinforced by bundles of fibers that provide tensile strength, elasticity, and protection. In loose connective tissue, the fibers are loosely organized, leaving large spaces in between. **Supportive connective tissue**—bone and cartilage—provide structure and strength to the body and protect soft tissues. A few distinct cell types and densely packed fibers in a matrix characterize these tissues. In bone, the matrix is rigid and described as calcified because of the deposited calcium salts. In **fluid connective tissue**, in other words, lymph and blood, various specialized cells circulate in a watery fluid containing salts, nutrients, and dissolved proteins.

Table 3.4.1: Connective Tissue Examples

Connective tissue proper	Supportive connective tissue	Fluid connective tissue
Loose connective tissue • Areolar • Adipose • Reticular	Cartilage • Hyaline • Fibrocartilage • Elastic	Blood
Dense connective tissue • Regular elastic • Irregular elastic	Bones • Compact bone • Cancellous bone	Lymph

Connective Tissue Proper

Fibroblasts are present in all connective tissue proper (Figure 3.4.1). Fibrocytes, adipocytes, and mesenchymal cells are fixed cells, which means they remain within the connective tissue. Other cells move in and out of the connective tissue in response to chemical signals. Macrophages, mast cells, lymphocytes, and plasma cells are found in connective tissue proper but are actually part of the immune system protecting the body.

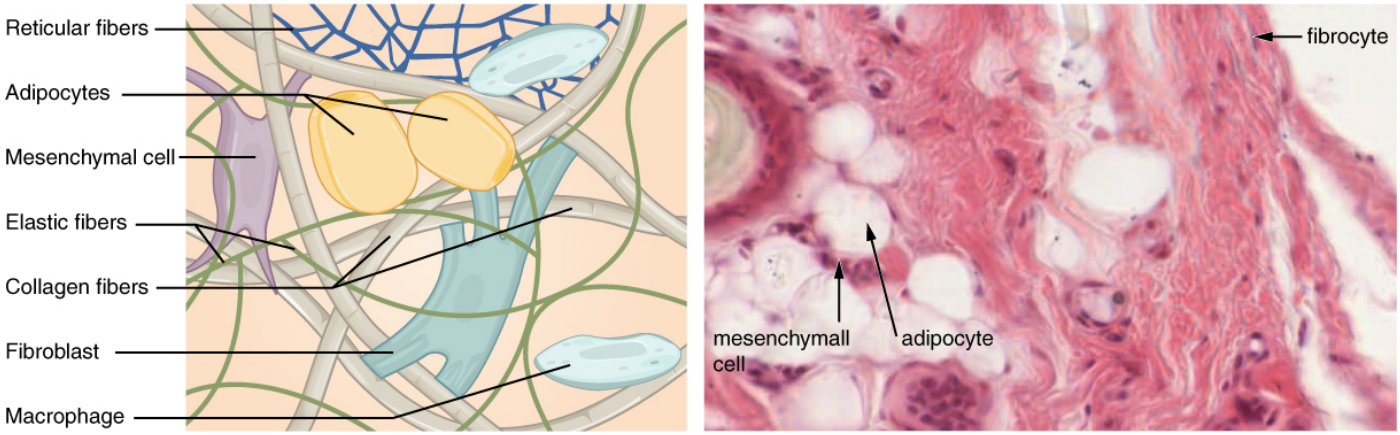

Figure 3.4.1: Connective Tissue Proper. Fibroblasts produce this fibrous tissue. Connective tissue proper includes the fixed cells fibrocytes, adipocytes, and mesenchymal cells. LM × 400. (Image credit: "Connective Tissue" by OpenStax is licensed under CC BY 3.0/ Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Cell Types

The most abundant cell in connective tissue proper is the **fibroblast**. Polysaccharides and proteins secreted by fibroblasts combine with extra-cellular fluids to produce a viscous ground substance that, with embedded fibrous proteins, forms the extra-cellular matrix. As you might expect, a **fibrocyte**, a less active form of fibroblast, is the second most common cell type in connective tissue proper.

Adipocytes are cells that store lipids as droplets that fill most of the cytoplasm. There are two basic types of adipocytes: white and brown. The brown adipocytes store lipids as many droplets, and have high metabolic activity. In contrast, white fat adipocytes store lipids as a single large drop and are metabolically less active. Their effectiveness at storing large amounts of fat is witnessed in obese individuals. The number and type of adipocytes depends on the tissue and location, and vary among individuals in the population.

The **mesenchymal cell** is a multipotent adult stem cell. These cells can differentiate into any type of connective tissue cells needed for repair and healing of damaged tissue.

The macrophage cell is a large cell derived from a monocyte, a type of blood cell, which enters the connective tissue matrix from the blood vessels. The macrophage cells are an essential component of the immune system, which is the body's defense against potential pathogens and degraded host cells. When stimulated, macrophages release cytokines, small proteins that act as chemical messengers. Cytokines recruit other cells of the immune system to infected sites and stimulate their activities. Roaming, or free, macrophages move rapidly by amoeboid movement, engulfing infectious agents and cellular debris. In contrast, fixed macrophages are permanent residents of their tissues.

The mast cell, found in connective tissue proper, has many cytoplasmic granules. These granules contain the chemical signals histamine and heparin. When irritated or damaged, mast cells release histamine, an inflammatory mediator, which causes vasodilation and increased blood flow at a site of injury or infection, along with itching, swelling, and redness you recognize as an allergic response. Heparin, also released as part of the inflammatory response, acts as an anticoagulant that prevents the formation of blood clots. Like blood cells, mast cells are derived from hematopoietic stem cells and are part of the immune system.

Connective Tissue Fibers and Ground Substance

Three main types of fibers are secreted by fibroblasts: collagen fibers, elastic fibers, and reticular fibers. **Collagen fibers** are made from fibrous protein subunits linked together to form a long and straight fiber. Collagen fibers, while flexible, have great tensile strength, resist stretching, and give ligaments and tendons their characteristic resilience and strength. These fibers hold connective tissues together, even during the movement of the body.

Elastic fibers contain the protein elastin along with lesser amounts of other proteins and glycoproteins. The main property of elastin is that after being stretched or compressed, it will return to its original shape. Elastic fibers are prominent in elastic tissues found in skin and the elastic ligaments of the vertebral column.

Reticular fibers are also formed from the same protein subunits as collagen fibers; however, these fibers remain narrow and are arrayed in a branching network. They are found throughout the body, but are most abundant in the reticular tissue of soft organs, such as liver and spleen, where they anchor and provide structural support to the **parenchyma** (the functional cells, blood vessels, and nerves of the organ).

All of these fiber types are embedded in ground substance. Secreted by fibroblasts, ground substance is made of polysaccharides, specifically hyaluronic acid, and proteins. These combine to form a proteoglycan with a protein core and polysaccharide branches. The proteoglycan attracts and traps available moisture forming the clear, viscous, colorless matrix you now know as ground substance.

Loose Connective Tissue

Loose connective tissue is found between many organs where it acts both to absorb shock and bind tissues together. It allows water, salts, and various nutrients to diffuse through to adjacent or embedded cells and tissues.

Adipose tissue consists mostly of fat storage cells, with little extracellular matrix (Figure 3.4.2). A large number of capillaries allow rapid storage and mobilization of lipid molecules. White adipose tissue is most abundant. It can appear yellow and owes its color to carotene and related pigments from plant food. White fat contributes mostly to lipid storage and can serve as insulation from cold temperatures and mechanical injuries. White adipose tissue can be found protecting the kidneys and cushioning the back of the eye. Brown adipose tissue is more common in infants, hence the term "baby fat." In adults, there is a reduced amount of brown fat and it is found mainly in the neck and clavicular regions of the body. The many mitochondria in the cytoplasm of brown adipose tissue help explain its efficiency at metabolizing stored fat. Brown adipose tissue is thermogenic, meaning that as it breaks down fats, it releases metabolic heat, rather than producing adenosine triphosphate (ATP), a key molecule used in metabolism.

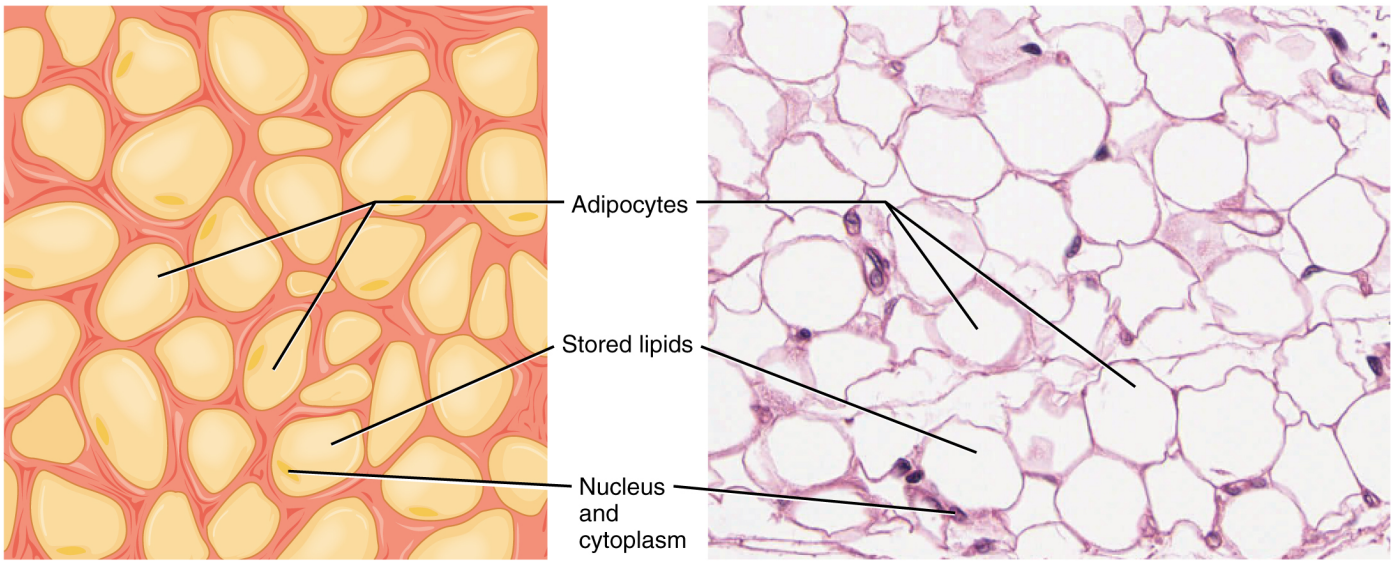

Figure 3.4.2: Adipose Tissue. This is a loose connective tissue that consists of fat cells with little extracellular matrix. It stores fat for energy and provides insulation. LM × 800. (Image credit:"Adipose Tissue" by OpenStax is licensed under CC BY 3.0/ Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Areolar tissue shows little specialization. It contains all the cell types and fibers previously described and is distributed in a random, web-like fashion. It fills the spaces between muscle fibers, surrounds blood and lymph vessels, and supports organs in the abdominal cavity. Areolar tissue underlies most epithelia and represents the connective tissue component of epithelial membranes, which are described further in a later section.

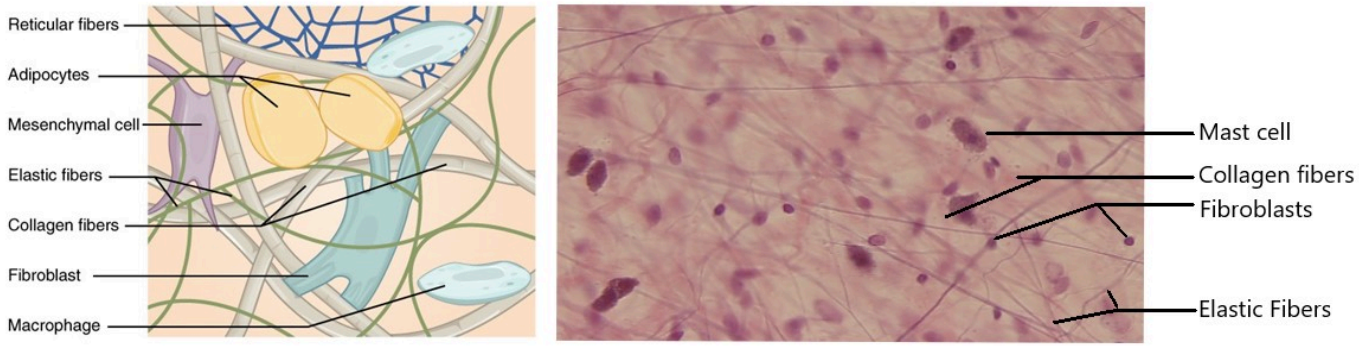

Figure 3.4.3: Areolar Connective Tissue. This is a loose connective tissue made up of all components found in connective tissue proper. (Image credit: Left: "Connective Tissue" by OpenStax is licensed under CC BY 3.0; Right: “Areolar Connective Tissue" by Jennifer MacDonald, Histotechnology Program, Mt. San Antonio College is licensed under CC BY-NC 4.0).

Reticular tissue is a mesh-like, supportive framework for soft organs such as lymphatic tissue, the spleen, and the liver (Figure 3.4.4). Reticular cells produce the reticular fibers that form the network onto which other cells attach. It derives its name from the Latin *reticulus*, which means “little net.”

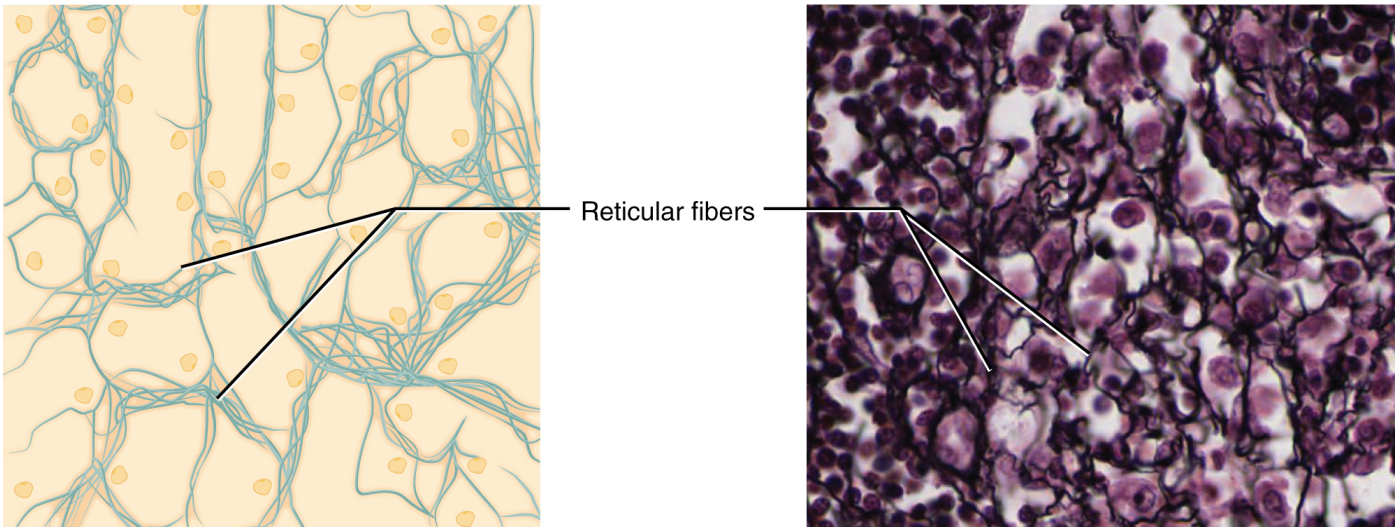

Figure 3.4.4: Reticular Tissue. This is a loose connective tissue made up of a network of reticular fibers that provides a supportive framework for soft organs. LM × 1600. (Image credit: "Reticular Tissue" by OpenStax is licensed under CC BY 3.0/ Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Dense Connective Tissue

Dense connective tissue contains more collagen fibers than does loose connective tissue. As a consequence, it displays greater resistance to stretching. There are two major categories of dense connective tissue: regular and irregular. Dense regular connective tissue fibers are parallel to each other, enhancing tensile strength and resistance to stretching in the direction of the fiber orientations. Ligaments and tendons are made of dense regular connective tissue, but in ligaments not all fibers are parallel. Dense regular elastic tissue contains elastic fibers in addition to collagen fibers. Some applications require a ligament to balance tensile strength and elasticity, and thus contain elastic fibers in addition to collagen fibers that allow the ligament to return to its original length after stretching. The ligaments in the vocal folds and between the vertebrae in the vertebral column are composed of dense regular elastic tissue.

In dense irregular connective tissue, the direction of fibers is random. This arrangement gives the tissue greater strength in all directions and less strength in one particular direction. In some tissues, fibers crisscross and form a mesh. In other tissues, stretching in several directions is achieved by alternating layers where fibers run in the same orientation in each layer, and it is the layers themselves that are stacked at an angle. The dermis of the skin is an example of dense irregular connective tissue rich in collagen fibers. As with dense regular connective tissue, when elastic fibers running in random directions outnumber collagen fibers, the tissue is a dense irregular elastic connective tissue. This type of tissue gives the walls of large arteries and respiratory passages strength and the ability to regain original shape after stretching. Examples of typical dense regular and dense irregular connective tissues consisting primarily of collagen fibers are shown in (Figure 3.4.5).

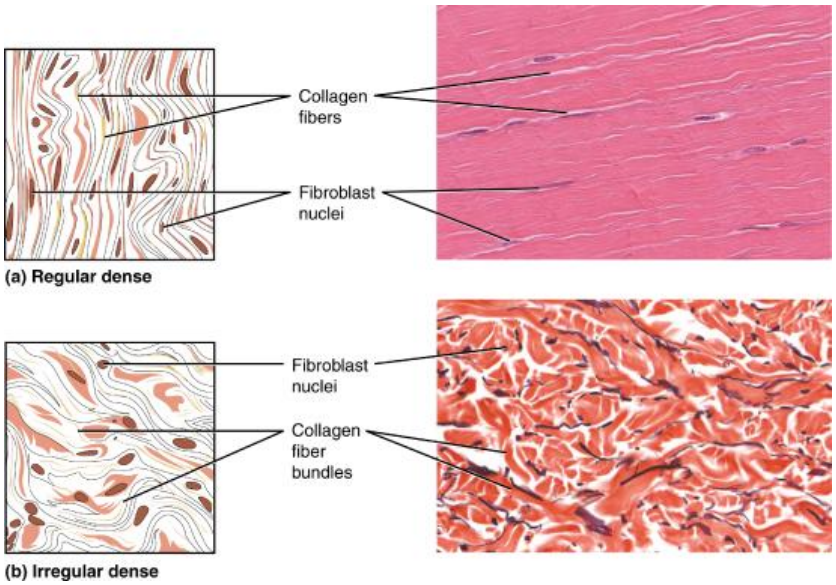

Figure 3.4.5: Dense Connective Tissue. (a) Dense regular connective tissue consists of collagenous fibers packed into parallel bundles. (b) Dense irregular connective tissue consists of collagenous fibers interwoven into a mesh-like network. From top, LM × 1000, LM × 200. (Image credit: "Reg Dense-Irregular Dense" by OpenStax is licensed under CC BY 3.0/ Micrographs provided by the Regents of University of Michigan Medical School © 2012)

DISORDERS OF THE.....

Connective Tissue: Tendinitis

Your opponent stands ready as you prepare to hit the serve, but you are confident that you will smash the ball past your opponent. As you toss the ball high in the air, a burning pain shoots across your wrist and you drop the tennis racket. That dull ache in the wrist that you ignored through the summer is now an unbearable pain. The game is over for now.

After examining your swollen wrist, the doctor in the emergency room announces that you have developed wrist tendinitis. She recommends icing the tender area, taking non-steroidal anti-inflammatory medication to ease the pain and to reduce swelling, and complete rest for a few weeks. She interrupts your protests that you cannot stop playing. She issues a stern warning about the risk of aggravating the condition and the possibility of surgery. She consoles you by mentioning that well known tennis players such as Venus and Serena Williams and Rafael Nadal have also suffered from tendinitis related injuries.

What is tendinitis and how did it happen? Tendinitis is the inflammation of a tendon, the thick band of dense regular connective tissue that attaches a muscle to a bone. The condition causes pain and tenderness in the area around a joint. On rare occasions, a sudden serious injury will cause tendinitis. Most often, the condition results from repetitive motions over time that strain the tendons needed to perform the tasks.

Persons whose jobs and hobbies involve performing the same movements over and over again are often at the greatest risk of tendinitis. You hear of tennis and golfer's elbow, jumper's knee, and swimmer's shoulder. In all cases, overuse of the joint causes a microtrauma that initiates the inflammatory response. Tendinitis is routinely diagnosed through a clinical examination. In case of severe pain, X-rays can be examined to rule out the possibility of a bone injury. Severe cases of tendinitis can even tear loose a tendon. Surgical repair of a tendon is painful. Connective tissue in the tendon does not have abundant blood supply and heals slowly.

While older adults are at risk for tendinitis because the elasticity of tendon tissue decreases with age, active people of all ages can develop tendinitis. Young athletes, dancers, and computer operators; anyone who performs the same movements constantly is at risk for tendinitis. Although repetitive motions are unavoidable in many activities and may lead to tendinitis, precautions can be taken that can lessen the probability of developing tendinitis. For active individuals, dynamic stretches before exercising and cross training or changing exercises are recommended. For the

passionate athlete, it may be time to take some lessons to improve technique. All of the preventive measures aim to increase the strength of the tendon and decrease the stress put on it. With proper rest and managed care, you will be back on the court to hit that slice-spin serve over the net.

Supportive Connective Tissues

Two major forms of supportive connective tissue, cartilage and bone, allow the body to maintain its posture and protect internal organs.

Cartilage

The distinctive appearance of cartilage is due to polysaccharides called chondroitin sulfates, which bind with ground substance proteins to form proteoglycans. Embedded within the cartilage matrix are **chondrocytes**, or cartilage cells, and the space they occupy are called **lacunae** (singular = lacuna). A layer of dense irregular connective tissue, the perichondrium, encapsulates the cartilage. Cartilaginous tissue is avascular, thus all nutrients need to diffuse through the matrix to reach the chondrocytes. This is a factor contributing to the very slow healing of cartilaginous tissues.

The three main types of cartilage tissue are hyaline cartilage, fibrocartilage, and elastic cartilage (Figure 3.4.6). **Hyaline cartilage**, the most common type of cartilage in the body, consists of short and dispersed collagen fibers and contains large amounts of proteoglycans. Under the microscope, tissue samples appear clear. The surface of hyaline cartilage is smooth. Both strong and flexible, it is found in the rib cage and nose and covers bones where they meet to form moveable joints. It makes up a template of the embryonic skeleton before bone formation. A plate of hyaline cartilage at the ends of bone allows continued growth until adulthood. **Fibrocartilage** is tough because it has thick bundles of collagen fibers dispersed through its matrix, which allows it to resist compression and absorb shock. The knee and jaw joints and the intervertebral discs are examples of fibrocartilage. **Elastic cartilage** contains elastic fibers as well as collagen and proteoglycans. This tissue gives rigid support as well as elasticity. Tug gently at your ear lobes, and notice that the lobes return to their initial shape. The external ear contains elastic cartilage.

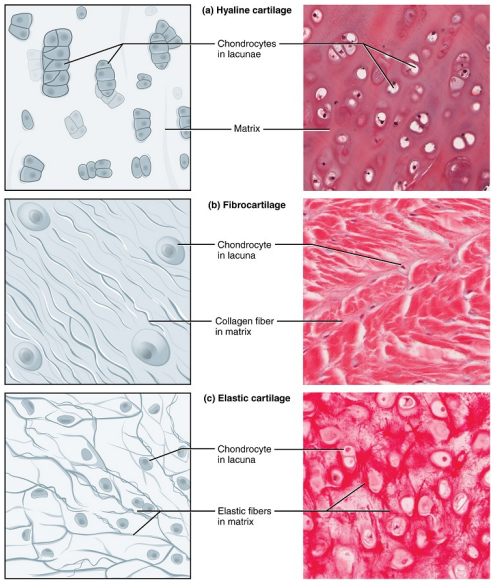

Figure 3.4.6: Types of Cartilage. Cartilage is a connective tissue consisting of collagenous fibers embedded in a firm matrix of chondroitin sulfates. (a) Hyaline cartilage provides support with some flexibility. The example is from dog tissue. (b) Fibrocartilage provides some compressibility and can absorb pressure. (c) Elastic cartilage provides firm but elastic support. From top, LM × 300, LM × 1200, LM × 1016. (Image credit: "Types of Cartilage" by OpenStax is licensed under CC BY 3.0/ Micrographs provided by the Regents of University of Michigan Medical School © 2012)

Bone

Bone is the hardest connective tissue. It provides protection to internal organs and supports the body. Bone's rigid extracellular matrix contains mostly collagen fibers embedded in a mineralized ground substance containing hydroxyapatite, a form of calcium

phosphate. Both components of the matrix, organic and inorganic, contribute to the unusual properties of bone. Without collagen, bones would be brittle and shatter easily. Without mineral crystals, bones would flex and provide little support. Osteocytes, bone cells like chondrocytes, are located within lacunae. The histology of transverse tissue from long bone (Figure 3.4.7) shows a typical arrangement of osteocytes in concentric circles around a central canal. Bone is a highly vascularized tissue. Unlike cartilage, bone tissue can recover from injuries in a relatively short time.

Cancellous bone, also known as spongy bone, looks like a sponge under the microscope (Figure 3.4.7) and contains empty spaces between trabeculae, or arches of bone proper. It is lighter than compact bone and found in the interior of some bones and at the end of long bones. Compact bone is solid and has greater structural strength.

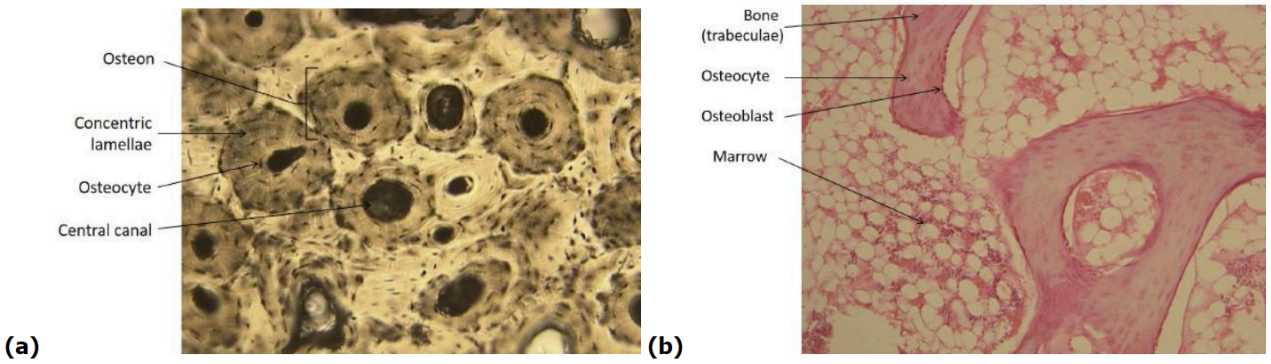

Figure 3.4.7: Bone Tissue. (a) Compact Bone Tissue (10x). (b) Cancellous Bone Tissue (10x). (Image credit: "Bone Tissue" by Jennifer MacDonald, Histotechnology Program, Mt. San Antonio College is licensed under CC BY-NC 4.0)

Fluid Connective Tissue

Blood and lymph are fluid connective tissues. Cells circulate in a liquid extracellular matrix. The formed elements circulating in blood are all derived from hematopoietic stem cells located in bone marrow (Figure 3.4.8). Erythrocytes, red blood cells, transport oxygen and some carbon dioxide. Leukocytes, white blood cells, are responsible for defending against potentially harmful microorganisms or molecules. Platelets are cell fragments involved in blood clotting. Some white blood cells have the ability to cross the endothelial layer that lines blood vessels and enter adjacent tissues. Nutrients, salts, and wastes are dissolved in the liquid matrix and transported through the body.

Lymph contains a liquid matrix and white blood cells. Lymphatic capillaries are extremely permeable, allowing larger molecules and excess fluid from interstitial spaces to enter the lymphatic vessels. Lymph drains into blood vessels, delivering molecules to the blood that could not otherwise directly enter the bloodstream. In this way, specialized lymphatic capillaries transport absorbed fats away from the intestine and deliver these molecules to the blood.

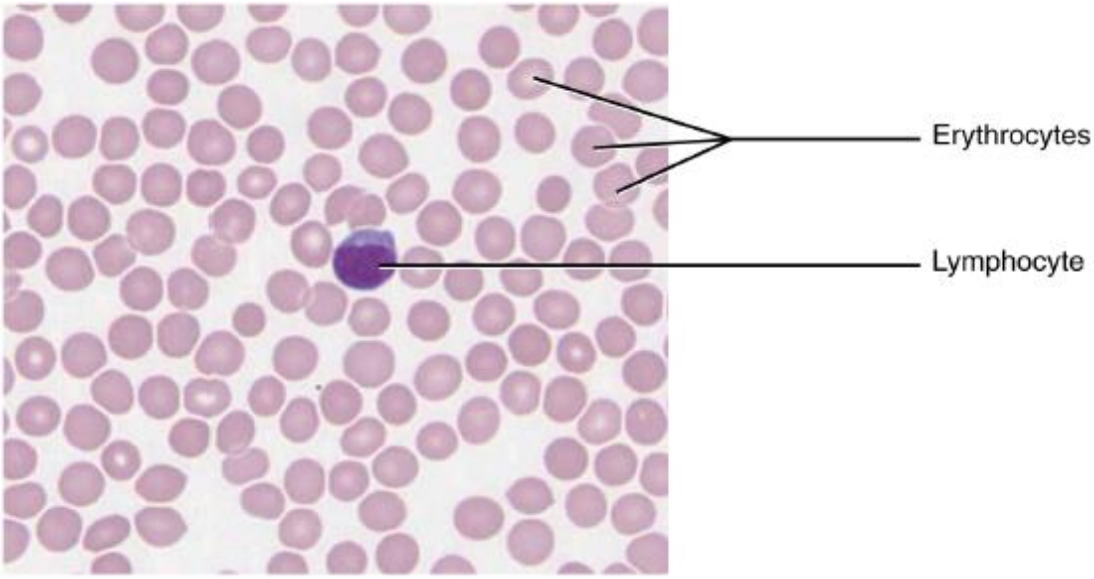

Figure 3.4.8: Blood: A Fluid Connective Tissue. Blood is a fluid connective tissue containing erythrocytes and various types of leukocytes that circulate in a liquid extracellular matrix. LM × 1600. (Image credit: "Blood A Fluid Connective Tissue" by OpenStax is licensed under CC BY 3.0/ Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Organization of Connective Tissues

Recall from the first section of this chapter that membranes form all the body linings and are made up of epithelial tissues with a layer of underlying connective tissue. This is not where connective tissue roles end. As you have seen from the tissue types discussed above, the main role of connective tissues is to form the structural framework of the body. Under membranes there can be several different layers of connective tissues, known as fascia, that function to connect internal structures to the rest of the body. These layers are organized into the superficial fascia, deep fascia, and subserous fascia (Figure 3.4.9).

The **superficial fascia** is found just deep to the cutaneous membrane (or skin) and is typically composed of a combination of areolar and adipose connective tissues. It serves to connect the cutaneous membrane to the underlying organs. Under, or deep to, the superficial fascia is the **deep fascia.** Composed mainly of dense connective tissues, it serves as a tough, internal framework that surrounds muscles, bones, and nerves. Lastly, found in between the deep fascia and the serous membranes, is the **subserous fascia.** This layer of areolar connective tissue serves as an anchor for the serous membranes to surrounding superficial structures.

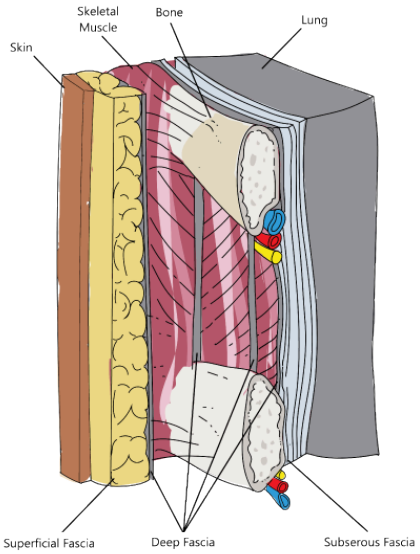

Figure 3.4.9: Fascia Organization. There are many layers of connective tissue that form the framework of the human body. These layers, or fascia, are the superficial fascia, deep fascia, and subserous fascia. (Image credit: “Fascia Organization" by Whitney Menefee is a derivative from the original work of Daniel Donnelly and is licensed under CC BY 4.0)

Interactive Link

Connective Tissues

QR Code representing a URL

Visit this interactive microscope slide link to test your connective tissue knowledge with this 10-question quiz. Can you name the 10 tissue types shown in the histology slides?

Answer available at the end of this section.

Concept Review

Connective tissue is a heterogeneous tissue class with assorted cell shapes and tissue architecture. Structurally, all connective tissues contain cells that are embedded in an extracellular matrix stabilized by proteins. The chemical nature and physical layout of the extracellular matrix and proteins vary enormously among tissues, reflecting the variety of functions that connective tissue fulfills in the body. Connective tissues separate and cushion organs, protecting them from shifting or traumatic injury. Connective tissues provide support and assist movement, store and transport energy molecules, protect against infections, and contribute to temperature homeostasis.

Many different cells contribute to the formation of connective tissues. They originate in the mesodermal germ layer and differentiate from mesenchyme and hematopoietic tissue in the bone marrow. Fibroblasts are the most abundant and secrete many protein fibers, adipocytes specialize in fat storage, hematopoietic cells from the bone marrow give rise to all the blood cells, chondrocytes form cartilage, and osteocytes form bone. The extracellular matrix contains fluid, proteins, polysaccharide derivatives, and, in the case of bone, mineral crystals. Protein fibers fall into three major groups: collagen fibers that are thick, strong, flexible, and resist stretch; reticular fibers that are thin and form a supportive mesh; and elastin fibers that are thin and elastic.

The major types of connective tissue are connective tissue proper, supportive tissue, and fluid tissue. Loose connective tissue proper includes adipose tissue, areolar tissue, and reticular tissue. These serve to hold organs and other tissues in place and, in the case of adipose tissue, isolate and store energy reserves. The matrix is the most abundant feature for loose tissue although adipose tissue does not have much extracellular matrix. Dense connective tissue proper is richer in fibers and may be regular, with fibers oriented in parallel as in ligaments and tendons, or irregular, with fibers oriented in several directions. Organ capsules (collagenous type) and walls of arteries (elastic type) contain dense irregular connective tissue. Cartilage and bone are supportive

tissue. Cartilage contains chondrocytes and is somewhat flexible. Hyaline cartilage is smooth and clear, covers the articulating surfaces of bones, and is found in the growing portion of bones. Fibrocartilage is tough because of extra collagen fibers and forms, among other things, the intervertebral discs. Elastic cartilage can stretch and recoil to its original shape because of its high content of elastic fibers. The matrix contains very few blood vessels. Bones are made of a rigid, mineralized matrix containing calcium salts, crystals, and osteocytes lodged in lacunae. Bone tissue is highly vascularized. Cancellous bone is spongy and less solid than compact bone. Fluid tissue, for example blood and lymph, is characterized by a liquid matrix and no supporting fibers.

Review Questions

Q. Connective tissue is made of which three essential components?

A. cells, ground substance, and carbohydrate fibers

B. cells, ground substance, and protein fibers

C. collagen, ground substance, and protein fibers

D. matrix, ground substance, and fluid

Answer

Answer: B

Q. Under the microscope, a tissue specimen shows cells located in spaces scattered in a transparent background. This is probably _____.

A. loose connective tissue

B. a tendon

C. bone

D. hyaline cartilage

Answer

Answer: D

Q. Which connective tissue specializes in storage of fat?

A. tendon

B. adipose tissue

C. reticular tissue

D. dense connective tissue

Answer

Answer: B

Q. Ligaments connect bones together and withstand a lot of stress. What type of connective tissue should you expect ligaments to contain?

A. areolar tissue

B. adipose tissue

C. dense regular connective tissue

D. dense irregular connective tissue

Answer

Answer: C

Q. In adults, new connective tissue cells originate from the _____.

A. mesoderm

B. mesenchyme

C. ectoderm

D. endoderm

Answer

Answer: B

Q. In bone, the main cells are _____.

A. fibroblasts

B. chondrocytes

C. lymphocytes

D. osteocytes

Answer

Answer: D

Critical Thinking Questions

Q. One of the main functions of connective tissue is to integrate organs and organ systems in the body. Discuss how blood fulfills this role.

Answer

A. Blood is a fluid connective tissue, a variety of specialized cells that circulate in a watery fluid containing salts, nutrients, and dissolved proteins in a liquid extracellular matrix. Blood contains formed elements derived from bone marrow. Erythrocytes, or red blood cells, transport the gases oxygen and carbon dioxide. Leukocytes, or white blood cells, are responsible for the defense of the organism against potentially harmful microorganisms or molecules. Platelets are cell fragments involved in blood clotting. Some cells have the ability to cross the endothelial layer that lines vessels and enter adjacent tissues. Nutrients, salts, and waste are dissolved in the liquid matrix and transported through the body.

Q. Why does an injury to cartilage, especially hyaline cartilage, heal much more slowly than a bone fracture?

Answer

A. A layer of dense irregular connective tissue covers cartilage. No blood vessels supply cartilage tissue. Injuries to cartilage heal very slowly because cells and nutrients needed for repair diffuse slowly to the injury site.

Glossary

adipocytes
: lipid storage cells

adipose tissue
: specialized areolar tissue rich in stored fat

areolar tissue
: (also, loose connective tissue) a type of connective tissue proper that shows little specialization with cells dispersed in the matrix

chondrocytes
: cells of the cartilage

collagen fiber
: flexible fibrous proteins that give connective tissue tensile strength

connective tissue proper
: connective tissue containing a viscous matrix, fibers, and cells.

deep fascia
: layer of dense connective tissue surrounding muscles, bones, and nerves

dense connective tissue
: connective tissue proper that contains many fibers that provide both elasticity and protection

elastic cartilage
: type of cartilage, with elastin as the major protein, characterized by rigid support as well as elasticity

elastic fiber
: fibrous protein within connective tissue that contains a high percentage of the protein elastin that allows the fibers to stretch and return to original size

fibroblast
: most abundant cell type in connective tissue, secretes protein fibers and matrix into the extracellular space

fibrocartilage
: tough form of cartilage, made of thick bundles of collagen fibers embedded in chondroitin sulfate ground substance

fibrocyte
: less active form of fibroblast

fluid connective tissue
: specialized cells that circulate in a watery fluid containing salts, nutrients, and dissolved proteins

ground substance
: fluid or semi-fluid portion of the matrix

hyaline cartilage
: most common type of cartilage, smooth and made of short collagen fibers embedded in a chondroitin sulfate ground substance

lacunae
: (singular = lacuna) small spaces in bone or cartilage tissue that cells occupy

loose connective tissue
: (also, areolar tissue) type of connective tissue proper that shows little specialization with cells dispersed in the matrix

matrix
extracellular material which is produced by the cells embedded in it, containing ground substance and fibers

mesenchymal cell
adult stem cell from which most connective tissue cells are derived

mesenchyme
embryonic tissue from which connective tissue cells derive

mucous connective tissue
specialized loose connective tissue present in the umbilical cord

parenchyma
functional cells of a gland or organ, in contrast with the supportive or connective tissue of a gland or organ

reticular fiber
fine fibrous protein, made of collagen subunits, which cross-link to form supporting “nets” within connective tissue

reticular tissue
type of loose connective tissue that provides a supportive framework to soft organs, such as lymphatic tissue, spleen, and the liver

subserous fascia
layer of connective tissues between the deep fascia and serous membranes

superficial fascia
layer of connective tissues found deep to the cutaneous membrane

supportive connective tissue
type of connective tissue that provides strength to the body and protects soft tissue

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Answers

Interactive Link
Answer: Click at the bottom of the quiz for the answers.

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3.5: Muscle Tissue

By the end of the section, you will be able to:

- Identify the three types of muscle tissue
- Compare and contrast the functions of each muscle tissue type
- Explain how muscle tissue can enable motion

Muscle tissue is characterized by properties that allow movement. Muscle cells are excitable; they respond to a stimulus. They are contractile, meaning they can shorten and generate a pulling force. When attached between two movable objects, such as bones on either side of a joint, contractions of the muscles cause the bones to move. Some muscle movement is voluntary, which means it is under conscious control. For example, a person decides to open a book and read a chapter on anatomy. Other movements are involuntary, meaning they are not under conscious control, such as the contraction of your pupil in bright light. Muscle tissue is classified into three types according to structure and function: skeletal, cardiac, and smooth (Table 3.5.1 and Figure 3.5.2).

Table 3.5.1: Comparison of Structure and Properties of Muscle Tissue Types

Tissue	Histology	Function	Location
Skeletal	Long cylindrical fiber, striated, many peripherally located nuclei	Voluntary movement, produces heat, protects organs	Attached to bones and around entrance points to body (e.g., mouth, anus)
Cardiac	Short, branched, striated, single central nucleus	Contracts to pump blood	Heart
Smooth	Short, spindle-shaped, no evident striation, single nucleus in each fiber	Involuntary movement, moves food, involuntary control of respiration, moves secretions, regulates flow of blood in arteries by contraction	Walls of major organs and passageways

Skeletal muscle is attached to bones and its contraction makes possible locomotion, facial expressions, posture, and other voluntary movements of the body. Forty percent of your body mass is made up of skeletal muscle. Skeletal muscles generate heat as a byproduct of their contraction and thus participate in thermal homeostasis. Shivering is an involuntary contraction of skeletal muscles in response to perceived lower than normal body temperature. The muscle cell, or **myocyte**, develops from myoblasts derived from the mesoderm. Myocytes and their numbers remain relatively constant throughout life. Skeletal muscle tissue is arranged in bundles surrounded by connective tissue. Under the light microscope, muscle cells appear striated with many nuclei squeezed along the membranes. The **striation** is due to the regular alternation of the contractile proteins actin and myosin, along with the structural proteins that couple the contractile proteins to connective tissues. The cells are multinucleated as a result of the fusion of the many myoblasts that fuse to form each long muscle fiber. Skeletal muscle is discussed in much greater detail in a later chapter.

Cardiac muscle forms the contractile walls of the heart. The cells of cardiac muscle, known as cardiomyocytes, also appear striated under the microscope. Unlike skeletal muscle fibers, cardiomyocytes are single cells typically with a single centrally located nucleus. A principal characteristic of cardiomyocytes is that they contract on their own intrinsic rhythms without any external stimulation; they are described as **autorhythmic**. Cardiomyocytes attach to one another with specialized cell junctions called **intercalated discs** (Figure 3.5.1). Intercalated discs have both anchoring junctions and gap junctions. Attached cells form long, branching cardiac muscle fibers that are, essentially, a mechanical and electrochemical syncytium (interconnected mass of fibers) allowing the cells to synchronize their actions. The cardiac muscle pumps blood through the body and is under involuntary control. The attachment junctions hold adjacent cells together across the dynamic pressures changes of the cardiac cycle.

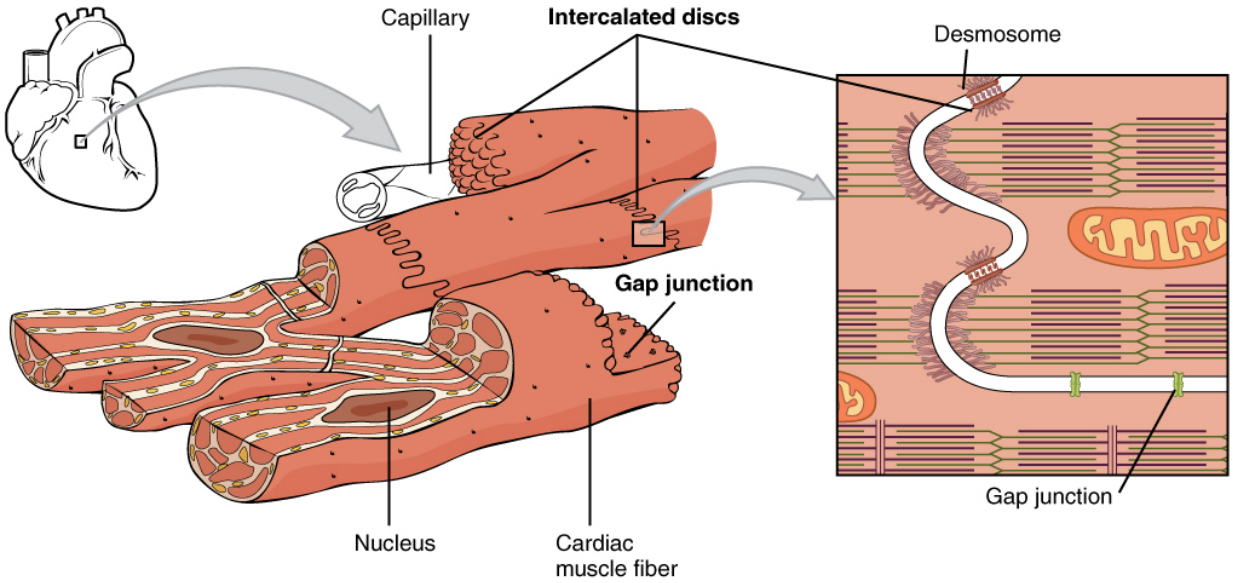

Figure 3.5.1: Cardiac Muscle. Intercalated discs are part of the cardiac muscle sarcolemma and they contain gap junctions and desmosomes. (Image credit: "Cardiac Muscle" by OpenStax is licensed under CC BY 3.0)

Smooth muscle tissue contraction is responsible for involuntary movements in the internal organs. It forms the contractile component of the digestive, urinary, and reproductive systems as well as the airways and arteries. Smooth muscle is also present in the eyes, where it functions to change the size of the iris and alter the shape of the lens; and in the skin where it causes hair to stand erect in response to cold temperature or fear. Each cell is spindle shaped with a single nucleus and no visible striations (Figure 3.5.2).

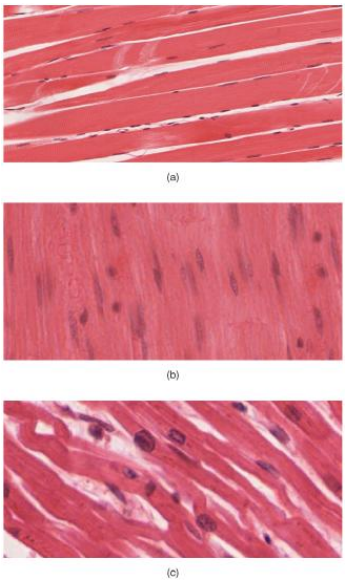

Figure 3.5.2: Muscle Tissue. (a) Skeletal muscle cells have prominent striation and nuclei on their periphery. (b) Smooth muscle cells have a single nucleus and no visible striations. (c) Cardiac muscle cells appear striated and have a single nucleus. From top, LM × 1600, LM × 1600, LM × 1600. (Image credit: "Skeletal Smooth Cardiac" by OpenStax is licensed under CC BY 3.0/ Micrographs provided by the Regents of University of Michigan Medical School © 2012)

Concept Review

The three types of muscle cells are skeletal, cardiac, and smooth. Their morphologies match their specific functions in the body. Skeletal muscle is voluntary and responds to conscious stimuli. The cells are striated and multinucleated appearing as long, unbranched cylinders. Cardiac muscle is involuntary and found only in the heart. Each cell is striated with a single nucleus and they attach to one another to form long fibers. Cells are attached to one another at intercalated discs. The cells are interconnected

physically and electrochemically to act as a syncytium. Cardiac muscle cells contract autonomously and involuntarily. Smooth muscle is involuntary. Each cell is a spindle-shaped fiber and contains a single nucleus. No striations are evident because the actin and myosin filaments do not align in the cytoplasm.

Review Questions

Q. Striations, cylindrical cells, and multiple nuclei are observed in _____.

A. skeletal muscle only

B. cardiac muscle only

C. smooth muscle only

D. skeletal and cardiac muscles

Answer

Answer: A

Q. The cells of muscles, myocytes, develop from _____.

A. myoblasts

B. endoderm

C. fibrocytes

D. chondrocytes

Answer

Answer: A

Q. Skeletal muscle is composed of very hard working cells. Which organelles do you expect to find in abundance in skeletal muscle cell?

A. nuclei

B. striations

C. golgi bodies

D. mitochondria

Answer

Answer: D

Critical Thinking Questions

Q. You are watching cells in a dish spontaneously contract. They are all contracting at different rates; some fast, some slow. After a while, several cells link up and they begin contracting in synchrony. Discuss what is going on and what type of cells you are looking at.

Answer

A. The cells in the dish are cardiomyocytes, cardiac muscle cells. They have an intrinsic ability to contract. When they link up, they form intercalating discs that allow the cells to communicate with each other and begin contracting

in synchrony.

Q. Why does skeletal muscle look striated?

Answer

A. Under the light microscope, cells appear striated due to the arrangement of the contractile proteins actin and myosin.

Glossary

cardiac muscle
heart muscle, under involuntary control, composed of striated cells that attach to form fibers, each cell contains a single nucleus, contracts autonomously

myocyte
muscle cells

skeletal muscle
usually attached to bone, under voluntary control, each cell is a fiber that is multinucleated and striated

smooth muscle
under involuntary control, moves internal organs, cells contain a single nucleus, are spindle-shaped, and do not appear striated; each cell is a fiber

striation
alignment of parallel actin and myosin filaments which form a banded pattern

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3.6: Nervous Tissue

By the end of the section, you will be able to:

- Identify the classes of cells that make up nervous tissue
- Discuss how nervous tissue mediates perception and response

Nervous tissue is characterized as being excitable and capable of sending and receiving electrochemical signals that provide the body with information. Two main classes of cells make up nervous tissue: the **neuron** and **neuroglia** (Figure 3.6.1). Neurons propagate information via electrochemical impulses, called action potentials, which are biochemically linked to the release of chemical signals. Neuroglia play an essential role in supporting neurons and modulating their information propagation.

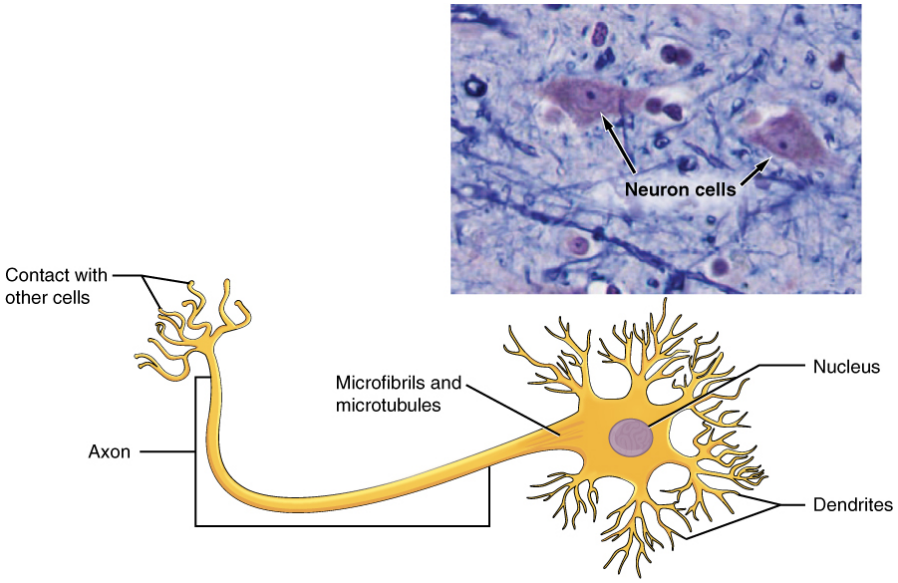

Figure 3.6.1: The Neuron. The cell body of a neuron, also called the soma, contains the nucleus and mitochondria. The dendrites transfer the nerve impulse to the soma. The axon carries the action potential away to another excitable cell. LM × 1600. (Image credit: "Neuron" by OpenStax is licensed under CC BY 3.0/ Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Neurons display distinctive morphology, well suited to their role as conducting cells, with three main parts. The cell body includes most of the cytoplasm, the organelles, and the nucleus. Dendrites branch off the cell body and appear as thin extensions. A long "tail," the axon, extends from the neuron body and can be wrapped in an insulating layer known as **myelin**, which is formed by accessory cells. The synapse is the gap between nerve cells, or between a nerve cell and its target, for example, a muscle or a gland, across which the impulse is transmitted by chemical compounds known as neurotransmitters. Neurons categorized as multipolar neurons have several dendrites and a single prominent axon. Bipolar neurons possess a single dendrite and axon with the cell body, while unipolar neurons have only a single process extending out from the cell body, which divides into a functional dendrite and into a functional axon. When a neuron is sufficiently stimulated, it generates an action potential that propagates down the axon towards the synapse. If enough neurotransmitters are released at the synapse to stimulate the next neuron or target, a response is generated.

The second class of neural cells comprises the neuroglia or glial cells, which have been characterized as having a simple support role. The word "glia" comes from the Greek word for glue. Recent research is shedding light on the more complex role of neuroglia in the function of the brain and nervous system. **Astrocyte cells**, named for their distinctive star shape, are abundant in the central nervous system. The astrocytes have many functions, including regulation of ion concentration in the intercellular space, uptake and/or breakdown of some neurotransmitters, and formation of the blood-brain barrier, the membrane that separates the circulatory system from the brain. Microglia protect the nervous system against infection; but are not nervous tissue because they are related to macrophages. **Oligodendrocyte cells** produce myelin in the central nervous system (brain and spinal cord) while the **Schwann cell** produces myelin in the peripheral nervous system (Figure 3.6.2).

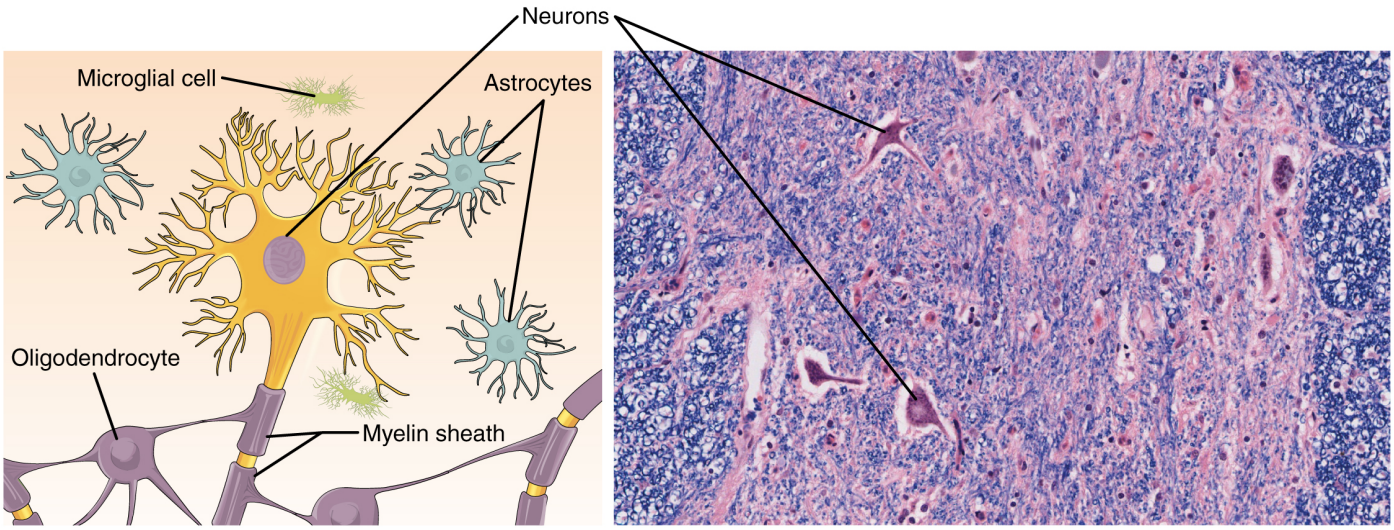

Figure 3.6.2: Nervous Tissue. Nervous tissue is made up of neurons and neuroglia. The cells of nervous tissue are specialized to transmit and receive impulses. LM × 872. (Image Credit: "Nervous Tissue" by OpenStax is licensed under CC BY 3.0/ Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Concept Review

The most prominent cell of the nervous tissue, the neuron, is characterized mainly by its ability to receive stimuli and respond by generating an electrical signal, known as an action potential, which can travel rapidly over great distances in the body. A typical neuron displays a distinctive morphology: a large cell body branches out into short extensions called dendrites, which receive chemical signals from other neurons, and a long tail called an axon, which relays signals away from the cell to other neurons, muscles, or glands. Many axons are wrapped by a myelin sheath, a lipid derivative that acts as an insulator and speeds up the transmission of the action potential. Other cells in the nervous tissue, the neuroglia, include the astrocytes, microglia, oligodendrocytes, and Schwann cells.

Review Questions

Q. The cells responsible for the transmission of the nerve impulse are _____.

A. neurons

B. oligodendrocytes

C. astrocytes

D. microglia

Answer

Answer: A

Q. The nerve impulse travels down a(n) _____, away from the cell body.

A. dendrite

B. axon

C. microglia

D. collagen fiber

Answer

Answer: B

Q. Which of the following central nervous system cells regulate ions, regulate the uptake and/or breakdown of some neurotransmitters, and contribute to the formation of the blood-brain barrier?

A. microglia

B. neuroglia

C. oligodendrocytes

D. astrocytes

Answer

Answer: D

Critical Thinking Questions

Q. Which morphological adaptations of neurons make them suitable for the transmission of nerve impulse?

Answer

A. Neurons are well suited for the transmission of nerve impulses because short extensions, dendrites, receive impulses from other neurons, while a long tail extension, an axon, carries electrical impulses away from the cell to other neurons.

Q. What are the functions of astrocytes?

Answer

A. Astrocytes regulate ions and uptake and/or breakdown of some neurotransmitters and contribute to the formation of the blood-brain-barrier.

References

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Glossary

astrocyte
star-shaped cell in the central nervous system that regulates ions and uptake and/or breakdown of some neurotransmitters and contributes to the formation of the blood-brain barrier

myelin
layer of lipid inside some neuroglial cells that wraps around the axons of some neurons

neuroglia
supportive neural cells

neuron
excitable neural cell that transfer nerve impulses

oligodendrocyte
: neuroglial cell that produces myelin in the brain

Schwann cell
: neuroglial cell that produces myelin in the peripheral nervous system

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3.7: Tissue Injury and Aging

By the end of the section, you will be able to:

- Identify the cardinal signs of inflammation
- List the body's response to tissue injury
- Explain the process of tissue repair
- Discuss the progressive impact of aging on tissue
- Describe cancerous mutations' effect on tissue

Tissues of all types are vulnerable to injury and, inevitably, aging. In the former case, understanding how tissues respond to damage can guide strategies to aid repair. In the latter case, understanding the impact of aging can help in the search for ways to diminish its effects.

Tissue Injury and Repair

Inflammation is the standard, initial response of the body to injury. Whether biological, chemical, physical, or radiation burns, all injuries lead to the same sequence of physiological events. Inflammation limits the extent of injury, partially or fully eliminates the cause of injury, and initiates repair and regeneration of damaged tissue. **Necrosis**, or accidental cell death, causes inflammation. **Apoptosis** is programmed cell death, a normal step-by-step process that destroys cells no longer needed by the body. By mechanisms still under investigation, apoptosis does not initiate the inflammatory response. Acute inflammation resolves over time by the healing of tissue. If inflammation persists, it becomes chronic and leads to diseased conditions. Arthritis and tuberculosis are examples of chronic inflammation. The suffix "-itis" denotes inflammation of a specific organ or type, for example, peritonitis is the inflammation of the peritoneum, and meningitis refers to the inflammation of the meninges, the tough membranes that surround the central nervous system.

The four cardinal signs of inflammation—redness, swelling, pain, and local heat—were first recorded in antiquity. Cornelius Celsus is credited with documenting these signs during the days of the Roman Empire, as early as the first century AD. A fifth sign, loss of function, may also accompany inflammation.

Upon tissue injury, damaged cells release inflammatory chemical signals that evoke local **vasodilation**, the widening of the blood vessels. Increased blood flow results in apparent redness and heat. In response to injury, mast cells present in tissue degranulate, releasing the potent vasodilator **histamine**. Increased blood flow and inflammatory mediators recruit white blood cells to the site of inflammation. The endothelium lining the local blood vessel becomes "leaky" under the influence of histamine and other inflammatory mediators allowing neutrophils, macrophages, and fluid to move from the blood into the interstitial tissue spaces. The excess liquid in tissue causes swelling, more properly called edema. The swollen tissues squeezing pain receptors cause the sensation of pain. Prostaglandins released from injured cells also activate pain neurons. Non-steroidal anti-inflammatory drugs (NSAIDs) reduce pain because they inhibit the synthesis of prostaglandins. High levels of NSAIDs reduce inflammation. Antihistamines decrease allergies by blocking histamine receptors and as a result the histamine response.

After containment of an injury, the tissue repair phase starts with removal of toxins and waste products. **Clotting** (coagulation) reduces blood loss from damaged blood vessels and forms a network of fibrin proteins that trap blood cells and bind the edges of the wound together. A scab forms when the clot dries, reducing the risk of infection. Sometimes a mixture of dead leukocytes and fluid called pus accumulates in the wound. As healing progresses, fibroblasts from the surrounding connective tissues replace the collagen and extracellular material lost by the injury. Angiogenesis, the growth of new blood vessels, results in vascularization of the new tissue known as granulation tissue. The clot retracts pulling the edges of the wound together, and it slowly dissolves as the tissue is repaired. When a large amount of granulation tissue forms and capillaries disappear, a pale scar is often visible in the healed area. A **primary union** describes the healing of a wound where the edges are close together. When there is a gaping wound, it takes longer to refill the area with cells and collagen. The process called **secondary union** occurs as the edges of the wound are pulled together by what is called **wound contraction**. When a wound is more than one quarter of an inch deep, sutures (stitches) are recommended to promote a primary union and avoid the formation of a disfiguring scar. Regeneration is the addition of new cells of the same type as the ones that were injured (Figure 3.7.1).

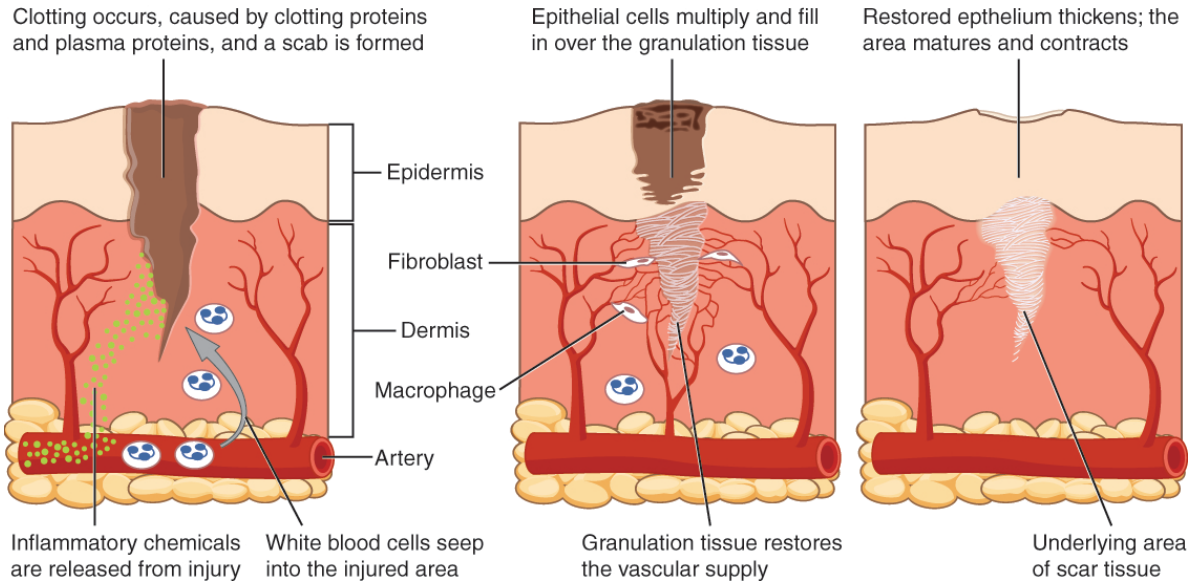

Figure 3.7.1: Tissue Healing. During wound repair, collagen fibers are laid down randomly by fibroblasts that move into repair the area. (Image credit: "Tissue Repair" by OpenStax is licensed under CC BY 3.0)

Interactive Link

Wound healing on a hand

QR Code representing a URL

Watch this time lapse video of a wound on a hand healing. Over what period of time do you think these images were taken?

Answer available at the end of this section.

Tissue and Aging

According to poet Ralph Waldo Emerson, “The surest poison is time.” In fact, biology confirms that many functions of the body decline with age. All the cells, tissues, and organs are affected by senescence (deterioration with age), with noticeable variability between individuals owing to different genetic makeup and lifestyles. The outward signs of aging are easily recognizable. The skin and other tissues become thinner and drier, reducing their elasticity, contributing to wrinkles and high blood pressure. Hair turns gray because follicles produce less melanin, the brown pigment of hair and the iris of the eye. The face looks flabby because elastic and collagen fibers decrease in connective tissue and muscle tone is lost. Glasses and hearing aids may become parts of life as the senses slowly deteriorate, all due to reduced elasticity. Overall height decreases as the bones lose calcium and other minerals. With age, fluid decreases in the intervertebral discs of fibrocartilage between the vertebrae in the spine. Joints lose cartilage and stiffen. Many tissues, including those in muscles, lose mass through a process called **atrophy**. Lumps and rigidity become more widespread. As a consequence, the passageways, blood vessels, and airways become more rigid. The brain and spinal cord lose mass. Nerves do not transmit impulses with the same speed and frequency as in the past. Some loss of thought clarity and memory can accompany aging. More severe problems are not necessarily associated with the aging process and may be symptoms of underlying illness.

As exterior signs of aging increase, so do the interior signs, which are not as noticeable. The incidence of heart diseases, respiratory syndromes, and type 2 diabetes increases with age, though these are not necessarily age-dependent effects. Wound healing is slower in the elderly, accompanied by a higher frequency of infection as the capacity of the immune system to fend off pathogen declines.

Aging is also apparent at the cellular level because all cells experience changes with aging. Telomeres, regions of the chromosomes necessary for cell division, shorten each time cells divide. As they do, cells are less able to divide and regenerate. Because of alterations in cell membranes, transport of oxygen and nutrients into the cell and removal of carbon dioxide and waste products from the cell are not as efficient in the elderly. Cells may begin to function abnormally, which may lead to diseases

associated with aging, including arthritis, memory issues, and some cancers.

The progressive impact of aging on the body varies considerably among individuals, but studies indicate, however, that exercise and healthy lifestyle choices can slow down the deterioration of the body that comes with old age.

HOMEOSTATIC IMBALANCES

Tissues and Cancer

Cancer is a generic term for many diseases in which cells escape regulatory signals. Uncontrolled growth, invasion into adjacent tissues, and colonization of other organs, if not treated early enough, are its hallmarks. Health suffers when tumors “rob” blood supply from the “normal” organs.

A mutation is defined as a permanent change in the DNA of a cell. Epigenetic modifications, changes that do not affect the code of the DNA but alter how the DNA is decoded, are also known to generate abnormal cells. Alterations in the genetic material may be caused by environmental agents, infectious agents, or errors in the replication of DNA that accumulate with age. Many mutations do not cause any noticeable change in the functions of a cell. However, if the modification affects key proteins that have an impact on the cell’s ability to proliferate in an orderly fashion, the cell starts to divide abnormally. As changes in cells accumulate, they lose their ability to form regular tissues. A tumor, a mass of cells displaying abnormal architecture, forms in the tissue. Many tumors are benign, meaning they do not metastasize nor cause disease. A tumor becomes malignant, or cancerous, when it breaches the confines of its tissue, promotes angiogenesis, attracts the growth of capillaries, and metastasizes to other organs (Figure 3.7.2). The specific names of cancers reflect the tissue of origin. Cancers derived from epithelial cells are referred to as carcinomas. Cancer in myeloid tissue or blood cells form myelomas. Leukemias are cancers of white blood cells, whereas sarcomas derive from connective tissue. Cells in tumors differ both in structure and function. Some cells, called cancer stem cells, appear to be a subtype of cell responsible for uncontrolled growth. Recent research shows that contrary to what was previously assumed, tumors are not disorganized masses of cells, but have their own structures.

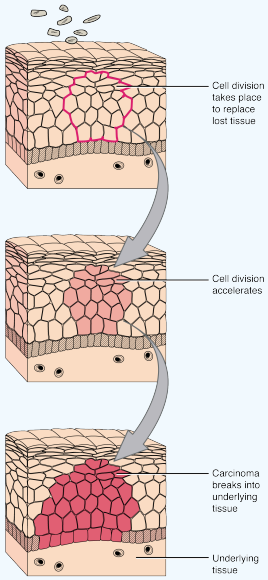

Figure 3.7.2: Development of Cancer. Note the change in cell size, nucleus size, and organization in the tissue. (Image credit: "Development of Cancer" by OpenStax is licensed under CC BY 3.0)

Inteactive Link

Tumors

QR Code representing a URL

Watch this video to learn more about tumors. What is a tumor?

Answer available at the end of this section.

Cancer treatments vary depending on the disease's type and stage. Traditional approaches, including surgery, radiation, chemotherapy, and hormonal therapy, aim to remove or kill rapidly dividing cancer cells, but these strategies have their limitations. Depending on a tumor's location, for example, cancer surgeons may be unable to remove it. Radiation and chemotherapy are difficult, and it is often impossible to target only the cancer cells. The treatments inevitably destroy healthy tissue as well. To address this, researchers are working on pharmaceuticals that can target specific proteins implicated in cancer-associated molecular pathways.

Concept Review

Inflammation is the classic response of the body to injury and follows a common sequence of events. The area is red, feels warm to the touch, swells, and is painful. Injured cells, mast cells, and resident macrophages release chemical signals that cause vasodilation and fluid leakage in the surrounding tissue. The repair phase includes blood clotting, followed by regeneration of tissue as fibroblasts deposit collagen. Some tissues regenerate more readily than others. Epithelial and connective tissues replace damaged or dead cells from a supply of adult stem cells. Muscle and nervous tissues undergo either slow regeneration or do not repair at all.

Age affects all the tissues and organs of the body. Damaged cells do not regenerate as rapidly as in younger people. Perception of sensation and effectiveness of response are lost in the nervous system. Muscles atrophy, and bones lose mass and become brittle. Collagen decreases in some connective tissue, and joints stiffen.

Review Questions

Q. Which of the following processes is not a cardinal sign of inflammation?

A. redness

B. heat

C. fever

D. swelling

Answer

Answer: C

Q. When a mast cell reacts to an irritation, which of the following chemicals does it release?

A. collagen

B. histamine

C. hyaluronic acid

D. meylin

Answer

Answer: B

Q. Atrophy refers to _____.

A. loss of elasticity

B. loss of mass

C. loss of rigidity

D. loss of permeability

Answer

Answer: B

Q. Individuals can slow the rate of aging by modifying all of these lifestyle aspects except for _____.

A. diet

B. exercise

C. genetic factors

D. stress

Answer

Answer: C

Critical Thinking Questions

Q. Why is it important to watch for increased redness, swelling and pain after a cut or abrasion has been cleaned and bandaged?

Answer

A. These symptoms would indicate that infection is present.

Q. Aspirin is a non-steroidal anti-inflammatory drug (NSAID) that inhibits the formation of blood clots and is taken regularly by individuals with a heart condition. Steroids such as cortisol are used to control some autoimmune diseases and severe arthritis by down-regulating the inflammatory response. After reading the role of inflammation in the body's response to infection, can you predict an undesirable consequence of taking anti-inflammatory drugs on a regular basis?

Answer

A. Since NSAIDs or other anti-inflammatory drugs inhibit the formation of blood clots, regular and prolonged use of these drugs may promote internal bleeding, such as bleeding in the stomach. Excessive levels of cortisol would suppress inflammation, which could slow the wound healing process.

Q. As an individual ages, a constellation of symptoms begins the decline to the point where an individual's functioning is compromised. Identify and discuss two factors that have a role in factors leading to the compromised situation.

Answer

A. The genetic makeup and the lifestyle of each individual are factors which determine the degree of decline in cells, tissues, and organs as an individual ages.

Q. Discuss changes that occur in cells as a person ages.

Answer

A. All cells experience changes with aging. They become larger, and many cannot divide and regenerate. Because of alterations in cell membranes, transport of oxygen and nutrients into the cell and removal of carbon dioxide and waste products are not as efficient in the elderly. Cells lose their ability to function, or they begin to function abnormally, leading to disease and cancer.

References

Emerson, RW. Old age. Atlantic. 1862 [cited 2012 Dec 4]; 9(51):134–140.

Glossary

apoptosis
: programmed cell death

atrophy
: loss of mass and function

clotting
: also called coagulation; complex process by which blood components form a plug to stop bleeding

histamine
: chemical compound released by mast cells in response to injury that causes vasodilation and endothelium permeability

inflammation
: response of tissue to injury

necrosis
: accidental death of cells and tissues

primary union
: edges of a wound are close enough together to promote healing without the use of stitches to hold them close

secondary union
: wound healing facilitated by wound contraction

vasodilation
: widening of blood vessels

wound contraction
: process whereby the borders of a wound are physically drawn together

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Answers

Interactive Link

Answer: Approximately one month.

Inteactive Link

Answer: A mass of cancer cells that continue to grow and divide.

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4: INTEGUMENTARY SYSTEM

4.1: Introduction to the Integumentary System

4.2: Layers of the Skin

4.3: Accessory Structures of the Skin

4.4: Functions of the Integumentary System

4.5: Diseases, Disorders, and Injuries of the Integumentary System

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4.1: Introduction to the Integumentary System

Chapter Learning Objectives

After studying the chapter, you will be able to:

- Describe the integumentary system and the role it plays in homeostasis
- Describe the layers of the skin and the functions of each layer
- Describe the accessory structures of the skin and the functions of each
- Describe the changes that occur in the integumentary system during the aging process
- Discuss several common diseases, disorders, and injuries that affect the integumentary system
- Explain treatments for some common diseases, disorders, and injuries of the integumentary system.

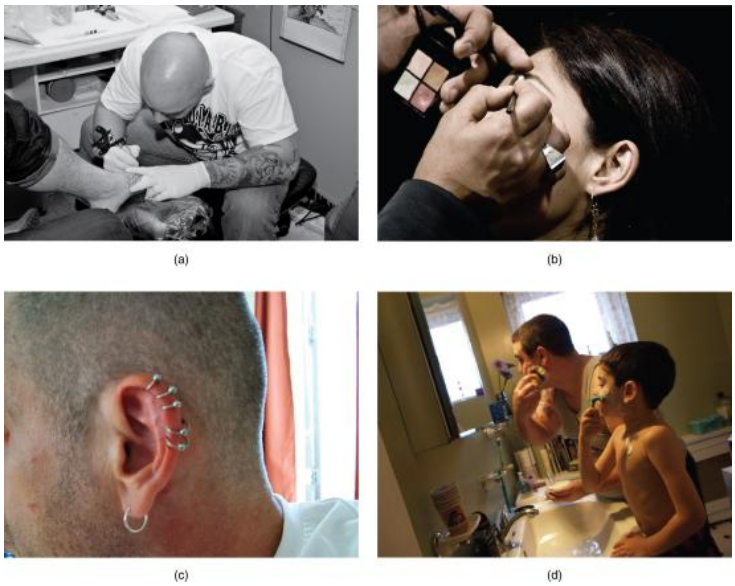

Figure 4.1.1: Your skin is a vital part of your life and appearance (a–d). Some people choose to embellish it with tattoos (a), makeup (b), and even piercings (c). Others may choose to alter it by removing hair, such as in the act of shaving (d). (Image credit: "Splash Image" by OpenStax is licensed under CC BY 3.0)

What do you think when you look at your skin in the mirror? Do you think about covering it with makeup, adding a tattoo, or maybe a body piercing? Or do you think about the fact that the skin belongs to one of the body's most essential and dynamic systems: the integumentary system? The integumentary system refers to the skin and its accessory structures, and it is responsible for much more than simply lending to your outward appearance. In the adult human body, the skin makes up about 16 percent of body weight and covers an area of 1.5 to 2 m^2. In fact, the skin and accessory structures are the largest organ system in the human body. As such, the skin protects your inner organs and it is in need of daily care and protection to maintain its health. This chapter will introduce the structure and functions of the integumentary system, as well as some of the diseases, disorders, and injuries that can affect this system.

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4.2: Layers of the Skin

By the end of the section, you will be able to:

- Identify the components of the integumentary system
- Describe the layers of the skin and the functions of each layer
- Identify and describe the hypodermis and deep fascia
- Describe the role of keratinocytes and their life cycle
- Describe the role of melanocytes in skin pigmentation

Although you may not typically think of the skin as an organ, it is in fact made of tissues that work together as a single structure to perform unique and critical functions. The skin and its accessory structures make up the **integumentary system**, which provides the body with overall protection. The skin is made of multiple layers of cells and tissues, which are held to underlying structures by connective tissue (Figure 4.2.1). The superficial layer, known as the **epidermis**, is composed primarily of tightly pack epithelial cells. The deeper layer of skin, the **dermis**, is well vascularized (has numerous blood vessels) and is where several accessory structures, such as hair follicles, sweat glands, and oil glands, can be found. It also has numerous sensory, and autonomic and sympathetic nerve fibers ensuring communication to and from the brain. Below the dermis lies the superficial fascia, or **hypodermis**, which is not technically part of the skin, but serves to connect the skin to the underlying fascia. This layer is mainly composed of loose, areolar and adipose connective tissues.

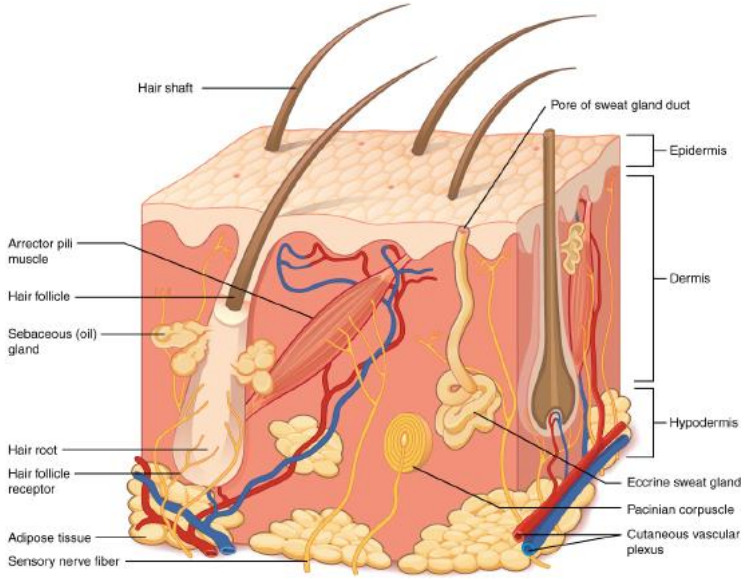

Figure 4.2.1: Layers of Skin. The skin is composed of two main layers: the epidermis, made of closely packed epithelial cells, and the dermis, that houses blood vessels, hair follicles, sweat glands, and other structures. Beneath the dermis lies the hypodermis. (Image credit: "Structure of the Skin" by OpenStax is licensed under CC BY 3.0)

The Epidermis

The **epidermis** is composed of keratinized, stratified squamous epithelium. It is made of four or five layers of epithelial cells, depending on its location in the body. It does not have any blood vessels within it (i.e., it is avascular). Skin that has four layers of cells is referred to as “thin skin.” From deep to superficial, these layers are the stratum basale, stratum spinosum, stratum granulosum, and stratum corneum. Most of the skin can be classified as thin skin. “Thick skin” is found only on the palms of the hands and the soles of the feet. It has a fifth layer, called the stratum lucidum, located between the stratum corneum and the stratum granulosum (Figure 4.2.2).

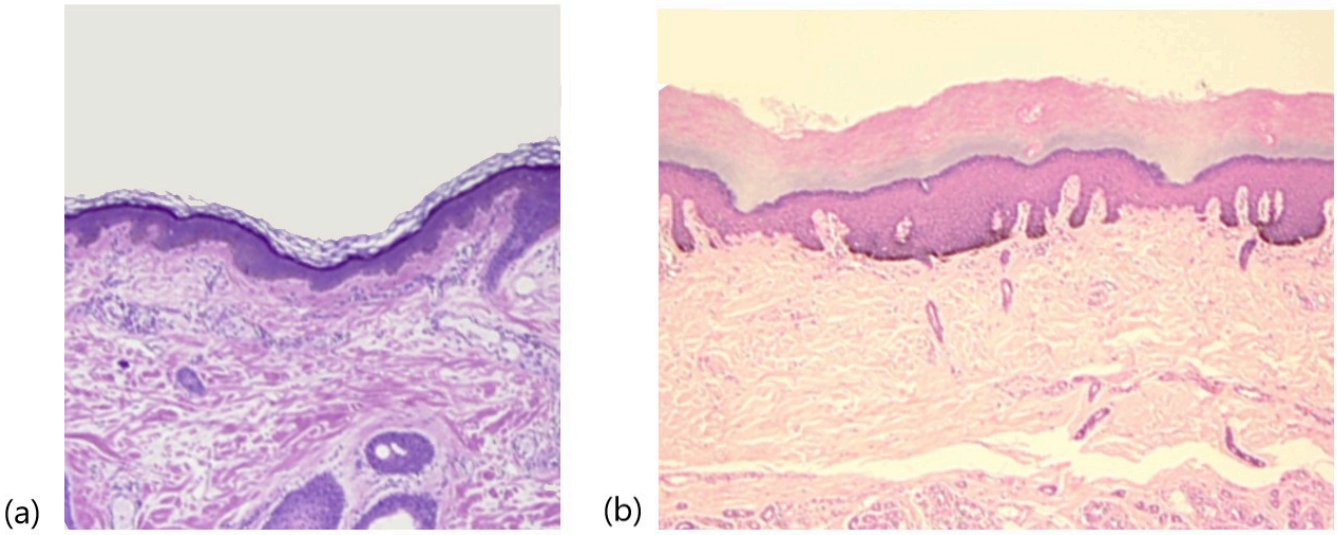

Figure 4.2.2: Thin Skin versus Thick Skin. These slides show cross-sections of the epidermis and dermis of (a) thin and (b) thick skin. Note the significant difference in the thickness of the epithelial layer of the thick skin. LM × 50. (Image credit: "Thin Skin versus Thick Skin" by Jennifer MacDonald, Histotechnology Program, Mt. San Antonio College is licensed under CC BY-NC 4.0)

The majority of cells in the epidermis are called keratinocytes. A **keratinocyte** is a cell that manufactures and stores the protein keratin. **Keratin** is an intracellular fibrous protein that gives hair, nails, and skin their hardness and water-resistant properties. The keratinocytes in the stratum corneum are dead and regularly slough away, being replaced by cells from the deeper layers.

Stratum Basale

The **stratum basale** (also called the stratum germinativum) is the deepest epidermal layer and attaches the epidermis to the basal lamina, below which lie the layers of the dermis. The cells in the stratum basale bond to the dermis via intertwining collagen fibers, referred to as the basement membrane. A finger-like projection, or fold, known as the **dermal papilla** (plural = dermal papillae) is found in the superficial portion of the dermis. Dermal papillae increase the strength of the connection between the epidermis and dermis; the greater the surface area conveyed by folding, the stronger the connections made (Figure 4.2.3).

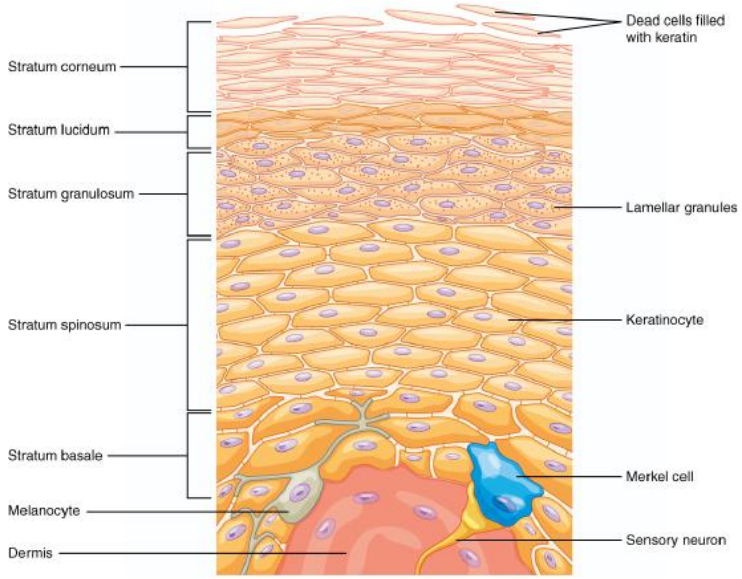

Figure 4.2.3: Layers of the Epidermis. The epidermis of thick skin has five layers: stratum basale, stratum spinosum, stratum granulosum, stratum lucidum, and stratum corneum. (Image credit: "Layers of Epidermis" by OpenStax is licensed under CC BY 3.0)

The stratum basale is a single layer of cells primarily made of basal cells. A **basal cell** is a cuboidal-shaped stem cell that is

a precursor of the keratinocytes of the epidermis. All of the keratinocytes are produced from this single layer of cells, which are constantly going through mitosis to produce new cells. As new cells are formed, the existing cells are pushed superficially away from the stratum basale. Two other cell types are found dispersed among the basal cells in the stratum basale. The first is a **Merkel cell,** also known as a tactile cell, which functions as a receptor and is responsible for stimulating sensory nerves that the brain perceives as touch. These cells are especially abundant on the surfaces of the hands and feet. The second is a **melanocyte**, a cell that produces the pigment melanin. **Melanin** gives hair and skin its color, and also helps protect the living cells of the epidermis from ultraviolet (UV) radiation damage.

In a growing fetus, fingerprints form where the cells of the stratum basale meet the papillae of the underlying dermal layer (papillary layer), resulting in the formation of the ridges on your fingers that you recognize as fingerprints. Fingerprints are unique to each individual and are used for forensic analyses because the patterns do not change with the growth and aging processes.

Stratum Spinosum

As the name suggests, the **stratum spinosum** is spiny in appearance due to the protruding cell processes that join the cells via an anchoring junction common in epithelial tissues called a **desmosome**. The desmosomes interlock with each other and strengthen the bond between the cells. It is interesting to note that the “spiny” nature of this layer is an artifact of the staining process. Unstained epidermis samples do not exhibit this characteristic appearance. The stratum spinosum is composed of eight to ten layers of keratinocytes, formed as a result of cell division in the stratum basale (Figure 4.2.4). The keratinocytes in the stratum spinosum begin the synthesis of keratin and release a water-repelling glycolipid that helps prevent water loss from the body, making the skin relatively waterproof. As new keratinocytes are produced atop the stratum basale, the keratinocytes of the stratum spinosum are pushed into the stratum granulosum. Wandering among the keratinocytes of this layer is a type of dendritic cell called the **Langerhans cell**, also known as a dendritic cell, which differentiates from and functions similarly to a macrophage by engulfing bacteria, foreign particles, and damaged cells that occur in this layer.

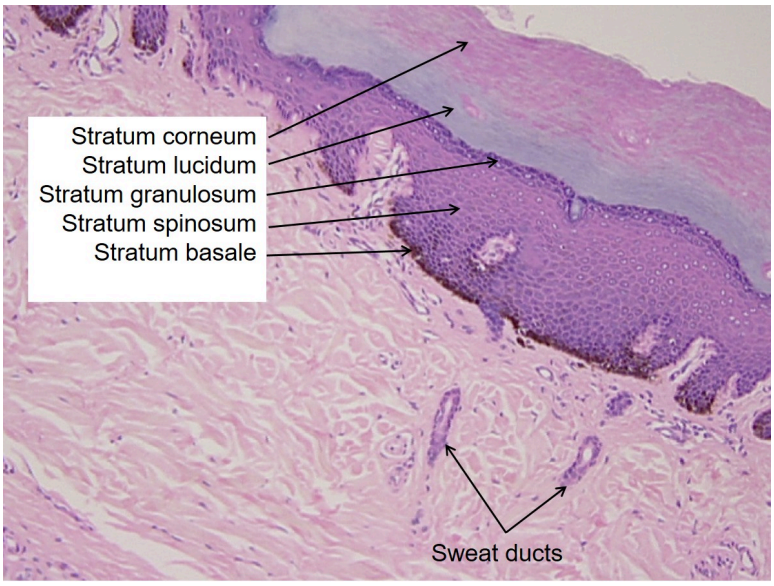

Figure 4.2.4: Cells of the Epidermis. The keratinocytes in the different layers of the epidermis originate from basal cells located in the stratum basale, yet the cells of each layer change as they are pushed up through the layers of the epidermis. LM × 100. (Image credit: “Cells of the Epidermis" by Jennifer MacDonald, Histotechnology Program, Mt. San Antonio College is licensed under CC BY-NC 4.0)

Stratum Granulosum

The **stratum granulosum** has a grainy appearance due to further changes to the keratinocytes as they are pushed from the stratum spinosum. The cells here (three to five layers thick) become flatter, their cell membranes thicken with a coating of lipids secreted by accumulated **lamellar granules**, and they generate large amounts of the fibrous proteins keratin, incorporating intermediate filaments of the cytoskeleton with filaggrin derived from proteins secreted by accumulated **keratohyalin granules** (see Figure 4.2.3). These proteins of the late stages of keratin synthesis account for the bulk of the keratinocyte mass in the stratum granulosum. The accumulated granules give the layer its grainy appearance. The nuclei and other cell organelles disintegrate as the cells die, leaving behind the keratin and coated cell membranes that will form the stratum lucidum, the stratum

corneum, and the accessory structures of hair and nails.

Stratum Lucidum

The **stratum lucidum** is a smooth, seemingly translucent layer of the epidermis located just above the stratum granulosum and below the stratum corneum. This thin layer of cells is found only in the thick skin of the palms, soles, and digits. The keratinocytes that compose the stratum lucidum are dead and flattened (see Figure 4.2.3). These cells are densely packed with **eleiden**, a clear protein rich in lipids, derived from keratohyalin, which gives these cells their transparent (i.e., lucid) appearance and provides a barrier to water.

Stratum Corneum

The **stratum corneum** is the most superficial layer of the epidermis and is the layer exposed to the outside environment (see Figure 4.2.3). The increased keratinization (also called cornification) of the cells in this layer gives it its name. There are usually 15 to 30 layers of cells in the stratum corneum. This dry, dead layer helps prevent the penetration of microbes and the dehydration of underlying tissues, and provides a mechanical protection against abrasion for the more delicate, underlying layers. Cells in this layer are shed periodically and are replaced by cells pushed up from the stratum granulosum (or stratum lucidum in the case of the palms and soles of feet). The entire layer is replaced during a period of about 4 weeks. Cosmetic procedures, such as microdermabrasion, help remove some of the dry, upper layer and aim to keep the skin looking “fresh” and healthy.

Dermis

The **dermis** might be considered the “core” of the integumentary system (derma- = “skin”), as distinct from the epidermis (epi- = “upon” or “over”) and hypodermis (hypo- = “below”). It contains blood and lymph vessels, nerves, and other structures, such as hair follicles and sweat glands. The dermis is made of two layers of connective tissue, the superficial **papillary layer** and deep **reticular layer**, that compose an interconnected mesh of elastic and collagen fibers, produced by fibroblasts (Figure 4.2.5).

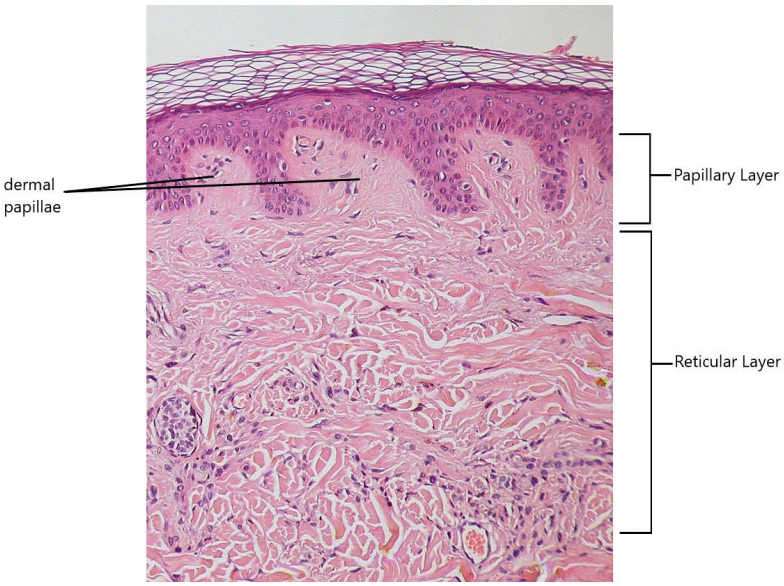

Figure 4.2.5: Layers of the Dermis. This stained slide shows the two components of the dermis—the papillary layer and the reticular layer. Both are made of connective tissue with fibers of collagen extending from one to the other, making the border between the two somewhat indistinct. The dermal papillae extending into the epidermis belong to the papillary layer, whereas the dense collagen fiber bundles below belong to the reticular layer. LM × 10. (Image credit: "Layers of the Dermis" by Whitney Menefee is licensed under CC BY 4.0 / A derivative from the original work)

Papillary Layer

The **papillary layer** is made of loose, areolar connective tissue, which means the collagen and elastic fibers of this layer form a loose mesh. This superficial layer of the dermis projects into the stratum basale of the epidermis to form finger-like dermal

papillae (see Figure 4.2.5). Within the papillary layer are fibroblasts, a small number of fat cells (adipocytes), and an abundance of small blood vessels. These small blood vessels form the subpapillary plexus, found just below the dermal papillae, which branch into the capillary beds that supply blood to the dermal papillae. In addition, the papillary layer contains phagocytes, defensive cells that help fight bacteria or other infections that have breached epidermis. This layer also contains lymphatic capillaries, nerve fibers, and touch receptors called the Meissner corpuscles. Also known as tactile corpuscles, Meissner corpuscles can be found located in the dermal papillae, and are responsible for sensing light touch. More details on the sensory functions of skin are covered later in this chapter.

Reticular Layer

Underlying the papillary layer is the much thicker **reticular layer**, composed of dense irregular connective tissue. This layer is well vascularized and has a rich sensory and sympathetic nerve supply. The reticular layer appears reticulated (net-like) due to a tight meshwork of fibers. **Elastic fibers** provide some elasticity to the skin, enabling movement. Collagen fibers provide structure and tensile strength, with strands of collagen extending into both the papillary layer and the hypodermis. In addition, collagen binds water to keep the skin hydrated. Collagen injections and Retin-A creams help restore skin turgor by either introducing collagen externally or stimulating blood flow and repair of the dermis, respectively.

Hypodermis

The **hypodermis** (also called the subcutaneous layer or superficial fascia) is a layer directly below the dermis and serves to connect the skin to the underlying fascia (fibrous tissue) of the bones and muscles. It is not strictly a part of the skin, although the border between the hypodermis and dermis can be difficult to distinguish. The hypodermis consists of well-vascularized, loose, areolar connective tissue and adipose tissue, which functions as a mode of fat storage and provides insulation and cushioning for the skin.

EVERYDAY CONNECTION

Lipid Storage

The hypodermis is home to most of the fat that concerns people when they are trying to keep their weight under control. Adipose tissue present in the hypodermis consists of fat-storing cells called adipocytes. This stored fat can serve as an energy reserve, insulate the body to prevent heat loss, and act as a cushion to protect underlying structures from trauma.

Where the fat is deposited and accumulates within the hypodermis depends on hormones (testosterone, estrogen, insulin, glucagon, leptin, and others), as well as genetic factors. Fat distribution changes as our bodies mature and age. Men tend to accumulate fat in different areas (neck, arms, lower back, and abdomen) than do women (breasts, hips, thighs, and buttocks). The body mass index (BMI) is often used as a measure of fat, although this measure is, in fact, derived from a mathematical formula that compares body weight (mass) to height. Therefore, its accuracy as a health indicator can be called into question in individuals who are extremely physically fit.

In many animals, there is a pattern of storing excess calories as fat to be used in times when food is not readily available. In much of the developed world, insufficient exercise coupled with the ready availability and consumption of high-calorie foods have resulted in unwanted accumulations of stored lipids in adipose tissue in many people. Although periodic accumulation of excess fat may have provided an evolutionary advantage to our ancestors, who experienced unpredictable bouts of famine, it is now becoming chronic and considered a major health threat. Recent studies indicate that a distressing percentage of our population is overweight and/or clinically obese. Not only is this a problem for the individuals affected, but it also has a severe impact on our healthcare system. Changes in lifestyle, specifically in diet and exercise, are the best ways to control body fat accumulation, especially when it reaches levels that increase the risk of heart disease and diabetes.

Pigmentation

The color of skin is influenced by a number of pigments, including melanin, carotene, and hemoglobin. Recall that melanin is produced by cells called melanocytes, which are found scattered throughout the stratum basale of the epidermis. The melanin is

transferred into the keratinocytes via a cellular vesicle called a **melanosome** (Figure 4.2.6).

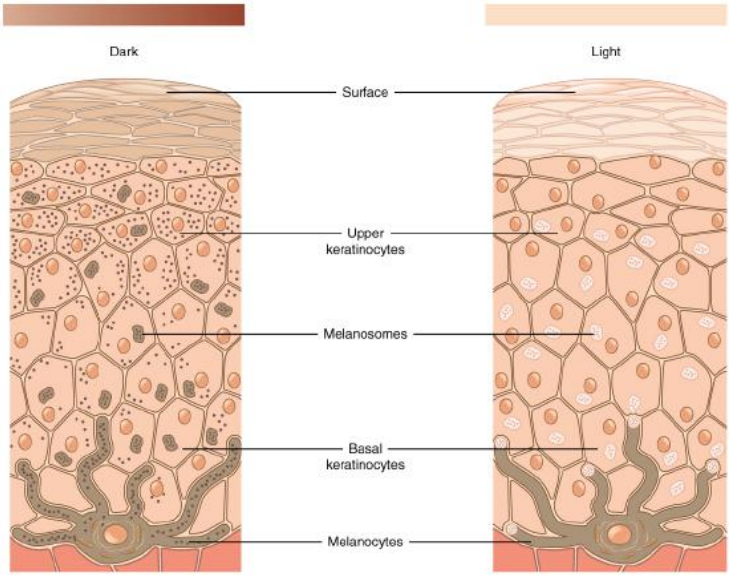

Figure 4.2.6: Skin Pigmentation. The relative coloration of the skin depends of the amount of melanin produced by melanocytes in the stratum basale and taken up by keratinocytes. (Image credit: "Melanocytes" by OpenStax is licensed under CC BY 4.0)

Melanin occurs in two primary forms. Eumelanin exists as black and brown, whereas pheomelanin provides a red color. Dark-skinned individuals produce more melanin than those with pale skin. Exposure to the UV rays of the sun or a tanning salon causes melanin to be manufactured and built up in keratinocytes, as sun exposure stimulates keratinocytes to secrete chemicals that stimulate melanocytes. The accumulation of melanin in keratinocytes results in the darkening of the skin, or a tan. This increased melanin accumulation is protection from UV radiation, which could damage the DNA of epidermal cells and breakdown folic acid, a nutrient necessary for our health and well-being, circulating through the bloodstream in the dermis. In contrast, too much melanin can interfere with the production of vitamin D, an important nutrient involved in calcium absorption, since UV radiation is required for its production. Thus, the amount of melanin present in our skin is dependent on a balance between available sunlight and folic acid destruction, and protection from UV radiation and vitamin D production.

It requires about 10 days after initial sun exposure for melanin synthesis to peak, which is why pale-skinned individuals tend to suffer sunburns of the epidermis initially. Dark-skinned individuals can also get sunburns, but are more protected than are pale-skinned individuals. Melanosomes are temporary structures that are eventually destroyed by fusion with lysosomes; this fact, along with melanin-filled keratinocytes in the stratum corneum sloughing off, makes tanning impermanent.

Too much sun exposure can eventually lead to wrinkling due to the destruction of the cellular structure of the skin, and in severe cases, can cause sufficient DNA damage to result in skin cancer. When there is an irregular accumulation of melanocytes in the skin, freckles appear. Moles are larger masses of melanocytes, and although most are benign, they should be monitored for changes that might indicate the presence of cancer (Figure 4.2.7).

Figure 4.2.7: Moles. Moles can range in size from benign accumulations of melanocytes. These structures populate the landscape of our skin. (Image credit: "Moles" by OpenStax and the National Cancer Institute is licensed under CC BY 3.0)

Carotene, an orange/red pigment found in many vegetables such as carrots, can also have an affect on skin pigmentation. Once consumed, carotene is converted by the human body into vitamin A, which in turn is used for vision, immune system function, and to stimulate fibroblasts in the skin. Recall that fibroblasts produce the elastic and collagen fibers of the dermis, so having active fibroblast helps with the firmness of skin. However, the over intake of carotene can cause the skin to turn yellowish-orange in color, as a result of the excess being stored just under the skin.

Another factor that can affect the appearance of skin is the activity of hemoglobin in the blood stream. Hemoglobin is a pigment found in red blood cells that is responsible for carrying oxygen throughout the body. A sudden drop in oxygenation can affect skin color, causing the skin to initially turn ashen (white). With a prolonged reduction in oxygen levels, dark red deoxyhemoglobin (hemoglobin not carrying oxygen) becomes dominant in the blood, making the skin appear blue, a condition referred to as cyanosis (kyanos is the Greek word for “blue”). This happens when the oxygen supply is restricted, as when someone is experiencing difficulty in breathing because of asthma or a heart attack. However, in these cases the effect on skin color has nothing do with the skin’s pigmentation.

DISORDER OF THE.....

Integumentary System

The first thing a clinician sees is the skin, and so the examination of the skin should be part of any thorough physical examination. Most skin disorders are relatively benign, but a few, including melanomas, can be fatal if untreated. A couple of the more noticeable disorders, albinism and vitiligo, affect the appearance of the skin and its accessory organs. Although neither is fatal, it would be hard to claim that they are benign, at least to the individuals so afflicted.

Albinism is a genetic disorder that affects (completely or partially) the coloring of skin, hair, and eyes. The defect is primarily due to the inability of melanocytes to produce melanin. Individuals with albinism tend to appear white or very pale due to the lack of melanin in their skin and hair. Recall that melanin helps protect the skin from the harmful effects of UV radiation. Individuals with albinism tend to need more protection from UV radiation, as they are more prone to sunburns and skin cancer. They also tend to be more sensitive to light and have vision problems due to the lack of pigmentation on the retinal wall. Treatment of this disorder usually involves addressing the symptoms, such as limiting UV light exposure to the skin and eyes. In vitiligo, the melanocytes in certain areas lose their ability to produce melanin, possibly due to an autoimmune reaction. This leads to a loss of color in patches (Figure 4.2.8). Neither albinism nor vitiligo directly affects the lifespan of an individual.

Figure 4.2.8: Vitiligo. Individuals with vitiligo experience depigmentation that results in lighter colored patches of skin. The condition is especially noticeable on darker skin. (Image credit: "Vitiligo and Poliosis" by Klaus D. Peter is licensed under CC BY 3.0)

Other changes in the appearance of skin coloration can be indicative of diseases associated with other body systems. Liver disease or liver cancer can cause the accumulation of bile and the yellow pigment bilirubin, leading to the skin appearing yellow or jaundiced (*jaune* is the French word for “yellow”). Tumors of the pituitary gland can result in the secretion of large amounts of melanocyte-stimulating hormone (MSH), which results in a darkening of the skin. Similarly, Addison’s disease can stimulate the release of excess amounts of adrenocorticotropic hormone (ACTH), which can give the skin a deep bronze color.

Concept Review

The skin is composed of two major layers: a superficial epidermis and a deeper dermis. The epidermis consists of several layers beginning with the innermost (deepest) stratum basale (germinatum), followed by the stratum spinosum, stratum granulosum, stratum lucidum (when present), and ending with the outermost layer, the stratum corneum. The topmost layer, the stratum corneum, consists of dead cells that shed periodically and is progressively replaced by cells formed from the basal layer. The stratum basale also contains melanocytes, cells that produce melanin, the pigment primarily responsible for giving skin its color. Melanin is transferred to keratinocytes in the stratum spinosum to protect from UV rays.

The dermis connects the epidermis to the hypodermis, and provides strength and elasticity due to the presence of collagen and elastic fibers. It has only two layers: the papillary layer composed of loose connective tissue with papillae that extend into the epidermis and the lower, reticular layer composed of dense irregular connective tissue. The hypodermis, deep to the dermis of skin, is the connective tissue that connects the dermis to underlying structures; it also harbors adipose tissue for fat storage and protection.

Review Questions

Q. The papillary layer of the dermis is most closely associated with which layer of the epidermis?

A. stratum spinosum

B. stratum corneum

C. stratum granulosum

D. stratum basale

Answer

Answer: D

Q. Langerhans cells are commonly found in the _____.

A. stratum spinosum

B. stratum corneum

C. stratum granulosum

D. stratum basale

Answer

Answer: A

Q. The papillary and reticular layers of the dermis are composed mainly of _____.

A. melanocytes

B. keratinocytes

C. connective tissue

D. adipose tissue

Answer

Answer: C

Q. Collagen lends _____ to the skin.

A. elasticity

B. structure

C. color

D. UV protection

Answer

Answer: B

Q. Which of the following is not a function of the hypodermis?

A. protects underlying organs

B. helps maintain body temperature

C. source of blood vessels in the epidermis

D. a site to long-term energy storage

Answer

Answer: C

Critical Thinking Questions

Q. What determines the color of skin, and what is the process that darkens skin when it is exposed to UV light?

Answer

A. The pigment melanin, produced by melanocytes, is primarily responsible for skin color. Melanin comes in different shades of brown and black. Individuals with darker skin have darker, more abundant melanin, whereas fair-skinned individuals accumulate less of a lighter shade of melanin. Exposure to UV irradiation stimulates the melanocytes to produce and secrete more melanin.

Q. Cells of the epidermis derive from stem cells of the stratum basale. Describe how the cells change as they become integrated into the different layers of the epidermis.

Answer

A. As the cells move into the stratum spinosum, they begin the synthesis of keratin and extend cell processes, desmosomes, which link the cells. As the stratum basale continues to produce new cells, the keratinocytes of the stratum spinosum are pushed into the stratum granulosum. The cells become flatter, their cell membranes thicken, and they generate large amounts of the proteins keratin and keratohyalin. The nuclei and other cell organelles disintegrate as the cells die, leaving behind the keratin, keratohyalin, and cell membranes that form the stratum lucidum and the stratum corneum. The keratinocytes in these layers are mostly dead and flattened. Cells in the stratum corneum are periodically shed.

Glossary

albinism
genetic disorder that affects the skin, in which there is no melanin production

basal cell
type of stem cell found in the stratum basale and in the hair matrix that continually undergoes cell division, producing the keratinocytes of the epidermis

dermal papilla
(plural = dermal papillae) extension of the papillary layer of the dermis that increases surface contact between the epidermis and dermis

dermis
layer of skin between the epidermis and hypodermis, composed mainly of connective tissue and containing blood vessels, hair follicles, sweat glands, and other structures

desmosome
structure that forms an impermeable junction between cells

elastic fibers
fibers made of the protein elastin that increase the elasticity of the dermis

eleiden
clear protein-bound lipid found in the stratum lucidum that is derived from keratohyalin and helps to prevent water loss

epidermis
outermost tissue layer of the skin

hypodermis
connective tissue connecting the integument to the underlying bone and muscle

integumentary system
skin and its accessory structures

keratin
type of structural protein that gives skin, hair, and nails its hard, water-resistant properties

keratinocyte
cell that produces keratin and is the most predominant type of cell found in the epidermis

keratohyalin
granulated protein found in the stratum granulosum

Langerhans cell
specialized dendritic cell found in the stratum spinosum that functions as a macrophage

melanin
pigment that determines the color of hair and skin

melanocyte
cell found in the stratum basale of the epidermis that produces the pigment melanin

melanosome
intercellular vesicle that transfers melanin from melanocytes into keratinocytes of the epidermis

Merkel cell
receptor cell in the stratum basale of the epidermis that responds to the sense of touch

papillary layer
superficial layer of the dermis, made of loose, areolar connective tissue

reticular layer
deeper layer of the dermis; it has a reticulated appearance due to the presence of abundant collagen and elastin fibers

stratum basale
deepest layer of the epidermis, made of epidermal stem cells

stratum corneum
most superficial layer of the epidermis

stratum granulosum
layer of the epidermis superficial to the stratum spinosum

stratum lucidum
layer of the epidermis between the stratum granulosum and stratum corneum, found only in thick skin covering the palms, soles of the feet, and digits

stratum spinosum
layer of the epidermis superficial to the stratum basale, characterized by the presence of desmosomes

vitiligo
skin condition in which melanocytes in certain areas lose the ability to produce melanin, possibly due an autoimmune reaction that leads to loss of color in patches

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4.3: Accessory Structures of the Skin

By the end of the section, you will be able to:

- Identify the accessory structures of the skin
- Describe the structure and function of hair and nails
- Describe the structure and function of sweat glands and sebaceous glands

Accessory structures of the skin include hair, nails, sweat glands, and sebaceous glands. These structures embryologically originate from the epidermis and can extend down through the dermis into the hypodermis.

Hair

Hair is a keratinous filament growing out of the epidermis. It is primarily made of dead, keratinized cells. Strands of hair originate in an epidermal penetration of the dermis called the **hair follicle**. The **hair shaft** is the part of the hair not anchored to the follicle, and much of this is exposed at the skin's surface. The rest of the hair, which is anchored in the follicle, lies below the surface of the skin and is referred to as the **hair root**. The hair root ends deep in the dermis at the **hair bulb**, and includes a layer of mitotically active basal cells called the **hair matrix**. The hair bulb surrounds the **hair papilla**, which is made of connective tissue and contains blood capillaries and nerve endings from the dermis (Figure 4.3.1).

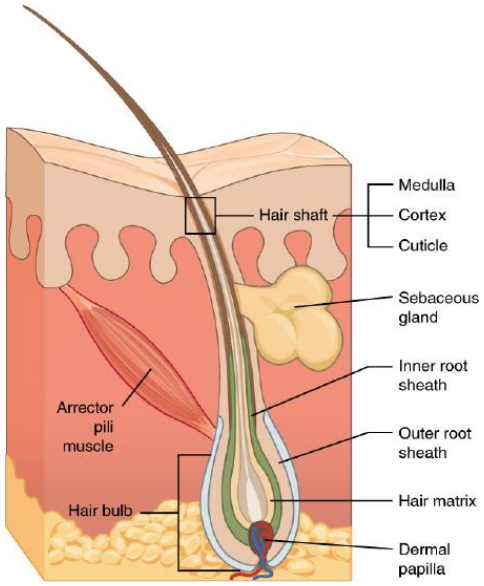

Figure 4.3.1: Hair. Hair follicles originate in the epidermis, but extend deep into the dermis, and have many different parts related to the growth of hair. (Image credit: "Hair" by OpenStax is licensed under CC BY 4.0)

Just as the basal layer of the epidermis forms the layers of epidermis that get pushed to the surface as the dead skin on the surface sheds, the basal cells of the hair bulb divide and push cells outward in the hair root and shaft as the hair grows. The **medulla** forms the central core of the hair, which is surrounded by the **cortex**, a layer of compressed, keratinized cells that is covered by an outer layer of very hard, keratinized cells known as the **cuticle**. These layers are depicted in a longitudinal cross-section of the hair follicle (Figure 4.3.2), although not all hair has a medullary layer. Hair texture (straight, curly) is determined by the shape and structure of the cortex, and to the extent that it is present, the medulla. The shape and structure of these layers are, in turn, determined by the shape of the hair follicle. Hair growth begins with the production of keratinocytes by the basal cells of the hair bulb. As new cells are deposited at the hair bulb, the hair shaft is pushed through the follicle toward the surface. Keratinization is completed as the cells are pushed to the skin surface to form the shaft of hair that is externally visible. The external hair is completely dead and composed entirely of keratin. For this reason, our hair does not have sensation. Furthermore, you can cut your hair or shave without damaging the hair structure because the cut is superficial. Most chemical hair removers also act superficially; however, electrolysis and yanking both attempt to destroy the hair bulb so hair cannot grow.

Figure 4.3.2: Hair Follicle. The slide shows a cross-section of a hair follicle. LM × 4. (Image credit: "Hair Follicle - Microscopic" by Whitney Menefee is licensed under CC BY 3.0 / A derivative from the original work)

The wall of the hair follicle is made of three concentric layers of cells. The cells of the **internal root sheath** surround the root of the growing hair and extend just up to the hair shaft. They are derived from the basal cells of the hair matrix. The **external root sheath**, which is an extension of the epidermis, encloses the hair root. It is made of basal cells at the base of the hair root and tends to be more keratinous in the upper regions. The **glassy membrane** is a thick, clear connective tissue sheath covering the hair root, connecting it to the tissue of the dermis.

Hair serves a variety of functions, including protection, sensory input, thermoregulation, and communication. For example, hair on the head protects the skull from the sun. The hair in the nose and ears, and around the eyes (eyelashes) defends the body by trapping and excluding dust particles that may contain allergens and microbes. Hair of the eyebrows prevents sweat and other particles from dripping into and bothering the eyes. Hair also has a sensory function due to sensory innervation by a hair root plexus surrounding the base of each hair follicle. Hair is extremely sensitive to air movement or other disturbances in the environment, much more so than the skin surface. This feature is also useful for the detection of the presence of insects or other potentially damaging substances on the skin surface. Each hair root is connected to a smooth muscle called the **arrector pili** that contracts in response to nerve signals from the sympathetic nervous system, making the external hair shaft "stand up." The primary purpose for this is to trap a layer of air to add insulation. This is visible in humans as goose bumps and even more obvious in animals with a heavier coat than most humans, such as dogs and cats that raise their fur when alarmed.

Hair Growth

Hair grows and is eventually shed and replaced by new hair. This occurs in three phases. The first is the **anagen** phase, during which cells divide rapidly at the root of the hair, pushing the hair shaft up and out. The length of this phase is measured in years, typically from 2 to 7 years. The **catagen** phase lasts only 2 to 3 weeks, and marks a transition from the hair follicle's active growth. Finally, during the **telogen** phase, the hair follicle is at rest and no new growth occurs. At the end of this phase, which lasts about 2 to 4 months, another anagen phase begins. The basal cells in the hair matrix then produce a new hair follicle, which pushes the old hair out as the growth cycle repeats itself. Hair typically grows at the rate of 0.3 mm per day during the anagen phase. On average, 50 hairs are lost and replaced per day. Hair loss occurs if there is more hair shed than what is replaced and can happen due to hormonal or dietary changes. Hair loss can also result from the aging process, or the influence of hormones.

Hair Color

Similar to the skin, hair gets its color from the pigment melanin, produced by melanocytes in the hair papilla. Different hair color results from differences in the type of melanin, which is genetically determined. As a person ages, the melanin production decreases, and hair tends to lose its color and becomes gray and/or white.

Nails

The nail bed is a specialized structure of the epidermis that is found at the tips of our fingers and toes. The **nail body** is formed on the **nail bed**, and protects the tips of our fingers and toes as they are the farthest extremities and the parts of the body that experience the maximum mechanical stress (Figure 4.3.3). In addition, the nail body forms a back-support for picking up small objects with the fingers. The nail body is composed of densely packed dead keratinocytes. The epidermis in this part of the body has evolved a specialized structure upon which nails can form. The nail body forms at the **nail root**, which has a matrix of proliferating cells from the stratum basale that enables the nail to grow continuously. The lateral **nail fold** overlaps the nail on the sides, helping to anchor the nail body. The nail fold that meets the proximal end of the nail body forms the **nail cuticle**, also called the **eponychium**. The nail bed is rich in blood vessels, making it appear pink, except at the base, where a thick layer of epithelium over the nail matrix forms a crescent-shaped region called the **lunula** (the "little moon"). The area beneath the free edge of the nail, furthest from the cuticle, is called the **hyponychium**. It consists of a thickened layer of stratum corneum.

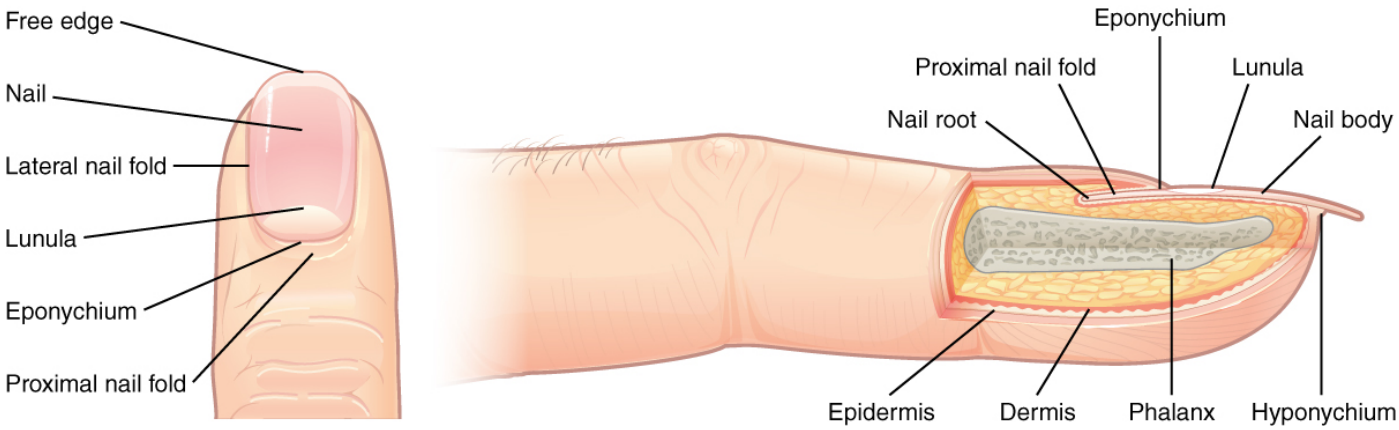

Figure 4.3.3: Nails. The nail is an accessory structure of the integumentary system. (Image credit: "Nails" by OpenStax is licensed under CC BY 4.0)

Sweat Glands

When the body becomes warm, **sudoriferous glands** produce sweat to cool the body. Sweat glands develop from epidermal projections into the dermis. There are two types of sweat glands, each secreting slightly different products.

An **eccrine sweat gland** is type of gland that produces a hypotonic sweat for thermoregulation. These glands are found all over the skin's surface, but are especially abundant on the palms of the hand, the soles of the feet, and the forehead (Figure 4.3.4). They are coiled glands lying deep in the dermis, with the duct rising up to a pore on the skin surface, where the sweat is released. This type of sweat, released by exocytosis, is hypotonic and composed mostly of water, with some salt, antibodies, traces of metabolic waste, and dermicidin, an antimicrobial peptide. Eccrine glands are a primary component of thermoregulation in humans and thus help to maintain homeostasis.

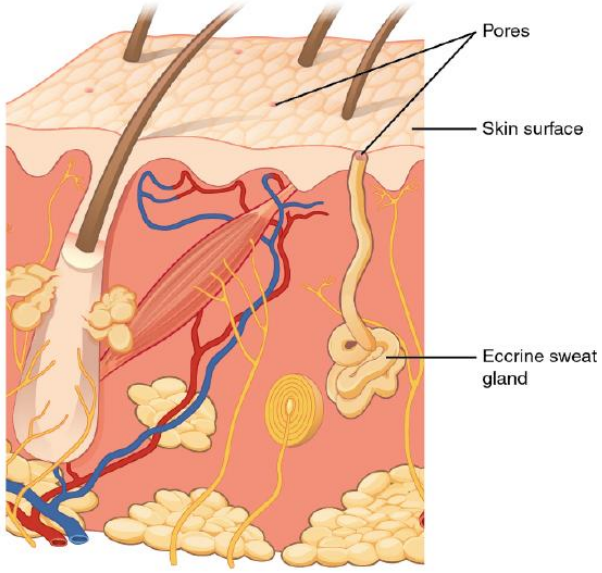

Figure 4.3.4: Eccrine Gland. Eccrine glands are coiled glands in the dermis that release sweat that is mostly water. (Image credit: "Eccrine gland" by OpenStax is licensed under CC BY 3.0)

An **apocrine sweat gland** is usually associated with hair follicles in densely hairy areas, such as armpits and genital regions. Apocrine sweat glands are larger than eccrine sweat glands and lie deeper in the dermis, sometimes even reaching the hypodermis, with the duct normally emptying into the hair follicle. In addition to water and salts, apocrine sweat includes organic compounds that make the sweat thicker and subject to bacterial decomposition and subsequent smell. The release of this sweat is under both nervous and hormonal control, and plays a role in the poorly understood human pheromone response. Most commercial antiperspirants use an aluminum-based compound as their primary active ingredient to stop sweat. When the antiperspirant enters the sweat gland duct, the aluminum-based compounds precipitate due to a change in pH and form a physical block in the duct, which prevents sweat from coming out of the pore.

Sebaceous Glands

A **sebaceous gland** is a type of oil gland that is found all over the body and helps to lubricate and waterproof the skin and hair. Most sebaceous glands are associated with hair follicles. They generate and excrete **sebum**, a mixture of lipids, onto the skin surface, thereby naturally lubricating the dry and dead layer of keratinized cells of the stratum corneum, keeping it pliable. The fatty acids of sebum also have antibacterial properties, and prevent water loss from the skin in low-humidity environments. The secretion of sebum is stimulated by hormones, many of which do not become active until puberty. Thus, sebaceous glands are relatively inactive during childhood.

Concept Review

Accessory structures of the skin include hair, nails, sweat glands, and sebaceous glands. Hair is made of dead keratinized cells, and gets its color from melanin pigments. Nails, also made of dead keratinized cells, protect the extremities of our fingers and toes from mechanical damage. Sweat glands and sebaceous glands produce sweat and sebum, respectively. Each of these fluids has a role to play in maintaining homeostasis. Sweat cools the body surface when it gets overheated and helps excrete small amounts of metabolic waste. Sebum acts as a natural moisturizer and keeps the dead, flaky, outer keratin layer healthy.

Review Questions

Q. In response to stimuli from the sympathetic nervous system, the arrector pili _____.

A. are glands on the skin surface

B. can lead to excessive sweating

C. are responsible for goose bumps

D. secrete sebum

Answer

Answer: C

Q. The hair matrix contains _____.

A. the hair follicle

B. the hair shaft

C. the glassy membrane

D. a layer of basal cells

Answer

Answer: D

Q. Eccrine sweat glands _____.

A. are present on hair

B. are present in the skin throughout the body and produce watery sweat

C. produce sebum

D. act as a moisturizer

Answer

Answer: B

Q. Sebaceous glands _____.

A. are a type of sweat gland

B. are associated with hair follicles

C. may function in response to touch

D. release a watery solution of salt and metabolic waste

Answer

Answer: B

Q. Similar to the hair, nails grow continuously throughout our lives. Which of the following is furthest from the nail growth center?

A. nail bed

B. hyponychium

C. nail root

D. eponychium

Answer

Answer: B

Critical Thinking Questions

Q. Explain the differences between eccrine and apocrine sweat glands.

Answer

A. Eccrine sweat glands are all over the body, especially the forehead and palms of the hand. They release a watery sweat, mixed with some metabolic waste and antibodies. Apocrine glands are associated with hair follicles. They are larger than eccrine sweat glands and lie deeper in the dermis, sometimes even reaching the hypodermis. They release a thicker sweat that is often decomposed by bacteria on the skin, resulting in an unpleasant odor.

Q. Describe the structure and composition of nails.

Answer

A. Nails are composed of densely packed dead keratinocytes. They protect the fingers and toes from mechanical stress. The nail body is formed on the nail bed, which is at the nail root. Nail folds, folds of skin that overlap the nail on its side, secure the nail to the body. The crescent-shaped region at the base of the nail is the lunula.

Glossary

anagen
active phase of the hair growth cycle

apocrine sweat gland
type of sweat gland that is associated with hair follicles in the armpits and genital regions

arrector pili
smooth muscle that is activated in response to external stimuli that pull on hair follicles and make the hair “stand up”

catagen
transitional phase marking the end of the anagen phase of the hair growth cycle

cortex
in hair, the second or middle layer of keratinocytes originating from the hair matrix, as seen in a cross-section of the hair bulb

cuticle
in hair, the outermost layer of keratinocytes originating from the hair matrix, as seen in a cross-section of the hair bulb

eccrine sweat gland
type of sweat gland that is common throughout the skin surface; it produces a hypotonic sweat for thermoregulation

eponychium
nail fold that meets the proximal end of the nail body, also called the cuticle

external root sheath
outer layer of the hair follicle that is an extension of the epidermis, which encloses the hair root

glassy membrane
layer of connective tissue that surrounds the base of the hair follicle, connecting it to the dermis

hair
keratinous filament growing out of the epidermis

hair bulb
structure at the base of the hair root that surrounds the dermal papilla

hair follicle
cavity or sac from which hair originates

hair matrix
layer of basal cells from which a strand of hair grows

hair papilla
mass of connective tissue, blood capillaries, and nerve endings at the base of the hair follicle

hair root
part of hair that is below the epidermis anchored to the follicle

hair shaft
part of hair that is above the epidermis but is not anchored to the follicle

hyponychium
thickened layer of stratum corneum that lies below the free edge of the nail

internal root sheath
innermost layer of keratinocytes in the hair follicle that surround the hair root up to the hair shaft

lunula
basal part of the nail body that consists of a crescent-shaped layer of thick epithelium

medulla
in hair, the innermost layer of keratinocytes originating from the hair matrix

nail bed
layer of epidermis upon which the nail body forms

nail body
main keratinous plate that forms the nail

nail cuticle
fold of epithelium that extends over the nail bed, also called the eponychium

nail fold
fold of epithelium at that extend over the sides of the nail body, holding it in place

nail root
part of the nail that is lodged deep in the epidermis from which the nail grows

sebaceous gland
type of oil gland found in the dermis all over the body and helps to lubricate and waterproof the skin and hair by secreting sebum

sebum
oily substance that is composed of a mixture of lipids that lubricates the skin and hair

sudoriferous gland
sweat gland

telogen
resting phase of the hair growth cycle initiated with catagen and terminated by the beginning of a new anagen phase of hair growth

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4.4: Functions of the Integumentary System

By the end of the section, you will be able to:

- Describe the different functions of the skin and the structures that enable them
- Explain how the skin helps maintain body temperature

The skin and accessory structures perform a variety of essential functions, such as protecting the body from invasion by microorganisms, chemicals, and other environmental factors; preventing dehydration; acting as a sensory organ; modulating body temperature and electrolyte balance; and synthesizing vitamin D. The underlying hypodermis has important roles in storing fats, forming a “cushion” over underlying structures, and providing insulation from cold temperatures.

Protection

The skin protects the rest of the body from the basic elements of nature such as wind, water, and UV sunlight. It acts as a protective barrier against water loss, due to the presence of layers of keratin and glycolipids in the stratum corneum. It also is the first line of defense against abrasive activity due to contact with grit, microbes, or harmful chemicals. Sweat excreted from sweat glands deters microbes from over-colonizing the skin surface by generating dermicidin, which has antibiotic properties.

Everyday Connection

Tattoos and Piercings

The word “armor” evokes several images. You might think of a Roman centurion or a medieval knight in a suit of armor. The skin, in its own way, functions as a form of armor—body armor. It provides a barrier between your vital, life-sustaining organs and the influence of outside elements that could potentially damage them.

For any form of armor, a breach in the protective barrier poses a danger. The skin can be breached when a child skins a knee or an adult has blood drawn—one is accidental and the other medically necessary. However, you also breach this barrier when you choose to “accessorize” your skin with a tattoo or body piercing. Because the needles involved in producing body art and piercings must penetrate the skin, there are dangers associated with the practice. These include allergic reactions; skin infections; blood-borne diseases, such as tetanus, hepatitis C, and hepatitis D; and the growth of scar tissue. Despite the risk, the practice of piercing the skin for decorative purposes has become increasingly popular. According to the American Academy of Dermatology, 24 percent of people from ages 18 to 50 have a tattoo.

QR Code representing a URL

Watch this video about tattooing. Tattooing has a long history, dating back thousands of years ago. The dyes used in tattooing typically derive from metals. A person with tattoos should be cautious when having a magnetic resonance imaging (MRI) scan because an MRI machine uses powerful magnets to create images of the soft tissues of the body, which could react with the metals contained in the tattoo dyes.

Sensory Function

You can feel an ant crawling on your skin, allowing you to flick it off before it bites, because the skin, and especially the hairs projecting from hair follicles in the skin, can sense changes in the environment. The hair root plexus surrounding the base of the hair follicle senses a disturbance, and then transmits the information to the central nervous system (brain and spinal cord), which can then respond by activating the skeletal muscles of your eyes to see the ant and the skeletal muscles of the body to act against the ant.

The skin acts as a sense organ because the epidermis, dermis, and the hypodermis contain specialized sensory nerve structures

that detect touch, surface temperature, and pain. These receptors are more concentrated on the tips of the fingers, which are most sensitive to touch, especially the **Meissner corpuscle** (tactile corpuscle) (Figure 4.4.1), which responds to light touch, and the **Pacinian corpuscle** (lamellated corpuscle), which responds to vibration. Merkel cells, seen scattered in the stratum basale, are also touch receptors. In addition to these specialized receptors, there are sensory nerves connected to each hair follicle, pain and temperature receptors scattered throughout the skin, and motor nerves innervating the arrector pili muscles and glands. This rich innervation helps you sense your environment and react accordingly.

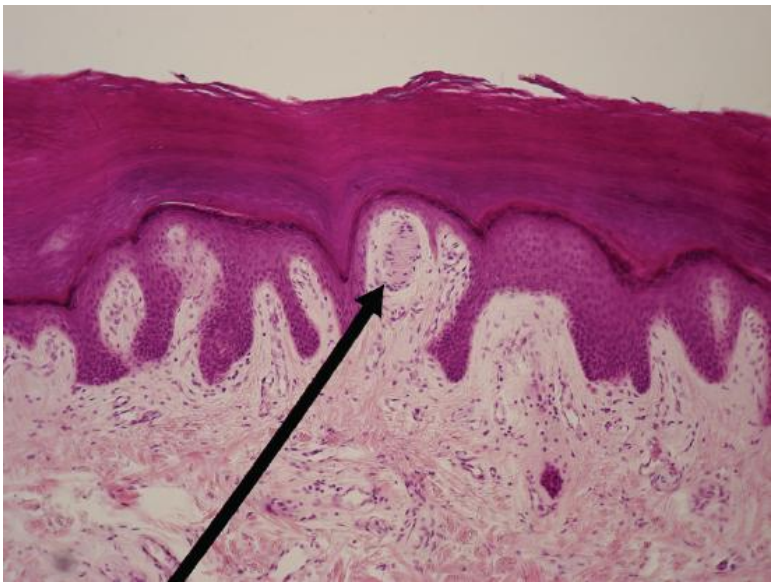

Figure 4.4.1: Light Micrograph of a Meissner Corpuscle. In this micrograph of a skin cross-section, you can see a Meissner corpuscle (arrow), a type of touch receptor located in a dermal papilla adjacent to the basement membrane and stratum basale of the overlying epidermis. LM × 100. (Image credit:"WVSOM Meissner's corpuslce" by Wbensmith is licensed under CC BY 3.0)

Thermoregulation

The integumentary system helps regulate body temperature through its tight association with the sympathetic nervous system, the division of the nervous system involved in our fight-or-flight responses. The sympathetic nervous system is continuously monitoring body temperature and initiating appropriate motor responses. Recall that sweat glands, accessory structures to the skin, secrete water, salt, and other substances to cool the body when it becomes warm. Even when the body does not appear to be noticeably sweating, approximately 500 mL of sweat (insensible perspiration) are secreted a day. If the body becomes excessively warm due to high temperatures, vigorous activity (Figure 4.4.2.$a-c$), or a combination of the two, sweat glands will be stimulated by the sympathetic nervous system to produce large amounts of sweat, as much as 0.7 to 1.5 L per hour for an active person. When the sweat evaporates from the skin surface, the body is cooled as body heat is dissipated.

In addition to sweating, arterioles (small blood vessels) in the dermis dilate so that excess heat carried by the blood can dissipate through the skin and into the surrounding environment (Figure 4.4.2.b). This accounts for the skin redness that many people experience when exercising as the red pigment of the blood more visibly contributes to skin tone.

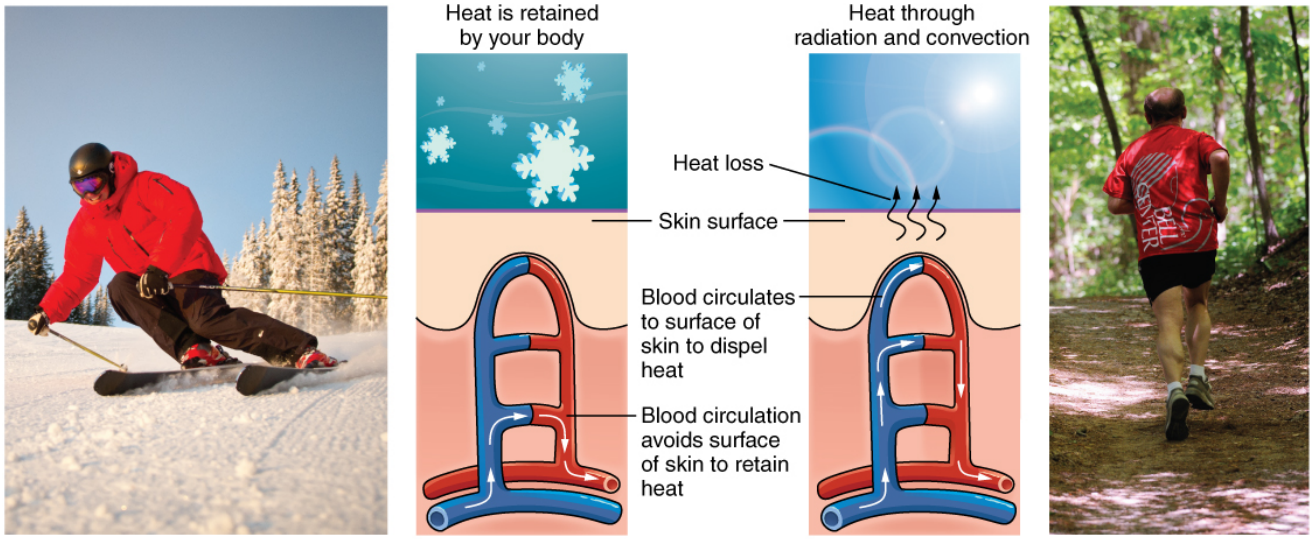

Figure 4.4.2: Thermoregulation. During strenuous physical activities, such as skiing (a) or running (c), the dermal blood vessels dilate and sweat secretion increases (b). These mechanisms prevent the body from overheating. In contrast, the dermal blood vessels constrict to minimize heat loss in response to low temperatures (b). (Image credit: "Thermoregulation" by OpenStax is licensed under CC BY 3.0)

Conversely, when body temperatures drop, the arterioles constrict to minimize heat loss, particularly in the ends of the digits and tip of the nose. This reduced circulation can result in the skin taking on a paler hue. Although the temperature of the skin drops as a result, passive heat loss is prevented, and internal organs and structures remain warm. If the temperature of the skin drops too much (such as environmental temperatures below freezing), the conservation of body core heat can result in the skin actually freezing, a condition called frostbite.

Vitamin D Synthesis

The epidermal layer of human skin synthesizes the inactive form of **vitamin D** when exposed to UV radiation, which is eventually converted to calcitriol (the active chemical form of the vitamin) in the kidneys. Vitamin D is essential for normal absorption of calcium and phosphorus, which are required for healthy bones. The absence of sun exposure can lead to a lack of vitamin D in the body, leading to a condition called **rickets**, a painful condition in children where the bones are misshapen due to a lack of calcium, causing bowleggedness. Elderly individuals who suffer from vitamin D deficiency can develop a condition called osteomalacia, a softening of the bones. In present day society, vitamin D is added as a supplement to many foods, including milk and orange juice, compensating for the need for sun exposure.

In addition to its essential role in bone health, vitamin D is essential for general immunity against bacterial, viral, and fungal infections. Recent studies are also finding a link between insufficient vitamin D and cancer.

AGING AND THE.....

Integumentary System

All systems in the body accumulate subtle and some not-so-subtle changes as a person ages. Among these changes are reductions in cell division, metabolic activity, blood circulation, hormonal levels, and muscle strength (Figure 4.4.3). In the skin, these changes are reflected in decreased mitosis in the stratum basale, leading to a thinner epidermis. The dermis, which is responsible for the elasticity and resilience of the skin, also exhibits a reduced ability to regenerate, which leads to slower wound healing. The hypodermis, with its fat stores, loses structure due to the reduction and redistribution of fat, which in turn contributes to the thinning and sagging of skin.

Figure 4.4.3: Aging. Generally, skin, especially on the face and hands, starts to display the first noticeable signs of aging, as it loses its elasticity over time. (Image credit: "GRANDDAUGHTER and GRANDMOTHER" by Janet Ramsden is licensed under CC BY 2.0)

The accessory structures also have lowered activity, generating thinner hair and nails, and reduced amounts of sebum and sweat. A reduced sweating ability can cause some elderly to be intolerant to extreme heat. Other cells in the skin, such as melanocytes and dendritic cells, also become less active, leading to a paler skin tone and lowered immunity. Wrinkling of the skin occurs due to breakdown of its structure, which results from decreased collagen and elastin production in the dermis, weakening of muscles lying under the skin, and the inability of the skin to retain adequate moisture.

Many anti-aging products can be found in stores today. In general, these products try to rehydrate the skin and thereby fill out the wrinkles, and some stimulate skin growth using hormones and growth factors. Additionally, invasive techniques include collagen injections to plump the tissue and injections of BOTOX® (the name brand of the botulinum neurotoxin) that paralyze the muscles that crease the skin and cause wrinkling.

Concept Review

The skin plays important roles in protection, sensing stimuli, thermoregulation, and vitamin D synthesis. It is the first layer of defense to prevent dehydration, infection, and injury to the rest of the body. Sweat glands in the skin allow the skin surface to cool when the body gets overheated. Thermoregulation is also accomplished by the dilation or constriction of heat-carrying blood vessels in the skin. Immune cells present among the skin layers patrol the areas to keep them free of foreign materials. Fat stores in the hypodermis aid in both thermoregulation and protection. Finally, the skin plays a role in the synthesis of vitamin D, which is necessary for our well-being but not easily available in natural foods.

Review Questions

Q. In humans, exposure of the skin to sunlight is required for _____.

A. vitamin D synthesis

B. arteriole constriction

C. folate production

D. thermoregulation

Answer

Answer: A

Q. One of the functions of the integumentary system is protection. Which of the following does not directly contribute to that function?

A. stratum lucidum

B. desmosomes

C. folic acid synthesis

D. Merkel cells

Answer

Answer: C

Q. An individual using a sharp knife notices a small amount of blood where he just cut himself. Which of the following layers of skin did he have to cut into in order to bleed?

A. stratum corneum

B. stratum basale

C. papillary dermis

D. stratum granulosum

Answer

Answer: C

Q. As you are walking down the beach, you see a dead, dry, shriveled-up fish. Which layer of your epidermis keeps you from drying out?

A. stratum corneum

B. stratum basale

C. stratum spinosum

D. stratum granulosum

Answer

Answer: A

Q. If you cut yourself and bacteria enter the wound, which of the following cells would help get rid of the bacteria?

A. Merkel cells

B. keratinocytes

C. Langerhans cells

D. melanocytes

Answer

Answer: C

Critical Thinking Questions

Q. Why do people sweat excessively when exercising outside on a hot day?

Answer

A. Sweating cools the body when it becomes warm. When the body temperature rises, such as when exercising on a hot day, the dermal blood vessels dilate, and the sweat glands begin to secrete more sweat. The evaporation of the sweat from the surface of the skin cools the body by dissipating heat.

Q. Explain your skin's response to a drop in body core temperature.

Answer

A. When the core body temperature drops, the body switches to heat-conservation mode. This can include an inhibition to excessive sweating and a decrease of blood flow to the papillary layers of the skin. This reduction of blood flow helps conserve body heat.

References

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Glossary

Meissner corpuscle
(also, tactile corpuscle) receptor in the skin that responds to light touch

Pacinian corpuscle
(also, lamellated corpuscle) receptor in the skin that responds to vibration

rickets
disease in children caused by vitamin D deficiency, which leads to the weakening of bones

vitamin D
compound that aids absorption of calcium and phosphates in the intestine to improve bone health

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4.5: Diseases, Disorders, and Injuries of the Integumentary System

By the end of the section, you will be able to:

- Describe several different diseases and disorders of the skin
- Describe the effect of injury to the skin and the process of healing

The integumentary system is susceptible to a variety of diseases, disorders, and injuries. These range from annoying but relatively benign bacterial or fungal infections that are categorized as disorders, to skin cancer and severe burns, which can be fatal. In this section, you will learn several of the most common skin conditions.

Diseases

One of the most talked about diseases is skin cancer. Cancer is a broad term that describes diseases caused by abnormal cells in the body dividing uncontrollably. Most cancers are identified by the organ or tissue in which the cancer originates. One common form of cancer is skin cancer. The Skin Cancer Foundation reports that one in five Americans will experience some type of skin cancer in their lifetime. The degradation of the ozone layer in the atmosphere and the resulting increase in exposure to UV radiation has contributed to its rise. Overexposure to UV radiation damages DNA, which can lead to the formation of cancerous lesions. Although melanin offers some protection against DNA damage from the sun, often it is not enough. The fact that cancers can also occur on areas of the body that are normally not exposed to UV radiation suggests that there are additional factors that can lead to cancerous lesions.

In general, cancers result from an accumulation of DNA mutations. These mutations can result in cell populations that do not die when they should and uncontrolled cell proliferation that leads to tumors. Although many tumors are benign (harmless), some produce cells that can mobilize and establish tumors in other organs of the body; this process is referred to as **metastasis**. Cancers are characterized by their ability to metastasize.

Basal Cell Carcinoma

Basal cell carcinoma is a form of cancer that affects the mitotically active stem cells in the stratum basale of the epidermis. It is the most common of all cancers that occur in the United States and is frequently found on the head, neck, arms, and back, which are areas that are most susceptible to long-term sun exposure. Although UV rays are the main culprit, exposure to other agents, such as radiation and arsenic, can also lead to this type of cancer. Wounds on the skin due to open sores, tattoos, burns, etc. may be predisposing factors as well. Basal cell carcinomas start in the stratum basale and usually spread along this boundary. At some point, they begin to grow toward the surface and become an uneven patch, bump, growth, or scar on the skin surface (Figure 4.5.1). Like most cancers, basal cell carcinomas respond best to treatment when caught early. Treatment options include surgery, freezing (cryosurgery), and topical ointments (Mayo Clinic 2012).

Figure 4.5.1: Basal Cell Carcinoma. Basal cell carcinoma can take several different forms. Similar to other forms of skin cancer, it is readily cured if caught early and treated. (Image credit: "Basal Cell Carcinoma" by OpenStax and John Hendrix, MD is licensed under CC BY 4.0)

Squamous Cell Carcinoma

Squamous cell carcinoma is a cancer that affects the keratinocytes of the stratum spinosum and presents as lesions commonly found on the scalp, ears, and hands (Figure 4.5.2). It is the second most common skin cancer. The American Cancer Society reports that two of ten (20%) skin cancers are squamous cell carcinomas, and it is more aggressive than basal cell carcinoma. If not removed, these carcinomas can metastasize. Surgery and radiation are used to cure squamous cell carcinoma.

Figure 4.5.2: Squamous Cell Carcinoma. Squamous cell carcinoma presents here as a lesion on an individual's nose. (Image credit: "Squamous Cell Carcinoma" by OpenStax and the National Cancer Institute is licensed under CC BY 4.0)

Melanoma

A **melanoma** is a cancer characterized by the uncontrolled growth of melanocytes, the pigment-producing cells in the epidermis. Typically, a melanoma develops from a mole. It is the most fatal of all skin cancers, as it is highly metastatic and can be difficult to detect before it has spread to other organs. Melanomas usually appear as asymmetrical brown and black patches with uneven borders and a raised surface (Figure 4.5.3). Treatment typically involves surgical excision and immunotherapy.

Figure 4.5.3 Melanoma. Melanomas typically present as large brown or black patches with uneven borders and a raised surface. (Image credit: "Melanoma" by OpenStax and the National Cancer Institute is licensed under CC BY 4.0)

Doctors often give their patients the following ABCDE mnemonic to help with the diagnosis of early-stage melanoma. If you observe a mole on your body displaying these signs, consult a doctor.

- **A**symmetry – the two sides are not symmetrical
- **B**orders – the edges are irregular in shape
- **C**olor – the color is varied shades of brown or black
- **D**iameter – it is larger than 6 mm (0.24 in)
- **E**volving – its shape has changed

Some specialists cite the following additional signs for the most serious form, nodular melanoma:

- **E**levated – it is raised on the skin surface
- **F**irm – it feels hard to the touch
- **G**rowing – it is getting larger

Skin Disorders

Two common skin disorders are eczema and acne. Eczema is an inflammatory condition and occurs in individuals of all ages. Acne involves the clogging of pores, which can lead to infection and inflammation, and is often seen in adolescents. Other disorders, not discussed here, include seborrheic dermatitis (on the scalp), psoriasis, cold sores, impetigo, scabies, hives, and warts.

Eczema

Eczema is an allergic reaction that manifests as dry, itchy patches of skin that resemble rashes (Figure 4.5.4). It may be accompanied by swelling of the skin, flaking, and in severe cases, bleeding. Many who suffer from eczema have antibodies against dust mites in their blood, but the link between eczema and allergy to dust mites has not been proven. Symptoms are usually managed with moisturizers, corticosteroid creams, and immunosuppressants.

Figure 4.5.4: Eczema. Eczema is a common skin disorder that presents as a red, flaky rash. (Image credit: "Eczema-arms" by Jambula is in the Public Domain, CC0)

Acne

Acne is a skin disturbance that typically occurs on areas of the skin that are rich in sebaceous glands (face and back). It is most common along with the onset of puberty due to associated hormonal changes, but can also occur in infants and continue into adulthood. Hormones, such as androgens, stimulate the release of sebum. An overproduction and accumulation of sebum along with keratin can block hair follicles. This blockage of the pore and build up of materials allows acne-causing bacteria (*Propionibacterium* and *Staphylococcus*) to proliferate causing an infection, which can lead to redness and potential scarring due to the natural wound healing process (Figure 4.5.5). The plug is initially white, due to the accumulation of pus, which is a combination of the sebum, keratin, and dead white blood cells trying to fight off the infection. The sebum, when oxidized by exposure to air, turns black.

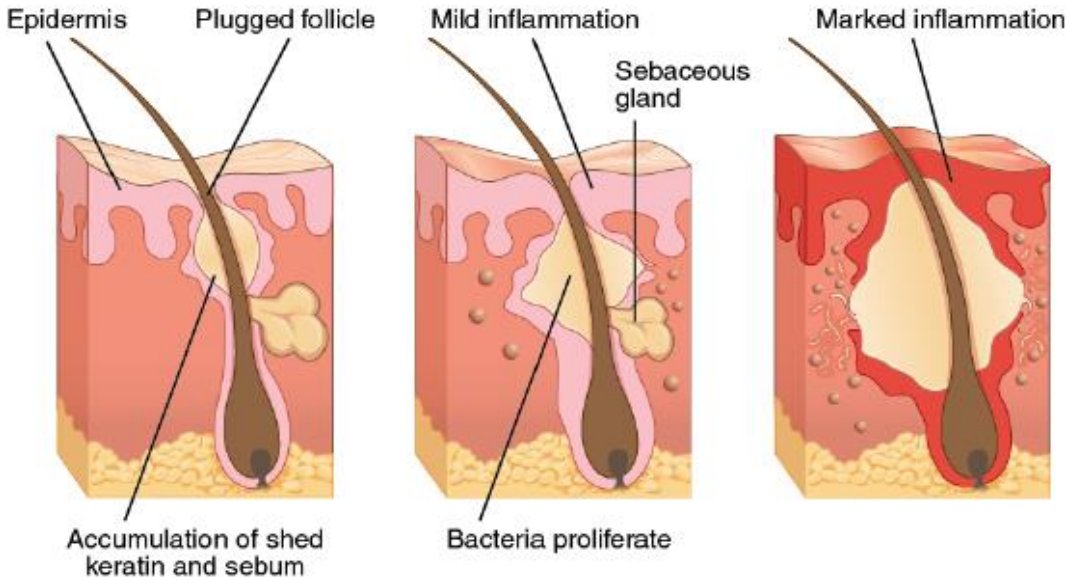

Figure 4.5.5: Acne. Acne is a result of over-productive sebaceous glands, which leads to formation of blackheads and inflammation of the skin. (Image credit: "Acne Formation" by OpenStax is licensed under CC BY 4.0)

CAREER CONNECTION

Dermatologist

Have you ever had a skin rash that did not respond to over-the-counter creams, or a mole that you were concerned about? Dermatologists help patients with these types of problems and more, on a daily basis. Dermatologists are medical doctors who specialize in diagnosing and treating skin disorders. Like all medical doctors, dermatologists earn a medical degree and then complete several years of residency training. In addition, dermatologists may then participate in a dermatology fellowship or complete additional, specialized training in a dermatology practice. If practicing in the United States, dermatologists must pass the United States Medical Licensing Exam (USMLE), become licensed in their state of practice, and be certified by the American Board of Dermatology.

Most dermatologists work in a medical office or private-practice setting. They diagnose skin conditions and rashes, prescribe oral and topical medications to treat skin conditions, and may perform simple procedures, such as mole or wart removal. In addition, they may refer patients to an oncologist if skin cancer that has metastasized is suspected. Recently, cosmetic procedures have also become a prominent part of dermatology. Botox injections, laser treatments, and collagen and dermal filler injections are popular among patients, hoping to reduce the appearance of skin aging.

Dermatology is a competitive specialty in medicine. Limited openings in dermatology residency programs mean that many medical students compete for a few select spots. Dermatology is an appealing specialty to many prospective doctors, because unlike emergency room physicians or surgeons, dermatologists generally do not have to work excessive hours or be “on-call” weekends and holidays. Moreover, the popularity of cosmetic dermatology has made it a growing field with many lucrative opportunities. It is not unusual for dermatology clinics to market themselves exclusively as cosmetic dermatology centers, and for dermatologists to specialize exclusively in these procedures.

Consider visiting a dermatologist to talk about why he or she entered the field and what the field of dermatology is like.

Injuries

Because the skin is the part of our bodies that meets the world most directly, it is especially vulnerable to injury. Injuries include burns and wounds, and the healing process can cause bothersome scars and calluses. They can be caused by sharp objects, heat, or excessive pressure or friction to the skin.

Skin injuries set off a healing process that occurs in several overlapping stages. The first step to repairing damaged skin is the formation of a blood clot that helps stop the flow of blood and scabs over with time. Many different types of cells are involved in wound repair, especially if the surface area that needs repair is extensive. Before the basal stem cells of the stratum basale can recreate the epidermis, fibroblasts mobilize and divide rapidly to repair the damaged tissue by collagen deposition, forming granulation tissue. Blood capillaries follow the fibroblasts and help increase blood circulation and oxygen supply to the area. Immune cells, such as macrophages, roam the area and engulf any foreign matter to reduce the chance of infection.

Burns

A burn results when the skin is damaged by intense heat, radiation, electricity, or chemicals. The damage results in the death of skin cells, which can lead to a massive loss of fluid. Dehydration, electrolyte imbalance, and renal and circulatory failure follow, which can be fatal. Burn patients are treated with intravenous fluids to offset dehydration, as well as intravenous nutrients that enable the body to repair tissues and replace lost proteins. Another serious threat to the lives of burn patients is infection. Burned skin is extremely susceptible to bacteria and other pathogens, due to the loss of protection by intact layers of skin.

Burns are sometimes measured in terms of the size of the total surface area affected. This is referred to as the “rule of nines,” which associates specific anatomical areas with a percentage that is a factor of nine (Figure $4.5.6$). Burns are also classified by the degree of their severity. A **first-degree burn** is a superficial burn that affects only the epidermis. Although the skin may be painful and swollen, these burns typically heal on their own within a few days. Mild sunburn fits into the category of a first-degree burn. A **second-degree burn** goes deeper and affects both the epidermis and a portion of the dermis. These burns result in swelling and a painful blistering of the skin. It is important to keep the burn site clean and sterile to prevent infection. If this is done, the burn will heal within several weeks. A **third-degree burn** fully extends into the epidermis and dermis, destroying the tissue and affecting the nerve endings and sensory function. These are serious burns that may appear white, red, or black; they require

medical attention and will heal slowly without it. A **fourth-degree burn** is even more severe, affecting the underlying muscle and bone. Oddly, third and fourth-degree burns are usually not as painful because the nerve endings themselves are damaged. Full-thickness burns cannot be repaired by the body, because the local tissues used for repair are damaged and require excision (debridement), or amputation in severe cases, followed by grafting of the skin from an unaffected part of the body, or from skin grown in tissue culture for grafting purposes.

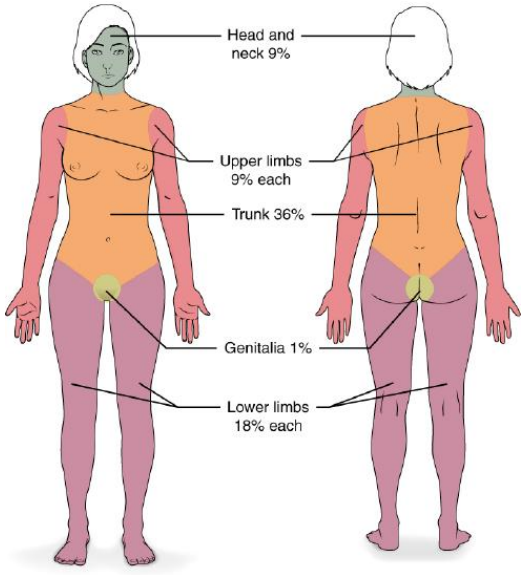

Figure 4.5.6: Calculating the Size of a Burn. The size of a burn will guide decisions made about the need for specialized treatment. Specific parts of the body are associated with a percentage of body area. (Image credit: "Degree of burns" by OpenStax is licensed under CC BY 3.0)

Scars and Keloids

Most cuts or wounds, with the exception of ones that only scratch the surface (the epidermis), lead to scar formation. A **scar** is collagen-rich skin formed after the process of wound healing that differs from normal skin. Scarring occurs in cases in which there is repair of skin damage, but the skin fails to regenerate the original skin structure. Fibroblasts generate scar tissue in the form of collagen, and the bulk of repair is due to the basket-weave pattern generated by collagen fibers and does not result in regeneration of the typical cellular structure of skin. Instead, the tissue is fibrous in nature and does not allow for the regeneration of accessory structures, such as hair follicles, sweat glands, or sebaceous glands.

Sometimes, there is an overproduction of scar tissue, because the process of collagen formation does not stop when the wound is healed; this results in the formation of a raised or hypertrophic scar called a **keloid**. In contrast, scars that result from acne and chickenpox have a sunken appearance and are called atrophic scars.

Scarring of skin after wound healing is a natural process and does not need to be treated further. Application of mineral oil and lotions may reduce the formation of scar tissue. However, modern cosmetic procedures, such as dermabrasion, laser treatments, and filler injections have been invented as remedies for severe scarring. All of these procedures try to reorganize the structure of the epidermis and underlying collagen tissue to make it look more natural.

Bedsores and Stretch Marks

Skin and its underlying tissue can be affected by excessive pressure. One example of this is called a **bedsore**. Bedsores, also called decubitis ulcers, are caused by constant, long-term, unrelieved pressure on certain body parts that are bony, reducing blood flow to the area and leading to necrosis (tissue death). Bedsores are most common in elderly patients who have debilitating conditions that cause them to be immobile. Most hospitals and long-term care facilities have the practice of turning the patients every few hours to prevent the incidence of bedsores. If left untreated by removal of necrotized tissue, bedsores can be fatal if they become infected.

The skin can also be affected by pressure associated with rapid growth. A **stretch mark** results when the dermis is stretched beyond its limits of elasticity, as the skin stretches to accommodate the excess pressure. Stretch marks usually accompany rapid weight gain during puberty and pregnancy. They initially have a reddish hue, but lighten over time. Other than for cosmetic

reasons, treatment of stretch marks is not required. They occur most commonly over the hips and abdomen.

Calluses

When you wear shoes that do not fit well and are a constant source of abrasion on your toes, you tend to form a **callus** at the point of contact. This occurs because the basal stem cells in the stratum basale are triggered to divide more often to increase the thickness of the skin at the point of abrasion to protect the rest of the body from further damage. This is an example of a minor or local injury, and the skin manages to react and treat the problem independent of the rest of the body. Calluses can also form on your fingers if they are subject to constant mechanical stress, such as long periods of yard work, writing, playing string instruments, or video games. A corn is a specialized form of callus. Corns form from abrasions on the skin that result from an elliptical-type motion.

Concept Review

Skin cancer is a result of damage to the DNA of skin cells, often due to excessive exposure to UV radiation. Basal cell carcinoma and squamous cell carcinoma are highly curable, and arise from cells in the stratum basale and stratum spinosum, respectively. Melanoma is the most dangerous form of skin cancer, affecting melanocytes, which can spread/metastasize to other organs. Burns are an injury to the skin that occur as a result of exposure to extreme heat, radiation, or chemicals. First-degree and second-degree burns usually heal quickly, but third-degree burns can be fatal because they penetrate the full thickness of the skin. Scars occur when there is repair of skin damage. Fibroblasts generate scar tissue in the form of collagen, which forms a basket-weave pattern that looks different from normal skin.

Bedsores and stretch marks are the result of excessive pressure on the skin and underlying tissue. Bedsores are characterized by necrosis of tissue due to immobility, whereas stretch marks result from rapid growth. Eczema is an allergic reaction that manifests as a rash, and acne results from clogged sebaceous glands. Eczema and acne are usually long-term skin conditions that may be treated successfully in mild cases. Calluses and corns are the result of abrasive pressure on the skin.

Review Questions

Q. In general, skin cancers _____.

A. are easily treatable and not a major health concern

B. occur due to poor hygiene

C. can be reduced by limiting exposure to the sun

D. affect only the epidermis

Answer

Answer: C

Q. Bedsores _____.

A. can be treated with topical moisturizers

B. can result from deep massages

C. are preventable by eliminating pressure points

D. are caused by dry skin

Answer

Answer: C

Q. An individual has spent too much time sun bathing. Not only is his skin painful to touch, but small blisters have appeared in the affected area. This indicates that he has damaged which layers of his skin?

A. epidermis only

B. hypodermis only

C. epidermis and hypodermis

D. epidermis and dermis

Answer

Answer: D

Q. After a skin injury, the body initiates a wound-healing response. The first step of this response is the formation of a blood clot to stop bleeding. Which of the following would be the next response?

A. increased production of melanin by melanocytes

B. increased production of connective tissue

C. an increase in Pacinian corpuscles around the wound

D. an increased activity in the stratum lucidum

Answer

Answer: B

Q. Squamous cell carcinomas are the second most common of the skin cancers and are capable of metastasizing if not treated. This cancer affects which cells?

A. basal cells of the stratum basale

B. melanocytes of the stratum basale

C. keratinocytes of the stratum spinosum

D. Langerhans cells of the stratum lucidum

Answer

Answer: C

Critical Thinking Questions

Q. Why do teenagers often experience acne?

Answer

A. Acne results from a blockage of sebaceous glands by sebum. The blockage causes blackheads to form, which are susceptible to infection. The infected tissue then becomes red and inflamed. Teenagers experience this at high rates because the sebaceous glands become active during puberty. Hormones that are especially active during puberty stimulate the release of sebum, leading in many cases to blockages.

Q. Why do scars look different from surrounding skin?

Answer

A. Scars are made of collagen and do not have the cellular structure of normal skin. The tissue is fibrous and does not allow for the regeneration of accessory structures, such as hair follicles, and sweat or sebaceous glands.

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Glossary

acne
: skin condition due to infected sebaceous glands

basal cell carcinoma
: cancer that originates from basal cells in the epidermis of the skin

bedsore
: sore on the skin that develops when regions of the body start necrotizing due to constant pressure and lack of blood supply; also called decubitis ulcers

callus
: thickened area of skin that arises due to constant abrasion

corn
: type of callus that is named for its shape and the elliptical motion of the abrasive force

eczema
: skin condition due to an allergic reaction, which resembles a rash

first-degree burn
: superficial burn that injures only the epidermis

fourth-degree burn
: burn in which full thickness of the skin and underlying muscle and bone is damaged

keloid
: type of scar that has layers raised above the skin surface

melanoma
: type of skin cancer that originates from the melanocytes of the skin

metastasis
: spread of cancer cells from a source to other parts of the body

scar
: collagen-rich skin formed after the process of wound healing that is different from normal skin

second-degree burn
: partial-thickness burn that injures the epidermis and a portion of the dermis

squamous cell carcinoma
: type of skin cancer that originates from the stratum spinosum of the epidermis

stretch mark
: mark formed on the skin due to a sudden growth spurt and expansion of the dermis beyond its elastic limits

third-degree burn
: burn that penetrates and destroys the full thickness of the skin (epidermis and dermis)

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5: BONE TISSUE AND SKELETAL SYSTEM

5.1: Introduction to Bone Tissue and the Skeletal System

5.2: Functions of the Skeletal System

5.3: Bone Structure

5.4: Bone Formation and Development

5.5: Fractures - Bone Repair

5.6: Exercise, Nutrition, Hormones, and Bone Tissue

5.7: Bone Classification

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5.1: Introduction to Bone Tissue and the Skeletal System

Chapter Learning Objectives

After studying this chapter, you will be able to:

- List and describe the functions of bones
- Describe the classes of bones
- Discuss the process of bone formation and development
- Explain how bone repairs itself after a fracture
- Discuss the effects of exercise, nutrition, and hormones on bone tissues

Bones make good fossils. While the soft tissue of a once living organism will decay and fall away over time, bone tissue will, under the right conditions, undergo a process of mineralization, effectively turning the bone to stone. A well-preserved fossil skeleton can give us a good sense of the size and shape of an organism, just as your skeleton helps to define your size and shape. Unlike a fossil skeleton, however, your skeleton is a structure of living tissue that grows, repairs, and renews itself. The bones within it are dynamic and complex organs that serve a number of important functions, including some necessary to maintain homeostasis.

Figure 5.1.1: Child Looking at Fossils. Bone is a living tissue. Unlike the bones of a fossil made inert by a process of mineralization, a child's bones will continue to grow and develop while contributing to the support and function of other body systems. (Image credit: "Child Looking at Bones" by OpenStax is licensed under CC BY 4.0)

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5.2: Functions of the Skeletal System

By the end of this section, you will be able to:

- Define bone, cartilage, and the skeletal system
- List and describe the functions of the skeletal system

Bone, or **osseous tissue**, is a hardened connective tissue that forms most of the adult skeleton, the support structure of the body. In the areas of the skeleton where bones move (for example, the ribcage and joints), **cartilage**, a semi-rigid form of connective tissue, provides flexibility and smooth surfaces for movement. The **skeletal system** is the body system composed of bones and cartilage and performs the following critical functions for the human body:

- supports the body
- facilitates movement
- protects internal organs
- produces blood cells
- stores and releases minerals and fat

Support, Movement, and Protection

The most apparent functions of the skeletal system are the gross functions—those visible by observation. Simply by looking at a person, you can see how the bones support, facilitate movement, and protect the human body.

Just as the steel beams of a building provide a scaffold to support its weight, the bones and cartilage of your skeletal system compose the scaffold that supports the rest of your body. Without the skeletal system, you would be a limp mass of organs, muscle, and skin.

Bones facilitate movement by serving as points of attachment for your muscles. While some bones only serve as a support for the muscles, others also transmit the forces produced when your muscles contract. From a mechanical point of view, bones act as levers and articulations (where two bones come together, also known as joints) serve as fulcrums. Unless a muscle spans an articulation and contracts, a bone is not going to move. Information on the interactions of the skeletal and muscular systems, that is the musculoskeletal system, will be covered in the upcoming chapters of this book.

Bones also protect internal organs from injury by covering or surrounding them. For example, your ribs protect your lungs and heart, the bones of your vertebral column (spine) protect your spinal cord, and the bones of your cranium (skull) protect your brain (Figure 5.2.1).

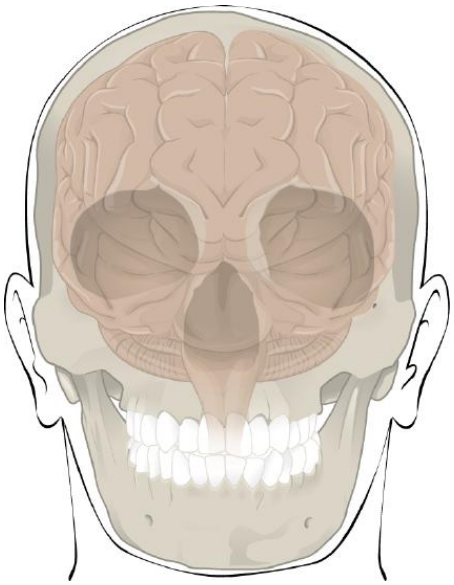

Figure 5.2.1: Bones Protect Brain. The cranium completely surrounds and protects the brain from non-traumatic injury. (Image credit: "Bones Protect Brain" by OpenStax is licensed under CC BY 3.0)

CAREER CONNECTION

Orthopedist

An **orthopedist** is a doctor who specializes in diagnosing and treating disorders and injuries related to the musculoskeletal system. Some orthopedic problems can be treated with medications, exercises, braces, and other devices, but others may be best treated with surgery (Figure 5.2.2).

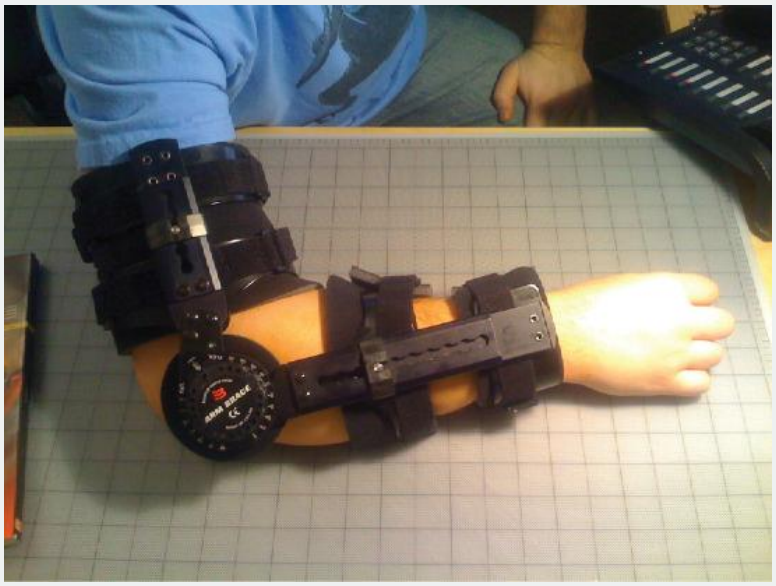

Figure 5.2.2: Arm Brace. An orthopedist will sometimes prescribe the use of a brace that reinforces the underlying bone structure it is being used to support. (Image credit: "Terminator-esque arm brace" by Juhan Sonin is licensed under CC BY 2.0).

While the origin of the word “orthopedics” (ortho- = “straight”; paed- = “child”), literally means “straightening of the child,” orthopedists can have patients who range from pediatric to geriatric. In recent years, orthopedists have even performed prenatal surgery to correct spina bifida, a congenital defect in which the neural canal in the spine of the fetus fails to close completely during embryologic development.

Orthopedists commonly treat bone and joint injuries but they also treat other bone conditions including curvature of the spine. Lateral curvatures (scoliosis) can be severe enough to slip under the shoulder blade (scapula) forcing it up as a hump. Spinal curvatures can also be excessive dorsoventrally (kyphosis) causing a hunch back and thoracic compression. These curvatures often appear in preteens as the result of poor posture, abnormal growth, or indeterminate causes. Mostly, they are readily treated by orthopedists. As people age, accumulated spinal column injuries and diseases like osteoporosis can also lead to curvatures of the spine, hence the stooping you sometimes see in the elderly.

Some orthopedists sub-specialize in sports medicine, which addresses both simple injuries, such as a sprained ankle, and complex injuries, such as a torn rotator cuff in the shoulder. Treatment can range from exercise to surgery.

Mineral Storage, Energy Storage, and Hematopoiesis

On a metabolic level, bone tissue performs several critical functions. For one, the bone matrix acts as a reservoir for a number of minerals important to the functioning of the body, especially calcium, and potassium. These minerals, incorporated into bone tissue, can be released back into the bloodstream to maintain levels needed to support physiological processes. Calcium ions, for example, are essential for muscle contractions and controlling the flow of other ions involved in the transmission of nerve impulses.

Bone also serves as a site for fat storage and blood cell production. The softer connective tissue that fills the interior of most bone is referred to as bone marrow (Figure 5.2.4). There are two types of bone marrow: yellow marrow (deep) and red marrow (superficial). **Yellow marrow** contains adipose tissue; the triglycerides (lipids) stored in the adipocytes of the tissue can serve as a source of energy. **Red marrow** is where **hematopoiesis**—the production of blood cells—takes place. Red blood cells, white blood cells, and platelets are all produced in the red marrow.

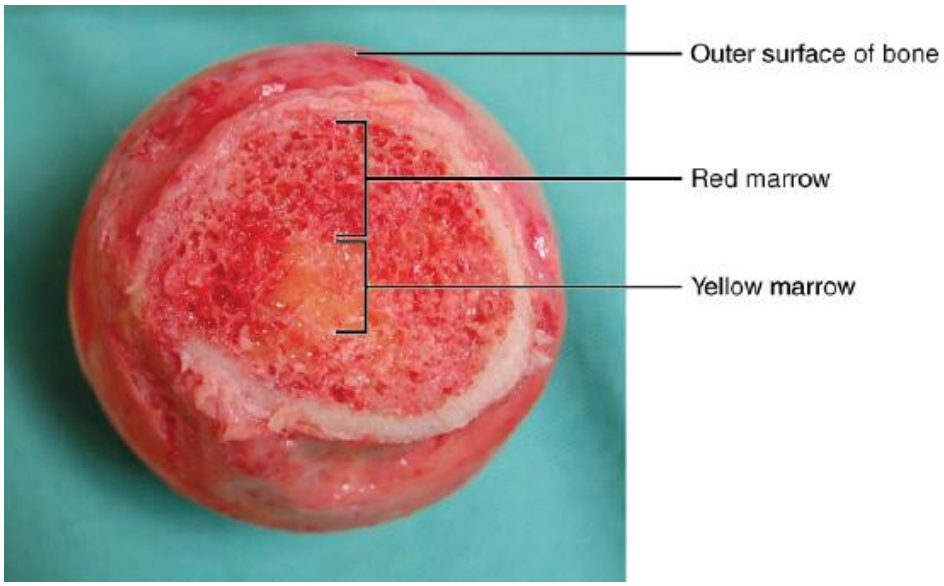

Figure 5.2.3: Head of Femur Showing Red and Yellow Marrow. The head of the femur contains both yellow and red marrow. Yellow marrow stores fat. Red marrow is responsible for hematopoiesis. (Image credit: "Caput femoris cortex medulla" by Stevenfruitsmaak is in the Public Domain, CC0)

Concept Review

The major functions of the bones are body support, facilitation of movement, protection of internal organs, storage of minerals and fat, and hematopoiesis. Together, the muscular system and skeletal system are known as the musculoskeletal system.

Review Questions

Q. Which function of the skeletal system would be especially important if you were in a car accident?

A. storage of minerals

B. protection of internal organs

C. facilitation of movement

D. fat storage

Answer

Answer: B

Q. Bone tissue can be described as _____.

A. dead calcified tissue

B. cartilage

C. the skeletal system

D. hardened connective tissue

Answer

Answer: D

Q. Without red marrow, bones would not be able to _____.

A. store phosphate

B. store calcium

C. facilitate making blood cells

D. move like levers

Answer

Answer: C

Q. Yellow marrow has been identified as _____.

A. an area of fat storage

B. a point of attachment for muscles

C. the hard portion of bone

D. the cause of kyphosis

Answer

Answer: A

Q. Which of the following can be found in areas of movement?

A. hematopoiesis

B. cartilage

C. yellow marrow

D. red marrow

Answer

Answer: B

Q. The skeletal system is primarily made of _____.

A. muscles and tendons

B. bones and cartilage

C. vitreous humor

D. minerals and fat

Answer

Answer: B

Critical Thinking Questions

The skeletal system is composed of bone and cartilage and has many functions. Choose three of its functions and discuss what features of the skeletal system allow it to accomplish these functions.

Answer

Answer:

It supports the body. The rigid, yet flexible skeleton acts as a framework to support the other organs of the body.

It facilitates movement. The skeletal system provides attachment points and moveable joints that allow skeletal muscles to change the shape and positions (move) of the body.

It protects internal organs. Parts of the skeleton enclose or partly enclose various organs of the body including our brain, ears, heart, and lungs. Any trauma to these organs has to be mediated through the skeletal system.

It facilitates blood cell production. The central cavity of long bones is filled with marrow. The red marrow is responsible for forming red and white blood cells.

It stores and releases minerals and fat. The mineral component of bone, in addition to providing hardness to bone, provides a mineral reservoir that can be tapped as needed. Additionally, the yellow marrow, which is found in the central cavity of long bones along with red marrow, serves as a storage site for fat.

Glossary

bone
hard, dense connective tissue that forms the structural elements of the skeleton

cartilage
semi-rigid connective tissue found on the skeleton in areas where flexibility and smooth surfaces support movement

hematopoiesis
production of blood cells, which occurs in the red marrow of the bones

orthopedist
: doctor who specializes in diagnosing and treating musculoskeletal disorders and injuries

osseous tissue
: bone tissue; a hard, dense connective tissue that forms the structural elements of the skeleton

red marrow
: connective tissue in the interior cavity of a bone where hematopoiesis takes place

skeletal system
: organ system composed of bones and cartilage that provides for movement, support, and protection

yellow marrow
: connective tissue in the interior cavity of a bone where fat is stored

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5.3: Bone Structure

By the end of this section, you will be able to:

- Identify the anatomical features of a bone
- Define and list examples of bone markings
- Describe the histology of bone tissue
- Compare and contrast compact and spongy bone
- Identify the structures that compose compact and spongy bone
- Describe how bones are nourished and innervated

Bone tissue (osseous tissue) differs greatly from other tissues in the body. Bone is hard and many of its functions depend on that characteristic hardness. Later discussions in this chapter will show that bone is also dynamic in that its shape adjusts to accommodate stresses. This section will examine the gross anatomy of bone first and then move on to its histology.

Gross Anatomy of Bone

The structure of a long bone allows for the best visualization of all of the parts of a bone (Figure 5.3.1). A long bone has two parts: the **diaphysis** and the **epiphysis**. The diaphysis is the tubular shaft that runs between the proximal and distal ends of the bone. The hollow region in the diaphysis is called the **medullary cavity**, which is filled with yellow marrow. The walls of the diaphysis are composed of dense, hard **compact bone**.

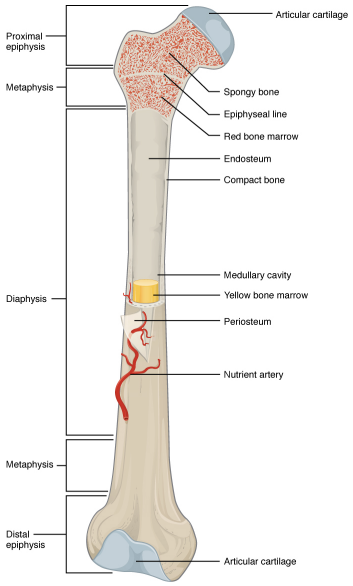

Figure 5.3.1: Anatomy of a Long Bone. A typical long bone shows the gross anatomical characteristics of bone. (Image credit: "Anatomy of a Long Bone" by OpenStax is licensed under CC BY 3.0)

The wider section at each end of the bone is called the epiphysis (plural = epiphyses), which is filled with spongy bone. Red marrow fills the spaces in the spongy bone. Each epiphysis meets the diaphysis at the metaphysis, the narrow area that contains the **epiphyseal plate** (growth plate), a layer of hyaline (transparent) cartilage in a growing bone. When the bone stops growing in early adulthood (approximately 18–21 years), the cartilage is replaced by osseous tissue and the epiphyseal plate becomes an epiphyseal line.

The medullary cavity has a delicate membranous lining called the **endosteum** (end- = “inside”; oste- = “bone”), where bone growth, repair, and remodeling occur. The outer surface of the bone is covered with a fibrous membrane called the **periosteum** (peri- = “around” or “surrounding”). The periosteum consists of two layers; an outer fibrous layer and a deeper cellular layer. Like the endosteum, the periosteum plays a role in bone growth, repair, and remodeling. It contains blood vessels, nerves, and

lymphatic vessels that nourish compact bone, and also serves as a point of attachment for tendons and ligaments. The periosteum covers the entire outer surface except where the epiphyses meet other bones to form joints (Figure 5.3.2). In this region, the epiphyses are covered with **articular cartilage**, a thin layer of hyaline cartilage that reduces friction and acts as a shock absorber.

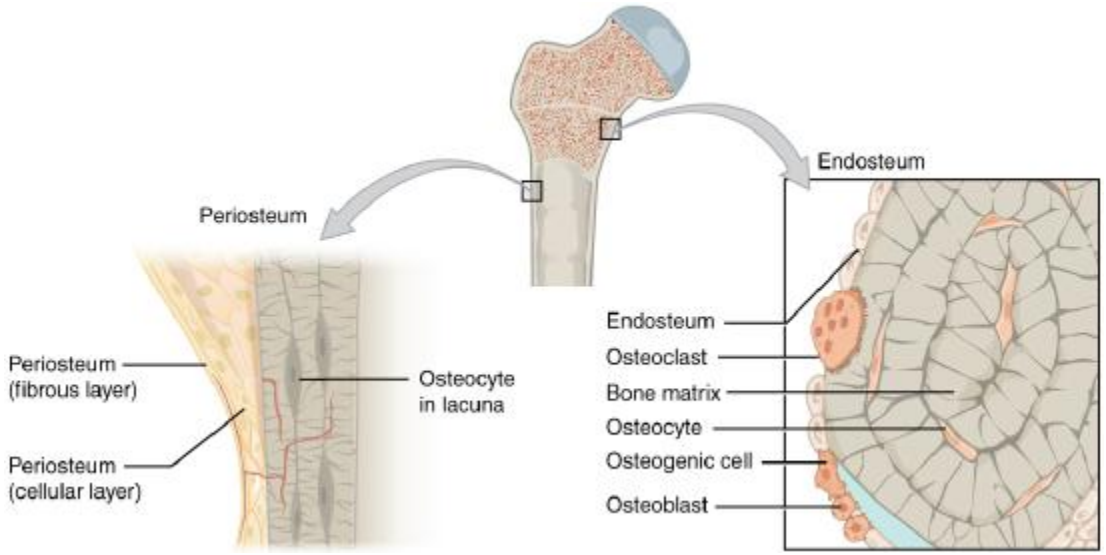

Figure 5.3.2: Periosteum and Endosteum. The periosteum forms the outer surface of bone, and the endosteum lines the medullary cavity. (Image credit: "Periosteum and Endosteum" by OpenStax is licensed under CC BY 3.0)

Flat bones, like those of the cranium, consist of a layer of **diploë** (spongy bone specifically found in skull bones), lined on either side by a layer of compact bone (Figure 5.3.3). The two layers of compact bone and the interior spongy bone work together to protect the internal organs. If the outer layer of a cranial bone fractures, the brain is still protected by the intact inner layer.

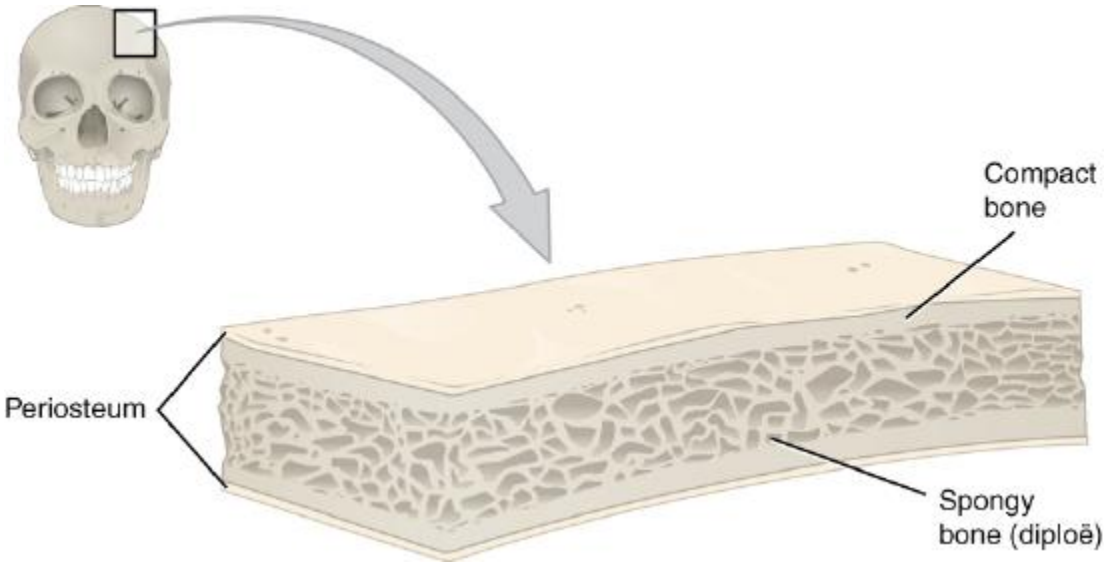

Figure 5.3.3: Anatomy of a Flat Bone. This cross-section of a flat bone shows the spongy bone (diploë) lined on either side by a layer of compact bone. (Image credit: "Anatomy of a Long Bone" by OpenStax is licensed under CC BY 3.0)

Bone Markings

The surface features of bones vary considerably, depending on the function and location in the body. Table 5.3.1 describes the bone markings, which are illustrated in (Figure 5.3.4). There are three general classes of bone markings: (1) articulations, (2) projections, and (3) holes. As the name implies, an **articulation** is where two bone surfaces come together (articulus = "joint"). These surfaces tend to conform to one another, such as one being rounded and the other cupped, to facilitate the function of the articulation. A **projection** is an area of a bone that projects above the surface of the bone. These are the attachment points for

tendons and ligaments. In general, their size and shape is an indication of the forces exerted through the attachment to the bone. A **hole** is an opening or groove in the bone that allows blood vessels and nerves to enter the bone. As with the other markings, their size and shape reflect the size of the vessels and nerves that penetrate the bone at these points.

Table 5.3.1: Bone Markings

Marking	Description	Example
Articulations	**Where two bones meet**	**Knee joint**
Head	Prominent rounded surface	Head of femur
Facet	Flat surface	Superior articular facet of vertebrae
Condyle	Rounded surface	Occipital condyles
Projections	**Raised markings**	**Spinous process of the vertebrae**
Protuberance	Protruding	Chin
Process	Prominence feature	Transverse process of vertebra
Spine	Sharp process	Ischial spine
Tubercle	Small, rounded process	Tubercle of humerus
Tuberosity	Rough surface	Deltoid tuberosity
Line	Slight, elongated ridge	Temporal lines of the parietal bones
Crest	Ridge	Iliac crest
Holes	**Holes and depressions**	**Foramen (holes through which blood vessels can pass through)**
Fossa	Elongated basin	Mandibular fossa
Fovea	Small pit	Fovea capitis on the head of the femur
Sulcus	Groove	Sigmoid sulcus of the temporal bones
Canal	Passage in bone	Auditory canal
Fissure	Slit through bone	Auricular fissure
Foramen	Hole through bone	Foramen magnum in the occipital bone
Meatus	Opening into canal	External auditory meatus
Sinus	Air-filled space in bone	Nasal sinus

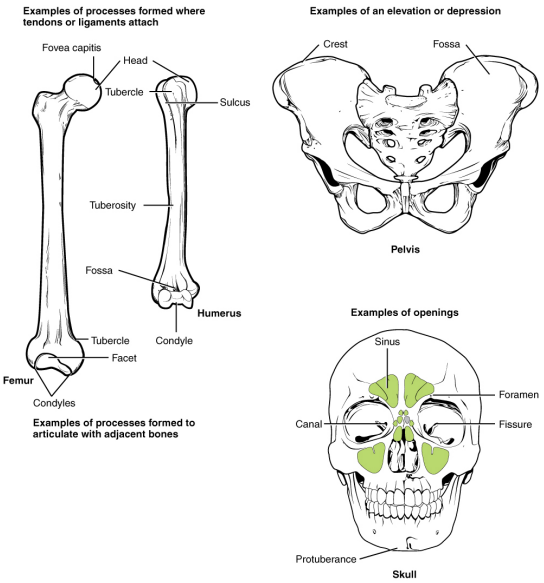

Figure 5.3.4: Bone Features. The surface features of bones depend on their function, location, attachment of ligaments and tendons, or the penetration of blood vessels and nerves. (Image credit: "Bone Markings" by OpenStax is licensed under CC BY 3.0)

Bone Cells and Tissue

Bone contains a relatively small number of cells entrenched in a matrix of collagen fibers that provide a framework to which inorganic salts adhere. These salt crystals form when calcium phosphate and calcium carbonate combine to create hydroxyapatite, which incorporates other inorganic salts like magnesium hydroxide, fluoride, and sulfate as it crystallizes, or calcifies, on the collagen fibers. The hydroxyapatite crystals give bones their hardness and strength, while the collagen fibers give them flexibility so that they are not brittle.

Although bone cells compose a small amount of the bone volume, they are crucial to the function of bones. Four types of cells are found within bone tissue: osteoblasts, osteocytes, osteogenic cells, and osteoclasts (Figure 5.3.5).

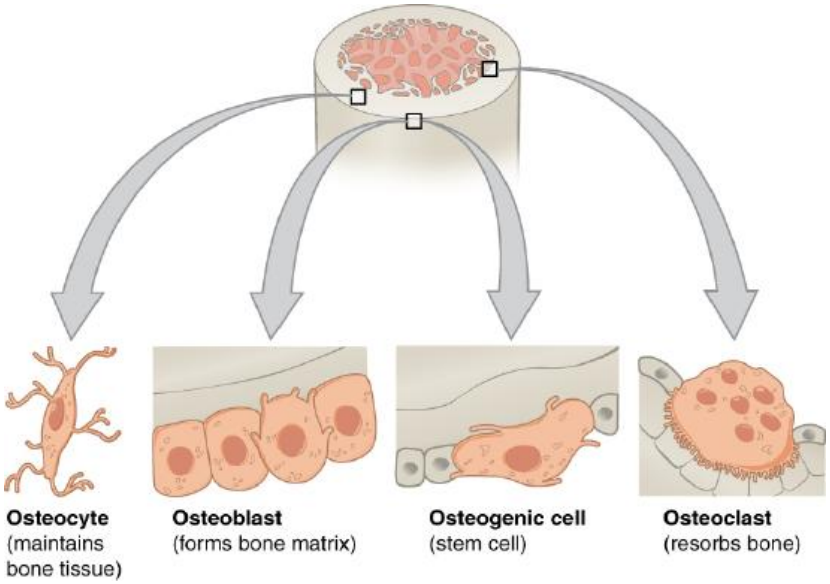

Figure 5.3.5: Bone Cells. Four types of cells are found within bone tissue. Osteogenic cells are undifferentiated and develop into osteoblasts. When osteoblasts get trapped within the calcified matrix, their structure and function changes, and they become osteocytes. Osteoclasts develop from monocytes and macrophages and differ in appearance from other bone cells. (Image credit: "Bone Cells" by OpenStax is licensed under CC BY 3.0)

The **osteoblast** is the bone cell responsible for forming new bone and is found in the growing portions of bone, including the

periosteum and endosteum. Osteoblasts, which do not divide, synthesize and secrete the collagen matrix and calcium salts. As the secreted matrix surrounding the osteoblast calcifies, the osteoblast becomes trapped within it; as a result, it changes in structure and becomes an **osteocyte**, the primary cell of mature bone and the most common type of bone cell. Each osteocyte is located in a space called a **lacuna** and is surrounded by bone tissue. Osteocytes maintain the mineral concentration of the matrix via the secretion of enzymes. Like osteoblasts, osteocytes lack mitotic activity. As osteoblasts differentiate into osteocytes structural changes occur that increase the surface area of the osteocyte cell membrane. Once trapped in lacunae, this increased surface area enables adjacent osteocytes to communicate with each other and receive nutrients via long cytoplasmic processes that extend through **canaliculi** (singular = canaliculus), channels within the bone matrix.

If osteoblasts and osteocytes are incapable of mitosis, then how are they replenished when old ones die? The answer lies in the properties of a third category of bone cells—the **osteogenic cell**. These osteogenic cells are undifferentiated with high mitotic activity and they are the only bone cells that divide. Immature osteogenic cells are found in the deep layers of the periosteum and the endosteum. They differentiate and develop into osteoblasts.

The dynamic nature of bone means that new tissue is constantly formed, and old, injured, or unnecessary bone is dissolved for repair or for calcium release. The cell responsible for bone resorption, or breakdown, is the **osteoclast**. They are found on bone surfaces, are multinucleated, and originate from monocytes and macrophages, two types of white blood cells, not from osteogenic cells. Osteoclasts are continually breaking down old bone while osteoblasts are continually forming new bone. The ongoing balance between osteoblasts and osteoclasts is responsible for the constant but subtle reshaping of bone. Table 5.3.2 reviews the bone cells, their functions, and locations.

Table 5.3.2: Bone Cells

Cell type	Function	Location
Osteogenic cells	Undergo mitosis and develop into osteoblasts	Deep layers of the periosteum and the marrow
Osteoblasts	Bone formation	Growing portions of bone, including periosteum and endosteum
Osteocytes	Maintain mineral concentration of matrix	Entrapped in matrix within lacunae
Osteoclasts	Bone resorption	Bone surfaces and at sites of old, injured, or unneeded bone

Compact and Spongy Bone

The differences between compact and spongy bone are best explored via their histology. Most bones contain compact and spongy osseous tissue, but their distribution and concentration vary based on the bone's overall function. Compact bone is dense so that it can withstand compressive forces, while spongy (cancellous) bone has open spaces and supports shifts in weight distribution.

Compact Bone

Compact bone is the denser, stronger of the two types of bone tissue (Figure 5.3.6). It can be found under the periosteum and in the diaphyses of long bones, where it provides support and protection.

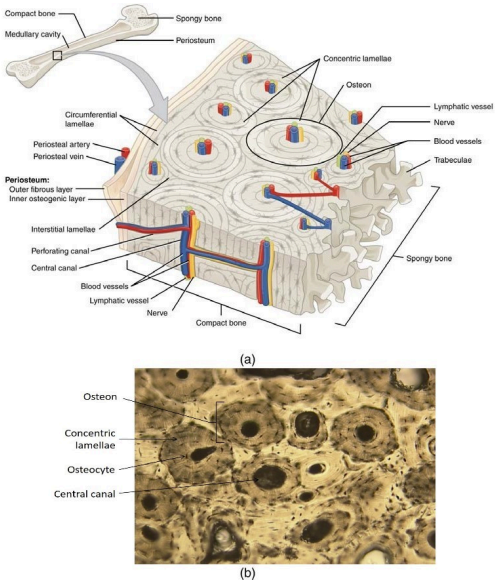

Figure 5.3.6: Diagram of Compact Bone. (a) This cross-sectional view of compact bone shows the basic structural unit, the osteon. (b) In this micrograph of the osteon, you can clearly see the concentric lamellae and central canals. LM × 10. (Image credit: (a) "Diagram of Compact Bone" by OpenStax is licensed under CC BY 3.0 (b) "Compact Bone" by Jennifer MacDonald, Histotechnology Program, Mt. San Antonio College is licensed under CC BY-NC 4.0)

The microscopic structural unit of compact bone is called an **osteon**, or Haversian system. Each osteon is composed of concentric rings of calcified matrix called lamellae (singular = lamella). The arrangement of collagen fibers within each lamella are aligned in a parallel direction that is diagonal with respect to the osteon for added strength in that direction. Then in adjacent lamellae, the directionality of the collagen fibers is perpendicular to those in the first so that when the lamellae are sandwiched together as concentric rings, the alternating pattern conveys triangulated strength to the osteon. Running down the center of each osteon, mostly parallel to the medullary cavity, is the **central canal**, or Haversian canal, which contains blood vessels, nerves, and lymphatic vessels. These vessels and nerves branch off at right angles through a **perforating canal**, also known as Volkmann's canals, to extend to the periosteum and endosteum.

The osteocytes are located inside spaces called lacunae (singular = lacuna), found at the borders of adjacent lamellae. As described earlier, canaliculi radiating out from each lacuna, connect with the canaliculi of other lacunae and eventually with the central canal (Figure 5.3.7). This system allows nutrients to be transported to the osteocytes and wastes to be removed from them.

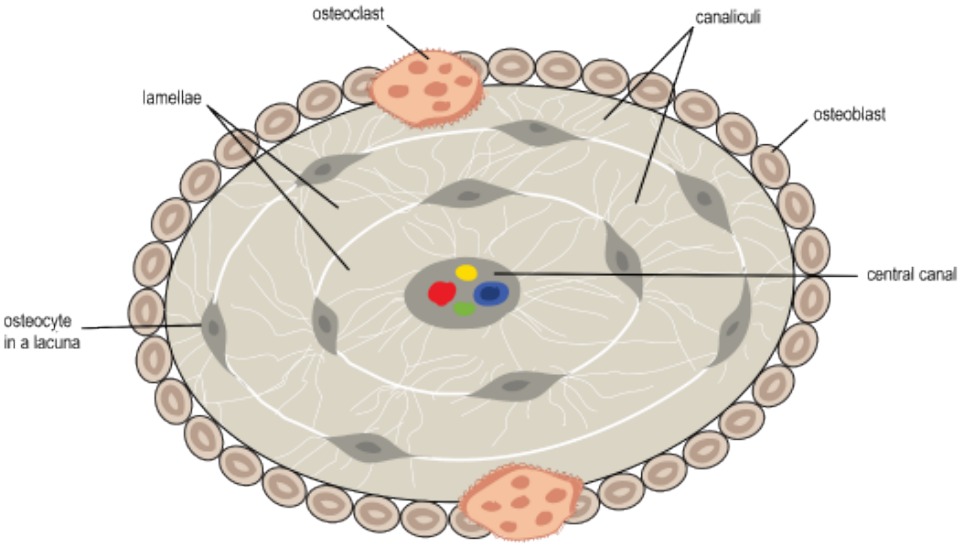

Figure 5.3.7: Diagram of an osteon. The canaliculi allow for nutrients to be transported to all of the osteocytes within an individual osteon. ("Osteon" by Whitney Menefee is a derivative from the original work of Daniel Donnelly and is licensed under CC BY 4.0)

Spongy (Cancellous) Bone

Like compact bone, **spongy bone**, also known as cancellous bone, contains osteocytes housed in lacunae, arranged in concentric lamellae. Unlike the osteons of compact bone, the sets of lamellae do not surround a hollow central canal and they are not arranged in parallel columns alongside each other, but rather in a lattice-like network of matrix spikes called **trabeculae** (singular = trabecula) (Figure 5.3.8). Each trabecula is wrapped in a layer of endosteum. The trabeculae may appear to be a random network, but each trabeculae forms along lines of stress to provide strength to the bone. The spaces of the trabeculated network provide balance to the dense and heavy compact bone by making bones lighter so that muscles can move them more easily. In addition, the spaces in some spongy bones contain red marrow, protected by the trabeculae, where hematopoiesis occurs.

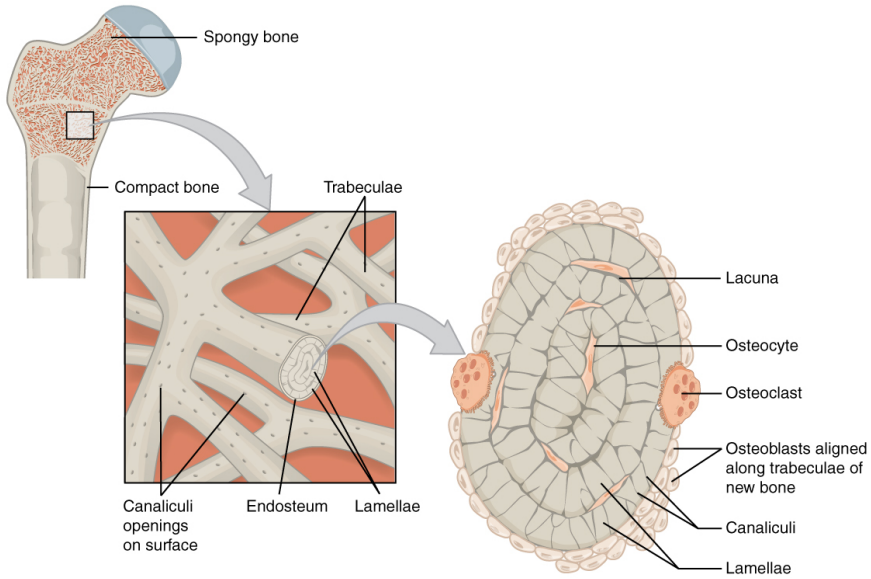

Figure 5.3.8: Diagram of Spongy Bone. Spongy bone is composed of trabeculae that contain the osteocytes. Red marrow fills the spaces in some bones. (Image credit: "Spongy Bone" by OpenStax is licensed under CC BY 3.0)

AGING AND THE....

Skeletal System: Paget's Disease

Paget's disease usually occurs in adults over age 40. It is a disorder of the bone remodeling process that begins with overactive osteoclasts. This means more bone is resorbed than is laid down. The osteoblasts try to compensate but the new bone they lay down is weak and brittle and therefore prone to fracture.

While some people with Paget's disease have no symptoms, others experience pain, bone fractures, and bone deformities (Figure 5.3.9). Bones of the pelvis, skull, spine, and legs are the most commonly affected. When occurring in the skull, Paget's disease can cause headaches and hearing loss.

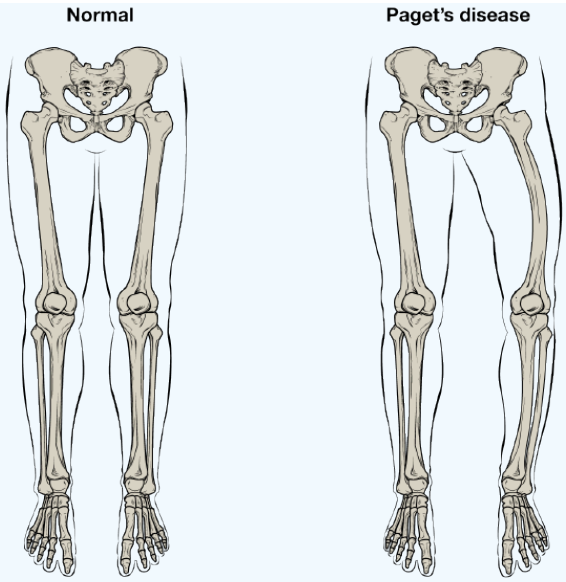

Figure 5.3.9: Paget's Disease. Normal leg bones are relatively straight, but those affected by Paget's disease are porous and curved. (Image credit: "Feature Pagets Disease" by OpenStax is licensed under CC BY 4.0)

What causes the osteoclasts to become overactive? The answer is still unknown, but hereditary factors seem to play a role. Some scientists believe Paget's disease is due to an as-yet-unidentified virus.

Paget's disease is diagnosed via imaging studies and lab tests. X-rays may show bone deformities or areas of bone resorption. Bone scans are also useful. In these studies, a dye containing a radioactive ion is injected into the body. Areas of bone resorption have an affinity for the ion, so they will light up on the scan if the ions are absorbed. In addition, blood levels of an enzyme called alkaline phosphatase are typically elevated in people with Paget's disease.

Bisphosphonates, drugs that decrease the activity of osteoclasts, are often used in the treatment of Paget's disease. However, in a small percentage of cases, bisphosphonates themselves have been linked to an increased risk of fractures because the old bone that is left after bisphosphonates are administered becomes worn out and brittle. Still, most doctors feel that the benefits of bisphosphonates more than outweigh the risk; the medical professional has to weigh the benefits and risks on a case-by-case basis. Bisphosphonate treatment can reduce the overall risk of deformities or fractures, which in turn reduces the risk of surgical repair and its associated complications.

Blood and Nerve Supply

The spongy bone and medullary cavity receive nourishment from three major groups of arteries that pass through the periosteum and compact bone. The nutrient artery enters through the **nutrient foramen**, a small opening in the diaphysis (Figure 5.3.10), where it branches to provide blood supply to the entire diaphysis. At the metaphyseal regions, the metaphyseal arteries enter the bone, while epiphyseal arteries enter and provide blood flow to the epiphyseal regions. As the blood passes through the marrow cavities, it is collected by veins, which then pass out of the bone through the same foramina that the arteries entered through.

In addition to the blood vessels, nerves follow the same paths into the bone where they tend to concentrate in the more metabolically active regions of the bone. The nerves sense pain, and it appears the nerves also play roles in regulating blood supplies and in bone growth, hence their concentrations in metabolically active sites of the bone.

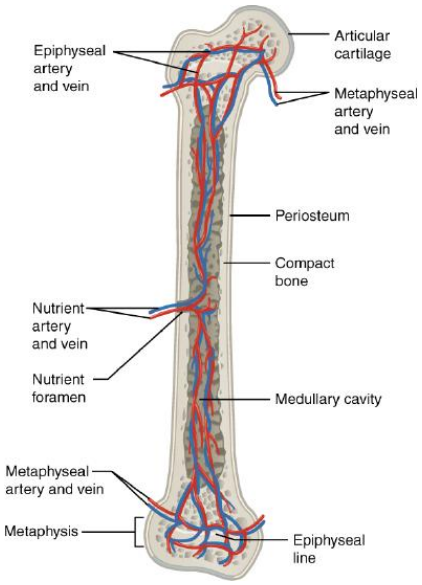

Figure 5.3.10: Diagram of Blood Supply to Bone. Three major groups of blood vessels, the nutrient, metaphyseal, and epiphyseal arteries and veins, supply bones with blood. (Image credit: "Body Supply to the Bone" by OpenStax is licensed under CC BY 3.0)

Concept Review

A hollow medullary cavity filled with yellow marrow runs the length of the diaphysis of a long bone. The walls of the diaphysis are compact bone. The epiphyses, which are wider sections at each end of a long bone, are filled with spongy bone and red marrow. The epiphyseal plate, a layer of hyaline cartilage, is replaced by osseous tissue as the organ grows in length. The medullary cavity has a delicate membranous lining called the endosteum. The outer surface of bone, except in regions covered with articular cartilage, is covered with a fibrous membrane called the periosteum. Flat bones consist of two layers of compact bone surrounding a layer of spongy bone. Bone markings depend on the function and location of bones. Articulations are places where two bones meet. Projections stick out from the surface of the bone and provide attachment points for tendons and ligaments. Holes are openings or depressions in the bones, and can serve as routes for blood vessels and nerves.

Bone matrix consists of collagen fibers and ground substance, primarily hydroxyapatite formed from calcium salts. Osteogenic cells develop into osteoblasts. Osteoblasts are cells that make new bone. They become osteocytes, the cells of mature bone, when they get trapped in the matrix. Osteoclasts engage in bone resorption. Compact bone is dense and composed of osteons, while spongy bone is less dense and made up of trabeculae. Blood vessels and nerves enter the bone through the nutrient foramina to nourish and innervate bones.

Review Questions

Q. Which of the following occurs in the spongy bone of the epiphysis?

A. bone growth

B. bone remodeling

C. hematopoiesis

D. shock absorption

Answer

Answer: C

Q. The fibrous membrane covering the outer surface of the bone is the _____.

A. periosteum

B. epiphysis

C. endosteum

D. diaphysis

Answer

Answer: A

Q. Which of the following are of undergoing mitosis?

A. osteoblasts and osteoclasts

B. osteocytes and osteoclasts

C. osteogenic cells and osteocytes

D. osteogenic cells only

Answer

Answer: D

Q. Which cells do not originate from osteogenic cells?

A. osteoblasts

B. osteoclasts

C. osteocytes

D. osteogenic cells

Answer

Answer: B

Q. Which of the following are *only* found in cancellous bone?

A. canaliculi

B. perforating canals

C. trabeculae

D. calcium salts

Answer

Answer: C

Q. The area of a bone where the nutrient foramen passes forms what kind of bone marking?

A. a hole

B. a facet

C. a canal

D. a fissure

Answer

Answer: A

Critical Thinking Questions

Q. If the articular cartilage at the end of one of your long bones were to degenerate, what symptoms do you think you would experience? Why?

Answer

A. If the articular cartilage at the end of one of your long bones were to deteriorate, which is actually what happens in osteoarthritis, you would experience joint pain at the end of that bone and limitation of motion at that joint because there would be no cartilage to reduce friction between adjacent bones and there would be no cartilage to act as a shock absorber.

Q. In what ways is the structural makeup of compact and spongy bone well suited to their respective functions?

Answer

A. The densely packed concentric rings of matrix in compact bone are ideal for resisting compressive forces, which is the function of compact bone. The open spaces of the trabeculated network of spongy bone allow spongy bone to support shifts in weight distribution, which is the function of spongy bone.

Glossary

articular cartilage
thin layer of cartilage covering an epiphysis; reduces friction and acts as a shock absorber

articulation
where two bone surfaces meet

canaliculi
(singular = canaliculus) channels within the bone matrix that house one of an osteocyte's many cytoplasmic extensions that it uses to communicate and receive nutrients

central canal
longitudinal channel in the center of each osteon; contains blood vessels, nerves, and lymphatic vessels; also known as the Haversian canal

compact bone
dense osseous tissue that can withstand compressive forces

diaphysis
tubular shaft that runs between the proximal and distal ends of a long bone

diploë
layer of spongy bone, that is sandwiched between two the layers of compact bone found in flat bones

endosteum
delicate membranous lining of a bone's medullary cavity

epiphyseal plate
(also, growth plate) sheet of hyaline cartilage in the metaphysis of an immature bone; replaced by bone tissue as the organ grows in length

epiphysis
wide section at each end of a long bone; filled with spongy bone and red marrow

hole
: opening or depression in a bone

lacunae
: (singular = lacuna) spaces in a bone that house an osteocyte

medullary cavity
: hollow region of the diaphysis; filled with yellow marrow

nutrient foramen
: small opening in the middle of the external surface of the diaphysis, through which an artery enters the bone to provide nourishment

osteoblast
: cell responsible for forming new bone

osteoclast
: cell responsible for resorbing bone

osteocyte
: primary cell in mature bone; responsible for maintaining the matrix

osteogenic cell
: undifferentiated cell with high mitotic activity; the only bone cells that divide; they differentiate and develop into osteoblasts

osteon
: (also, Haversian system) basic structural unit of compact bone; made of concentric layers of calcified matrix

perforating canal
: (also, Volkmann's canal) channel that branches off from the central canal and houses vessels and nerves that extend to the periosteum and endosteum

periosteum
: fibrous membrane covering the outer surface of bone and continuous with ligaments

projection
: bone markings where part of the surface sticks out above the rest of the surface, where tendons and ligaments attach

spongy bone
: (also, cancellous bone) trabeculated osseous tissue that supports shifts in weight distribution

trabeculae
: (singular = trabecula) spikes or sections of the lattice-like matrix in spongy bone

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5.4: Bone Formation and Development

By the end of this section, you will be able to:

- Explain the function of cartilage
- List the steps of intramembranous ossification
- List the steps of endochondral ossification
- Explain the growth activity at the epiphyseal plate
- Compare and contrast the processes of modeling and remodeling

In the early stages of embryonic development, the embryo's skeleton consists of fibrous membranes and hyaline cartilage. By the sixth or seventh week of embryonic life, the actual process of bone development, **ossification** (osteogenesis), begins. There are two osteogenic pathways—intramembranous ossification and endochondral ossification—but bone is the same regardless of the pathway that produces it.

Cartilage Templates

Bone is a replacement tissue; that is, it uses a model tissue on which to lay down its mineral matrix. For skeletal development, the most common template is cartilage. During fetal development, a framework is laid down that determines where bones will form. This framework is a flexible, semi-solid matrix produced by chondroblasts and consists of hyaluronic acid, chondroitin sulfate, collagen fibers, and water. As the matrix surrounds and isolates chondroblasts, they are called chondrocytes, which are surrounded by a lacuna. Unlike most connective tissues, cartilage is avascular, meaning that it has no blood vessels supplying nutrients and removing metabolic wastes. These functions are carried on by diffusion through the matrix. This is why damaged cartilage does not repair itself as readily as most tissues do.

Throughout fetal development and into childhood growth and development, bone forms on the cartilaginous matrix. By the time a fetus is born, most of the cartilage has been replaced with bone. Some additional cartilage will be replaced throughout childhood, and some cartilage remains in the adult skeleton.

Intramembranous Ossification

During **intramembranous ossification**, compact and spongy bone develops directly from sheets of mesenchymal (undifferentiated) connective tissue. The flat bones of the face, most of the cranial bones, and the clavicles (collarbones) are formed via intramembranous ossification.

The process begins when mesenchymal cells in the embryonic skeleton gather together and begin to differentiate into specialized cells (Figure $5.4.1.a$). Some of these cells differentiate and form the tissues of capillaries, while others will become osteogenic cells and then osteoblasts. Although they will ultimately be spread out by the formation of bone tissue, early osteoblasts appear in a cluster called an **ossification center**.

The osteoblasts secrete **osteoid**, uncalcified matrix, which calcifies (hardens) within a few days as mineral salts are deposited on it, thereby entrapping the osteoblasts within. Once entrapped, the osteoblasts become osteocytes (Figure $5.4.1.b$). As osteoblasts transform into osteocytes, osteogenic cells in the surrounding connective tissue differentiate into new osteoblasts.

Osteoid (unmineralized bone matrix) secreted around the capillaries results in a trabecular matrix. At the surfaces of the forming osseus tissue mesenchymal cells differentiate into fibroblasts which surround the forming structure with fibrous periosteum while osteoblasts, osteoclasts and osteogenic cells form the cellular (osteogenic) layer. (Figure $5.4.1.c$). The periosteum then creates a protective layer of compact bone superficial to the trabecular bone. The trabecular bone crowds nearby blood vessels, which eventually condense into red marrow (Figure $5.4.1.d$).

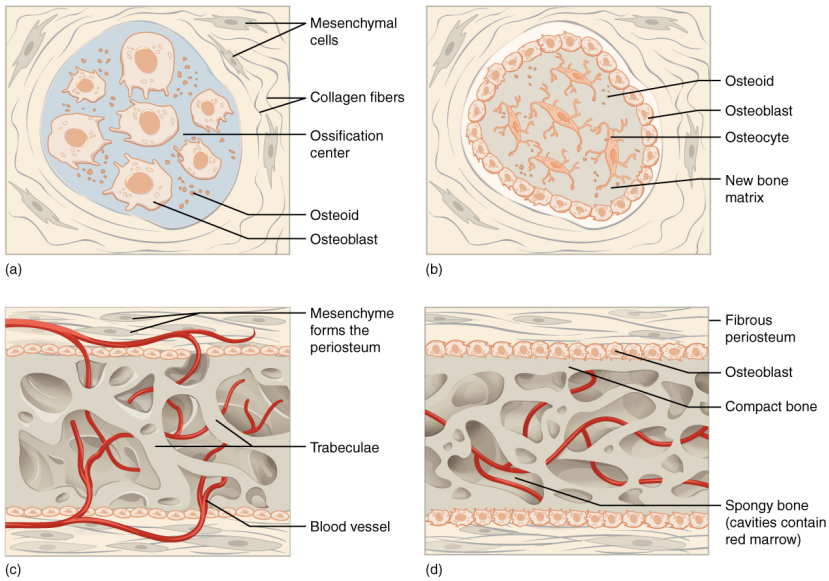

Figure 5.4.1: Intramembranous Ossification. Intramembranous ossification follows four steps. (a) Mesenchymal cells group into clusters, and ossification centers form. (b) Secreted osteoid traps osteoblasts, which then become osteocytes. (c) Trabecular matrix and periosteum form. (d) Compact bone develops superficial to the trabecular bone, and crowded blood vessels condense into red marrow.(Image credit: "Intramembraneous Ossification" by OpenStax is licensed under CC BY 3.0)

Intramembranous ossification begins *in utero* during fetal development and continues on into adolescence. At birth, the skull and clavicles are not fully ossified nor are the sutures of the skull closed. This allows the skull and shoulders to deform during passage through the birth canal. The last bones to ossify via intramembranous ossification are the flat bones of the face, which reach their adult size at the end of the adolescent growth spurt.

Endochondral Ossification

In **endochondral ossification**, bone develops by *replacing* hyaline cartilage. Cartilage does not become bone. Instead, cartilage serves as a template to be completely replaced by new bone. Endochondral ossification takes much longer than intramembranous ossification. Bones at the base of the skull and long bones are examples of bones that form via endochondral ossification.

In a long bone, for example, at about 6 to 8 weeks after conception, some of the mesenchymal cells differentiate into chondrocytes (cartilage cells) that form the cartilaginous skeletal precursor of the bones (Figure 5.4.2.a). Soon after, cellular differentiation produces cells that form the **perichondrium**, a membrane that covers the cartilage (Figure 5.4.2.b).

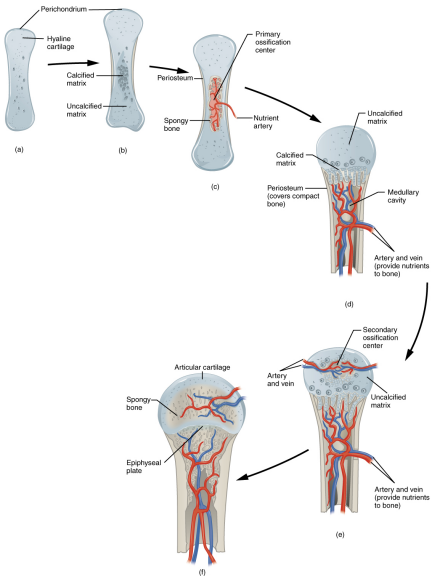

Figure 5.4.2: Endochondral Ossification. Endochondral ossification follows five steps. (a) Mesenchymal cells differentiate into chondrocytes. (b) The cartilage model of the future bony skeleton and the perichondrium form. (c) Capillaries penetrate cartilage. Perichondrium transforms into periosteum. Periosteal collar develops. Primary ossification center develops. (d) Cartilage and chondrocytes continue to grow at ends of the bone. (e) Secondary ossification centers develop. (f) Cartilage remains at epiphyseal (growth) plate and at joint surface as articular cartilage. (Image credit: "Endochondral Ossification" by OpenStax is licensed under CC BY 3.0)

As more matrix is produced, the chondrocytes in the center of the cartilaginous model grow in size. As the matrix calcifies, nutrients can no longer reach the chondrocytes. This results in their death and the disintegration of the surrounding cartilage. Blood vessels invade the resulting spaces, not only enlarging the cavities but also carrying osteogenic cells with them, many of which will become osteoblasts. These enlarging spaces eventually combine to become the medullary cavity.

This invasion of blood vessels initiates the transformation of the perichondrium into the bone-producing periosteum. Here, the osteoblasts form a periosteal collar of compact bone around the cartilage of the diaphysis. By the second or third month of fetal life, bone cell development and ossification ramps up and creates the **primary ossification center**, a region deep in the periosteal collar where ossification begins (Figure 5.4.2.*c*).

While these deep changes are occurring, chondrocytes and cartilage continue to grow at the ends of the bone (the future epiphyses), which increases the bone's length at the same time bone is replacing cartilage in the diaphyses. By the time the fetal skeleton is fully formed, cartilage only remains at the joint surface as articular cartilage and between the diaphysis and epiphysis as the epiphyseal plate, the latter of which is responsible for the longitudinal growth of bones. After birth, this same sequence of events (matrix mineralization, death of chondrocytes, invasion of blood vessels from the periosteum, and seeding with osteogenic cells that become osteoblasts) occurs in the epiphyseal regions, and each of these centers of activity is referred to as a **secondary ossification center** (Figure 5.4.2.*e*).

How Bones Grow in Length

The epiphyseal plate is the area of growth in a long bone. It is a layer of hyaline cartilage where ossification occurs in immature bones. On the epiphyseal side of the epiphyseal plate, cartilage is formed. On the diaphyseal side, cartilage is ossified, and the diaphysis grows in length. The epiphyseal plate is composed of four zones of cells and activity (Figure 5.4.3). The **reserve zone** is the region closest to the epiphyseal end of the plate and contains small chondrocytes within the matrix. These chondrocytes do not participate in bone growth but secure the epiphyseal plate to the osseous tissue of the epiphysis.

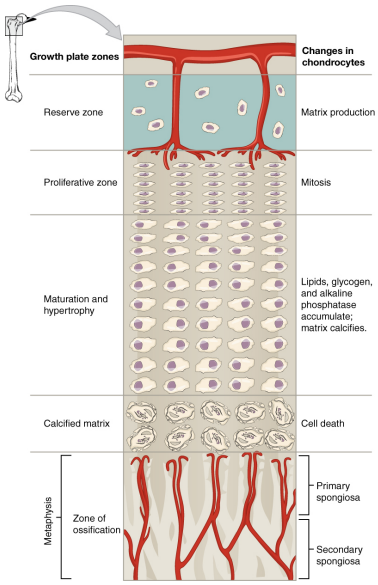

Figure 5.4.3: Longitudinal Bone Growth. The epiphyseal plate is responsible for longitudinal bone growth. (Image credit: "Longitudinal Bone Growth" by OpenStax is licensed under CC BY 3.0)

The **proliferative zone** is the next layer toward the diaphysis and contains stacks of slightly larger chondrocytes. It makes new chondrocytes (via mitosis) to replace those that die at the diaphyseal end of the plate. Chondrocytes in the next layer, the **zone of maturation and hypertrophy**, are older and larger than those in the proliferative zone. The more mature cells are situated closer to the diaphyseal end of the plate. The longitudinal growth of bone is a result of cellular division in the proliferative zone and the maturation of cells in the zone of maturation and hypertrophy.

Most of the chondrocytes in the **zone of calcified matrix**, the zone closest to the diaphysis, are dead because the matrix around them has calcified. Capillaries and osteoblasts from the diaphysis penetrate this zone, and the osteoblasts secrete bone tissue on the remaining calcified cartilage. Thus, the zone of calcified matrix connects the epiphyseal plate to the diaphysis. A bone grows in length when osseous tissue is added to the diaphysis.

Bones continue to grow in length until early adulthood. The rate of growth is controlled by hormones, which will be discussed later. When the chondrocytes in the epiphyseal plate cease their proliferation and bone replaces the cartilage, longitudinal growth stops. All that remains of the epiphyseal plate is the **epiphyseal line** (Figure 5.4.4).

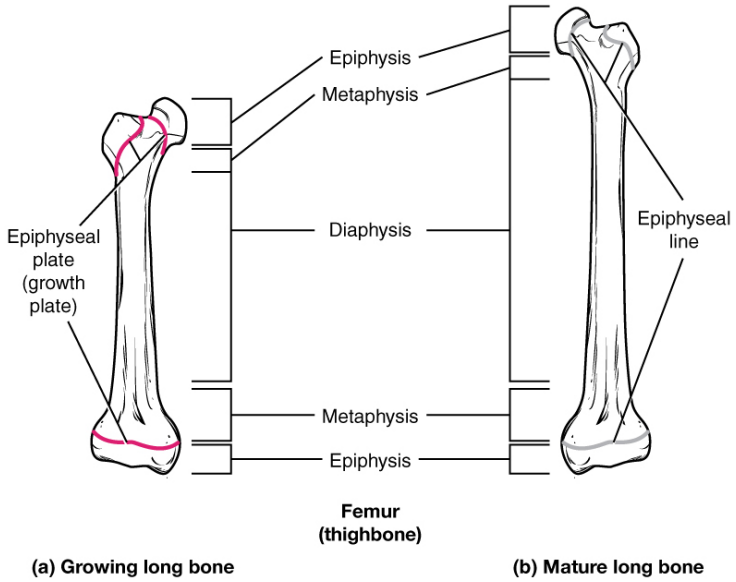

Figure 5.4.4: Progression from Epiphyseal Plate to Epiphyseal Line. As a bone matures, the epiphyseal plate progresses to an epiphyseal line. (a) Epiphyseal plates are visible in a growing bone. (b) Epiphyseal lines are the remnants of epiphyseal plates in a mature bone. (Image credit: "Epiphyseal Plate-Line" by OpenStax is licensed under CC BY 3.0)

How Bones Grow in Diameter

While bones are increasing in length, they are also increasing in diameter; growth in diameter can continue even after longitudinal growth ceases. This is called appositional growth (Figure 5.4.5). Osteoclasts resorb old bone that lines the medullary cavity, while osteoblasts produce new bone tissue beneath the periosteum. The erosion of old bone along the medullary cavity and the deposition of new bone beneath the periosteum not only increase the diameter of the diaphysis but also increase the diameter of the medullary cavity. This process is called **modeling**.

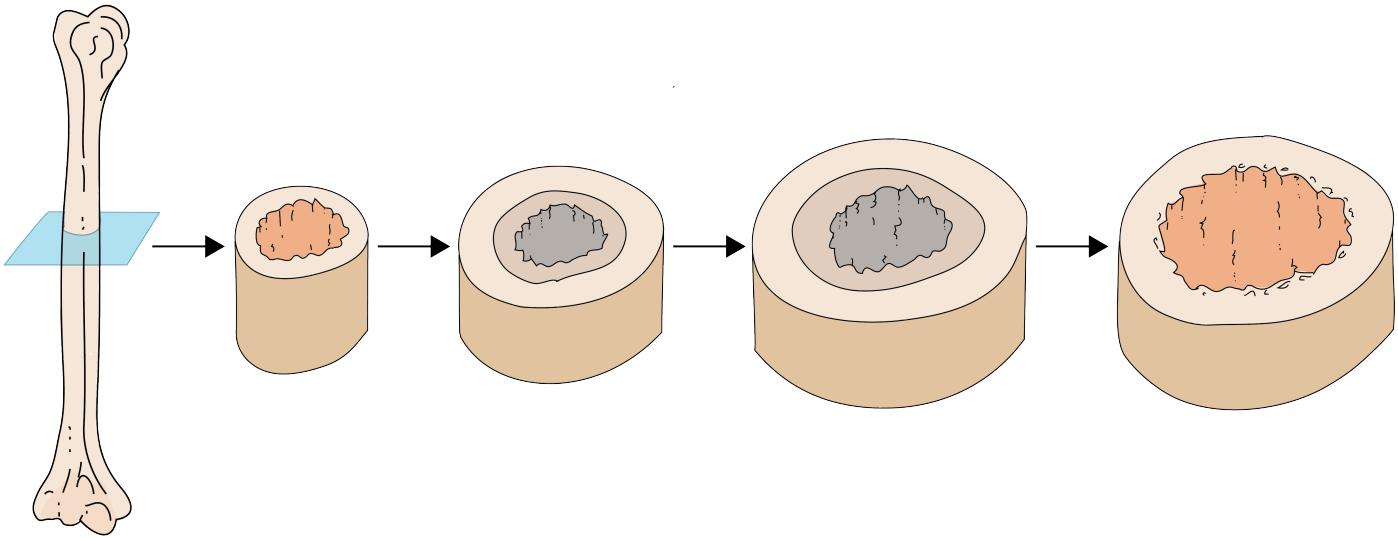

Figure 5.4.5: Appositional Growth. Growth in the diameter of a bone is known as appositional growth. Both osteoblasts and osteoclasts are active during the process of remodeling. ("Appositional Growth" by Daniel Donnelly is licensed under CC BY 4.0)

Bone Remodeling

The process in which matrix is resorbed on one surface of a bone and deposited on another is known as bone modeling. Modeling primarily takes place during a bone's growth. However, in adult life, bone undergoes **remodeling**, in which resorption of old or damaged bone takes place on the same surface where osteoblasts lay new bone to replace that which is resorbed. Injury, exercise, and other activities lead to remodeling. Those influences are discussed later in the chapter, but even without injury or exercise, about 5 to 10 percent of the skeleton is remodeled annually by destroying old bone and renewing it with fresh bone.

DISEASES OF THE...

Skeletal System

Osteogenesis imperfecta (OI) is a genetic disease in which bones do not form properly and therefore are fragile and break easily. It is also called *brittle bone disease*. The disease is present from birth and affects a person throughout life.

The genetic mutation that causes OI affects the body's production of collagen, one of the critical components of bone matrix. The severity of the disease can range from mild to severe. Those with the most severe forms of the disease sustain many more fractures than those with a mild form. Frequent and multiple fractures typically lead to bone deformities and short stature. Bowing of the long bones and curvature of the spine are also common in people afflicted with OI. Curvature of the spine makes breathing difficult because the lungs are compressed.

Because collagen is such an important structural protein in many parts of the body, people with OI may also experience fragile skin, weak muscles, loose joints, easy bruising, frequent nosebleeds, brittle teeth, blue sclera, and hearing loss. There is no known cure for OI. Treatment focuses on helping the person retain as much independence as possible

while minimizing fractures and maximizing mobility. Toward that end, safe exercises, like swimming, in which the body is less likely to experience collisions or compressive forces, are recommended. Braces to support legs, ankles, knees, and wrists are used as needed. Canes, walkers, or wheelchairs can also help compensate for weaknesses.

When bones do break, casts, splints, or wraps are used. In some cases, metal rods may be surgically implanted into the long bones of the arms and legs. Research is currently being conducted on using bisphosphonates to treat OI. Smoking and being overweight are especially risky in people with OI, since smoking is known to weaken bones, and extra body weight puts additional stress on the bones.

Concept Review

All bone formation is a replacement process. Embryos develop a cartilaginous skeleton and various membranes. During development, these are replaced by bone during the ossification process. In intramembranous ossification, bone develops directly from sheets of mesenchymal connective tissue. In endochondral ossification, bone develops by replacing hyaline cartilage. Activity in the epiphyseal plate enables bones to grow in length. Modeling allows bones to grow in diameter. Remodeling occurs as bone is resorbed and replaced by new bone. Osteogenesis imperfecta is a genetic disease in which collagen production is altered, resulting in fragile, brittle bones.

Review Questions

Q. Why is cartilage slow to heal?

A. because it eventually develops into bone

B. because it is semi-solid and flexible

C. because it does not have a blood supply

D. because endochondral ossification replaces all cartilage with bone

Answer

Answer: C

Q. Why are osteocytes spread out in bone tissue?

A. They develop from mesenchymal cells.

B. They are surrounded by osteoblasts.

C. They travel through the capillaries.

D. Formation of osteoid spreads out the osteoblasts that formed the ossification centers.

Answer

Answer: D

Q. In endochondral ossification, what happens to the chondrocytes?

A. They develop into osteocytes.

B. They die in the calcified matrix that surrounds them and form the medullary cavity.

C. They grow and form the periosteum.

D. They group together to form the primary ossification center.

Answer

Answer: B

Q. Which of the following bones is (are) formed by intramembranous ossification?

A. the metatarsals

B. the femur

C. the ribs

D. the flat bones of the cranium

Answer

Answer: D

Q. Bones grow in length due to activity in the _____.

A. epiphyseal plate

B. perichondrium

C. periosteum

D. medullary cavity

Answer

Answer: A

Q. Bones grow in diameter due to bone formation _____.

A. in the medullary cavity

B. beneath the periosteum

C. in the epiphyseal plate

D. within the metaphysis

Answer

Answer: B

Q. Which of the following represents the correct sequence of zones in the epiphyseal plate?

A. proliferation, reserved, maturation, calcification

B. maturation, proliferation, reserved, calcification

C. calcification, maturation, proliferation, reserved

D. calcification, reserved, proliferation, maturation

Answer

Answer: C

Critical Thinking Questions

Q. In what ways do intramembranous and endochondral ossification differ?

Answer

A. In intramembranous ossification, bone develops directly from sheets of mesenchymal connective tissue, but in endochondral ossification, bone develops by replacing hyaline cartilage. Intramembranous ossification is complete by the end of the adolescent growth spurt, while endochondral ossification lasts into young adulthood. The flat bones of the face, most of the cranial bones, and a good deal of the clavicles (collarbones) are formed via intramembranous ossification, while bones at the base of the skull and the long bones form via endochondral ossification.

Q. Considering how a long bone develops, what are the similarities and differences between a primary and a secondary ossification center?

Answer

A. A single primary ossification center is present, during endochondral ossification, deep in the periosteal collar. Like the primary ossification center, secondary ossification centers are present during endochondral ossification, but they form later, and there are two of them, one in each epiphysis.

Glossary

endochondral ossification
process in which bone forms by replacing hyaline cartilage

epiphyseal line
completely ossified remnant of the epiphyseal plate

intramembranous ossification
process by which bone forms directly from mesenchymal tissue

modeling
process, during bone growth, by which bone is resorbed on one surface of a bone and deposited on another

ossification
(also, osteogenesis) bone formation

ossification center
cluster of osteoblasts found in the early stages of intramembranous ossification

osteoid
uncalcified bone matrix secreted by osteoblasts

perichondrium
membrane that covers cartilage

primary ossification center
region, deep in the periosteal collar, where bone development starts during endochondral ossification

proliferative zone
region of the epiphyseal plate that makes new chondrocytes to replace those that die at the diaphyseal end of the plate and contributes to longitudinal growth of the epiphyseal plate

remodeling
process by which osteoclasts resorb old or damaged bone at the same time as and on the same surface where osteoblasts form new bone to replace that which is resorbed

reserve zone
region of the epiphyseal plate that anchors the plate to the osseous tissue of the epiphysis

secondary ossification center
region of bone development in the epiphyses

zone of calcified matrix
region of the epiphyseal plate closest to the diaphyseal end; functions to connect the epiphyseal plate to the diaphysis

zone of maturation and hypertrophy
region of the epiphyseal plate where chondrocytes from the proliferative zone grow and mature and contribute to the longitudinal growth of the epiphyseal plate

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5.5: Fractures - Bone Repair

By the end of this section, you will be able to:

- Differentiate among the different types of fractures
- Describe the steps involved in bone repair

A **fracture** is a broken bone. It will heal whether or not a physician resets it in its anatomical position. If the bone is not reset correctly, the healing process will keep the bone in its deformed position. When a broken bone is manipulated and set into its natural position without surgery, the procedure is called a **closed reduction**. **Open reduction** requires surgery to expose the fracture and reset the bone. While some fractures can be minor, others are quite severe and result in grave complications. For example, a fractured diaphysis of the femur has the potential to release fat globules into the bloodstream. These can become lodged in the capillary beds of the lungs, leading to respiratory distress and if not treated quickly, death.

Types of Fractures

Fractures are classified by their complexity, location, and other features (Figure 5.5.1). Table 5.5.1 outlines common types of fractures. Some fractures may be described using more than one term because it may have the features of more than one type (e.g., an open transverse fracture).

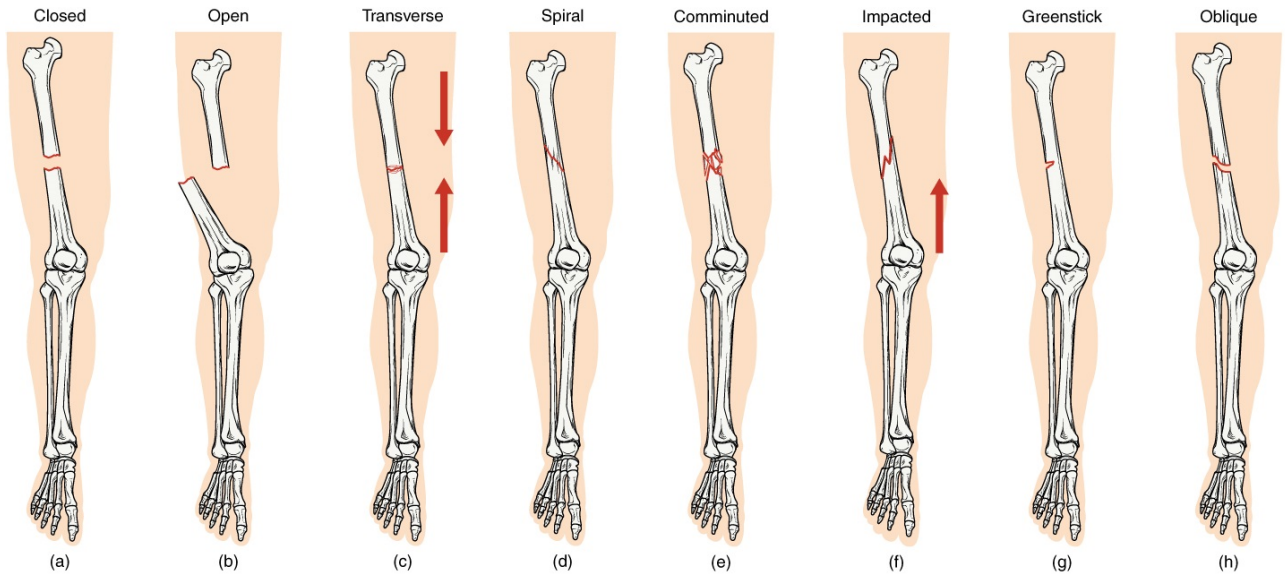

Figure 5.5.1: Types of Fractures. Compare healthy bone with different types of fractures: (a) closed fracture, (b) open fracture, (c) transverse fracture, (d) spiral fracture, (e) comminuted fracture, (f) impacted fracture, (g) greenstick fracture, and (h) oblique fracture. (Image credit: "Types of Fractures" by OpenStax is licensed under CC BY 3.0)

Table 5.5.1: Types of Fractures

Type of fracture	Description
Transverse	Occurs straight across the long axis of the bone
Oblique	Occurs at an angle that is not 90 degrees
Spiral	Bone segments are pulled apart as a result of a twisting motion
Comminuted	Several breaks result in many small pieces between two large segments
Impacted	One fragment is driven into the other, usually as a result of compression

Type of fracture	Description
Greenstick	A partial fracture in which only one side of the bone is broken
Open (or compound)	A fracture in which at least one end of the broken bone tears through the skin; carries a high risk of infection
Closed (or simple)	A fracture in which the skin remains intact

Bone Repair

When a bone breaks, blood flows from any vessel torn by the fracture. These vessels could be in the periosteum, osteons, and/or medullary cavity. The blood begins to clot, and about six to eight hours after the fracture, the clotting blood has formed a **fracture hematoma** (Figure $5.5.2.a$). The disruption of blood flow to the bone results in the death of bone cells around the fracture.

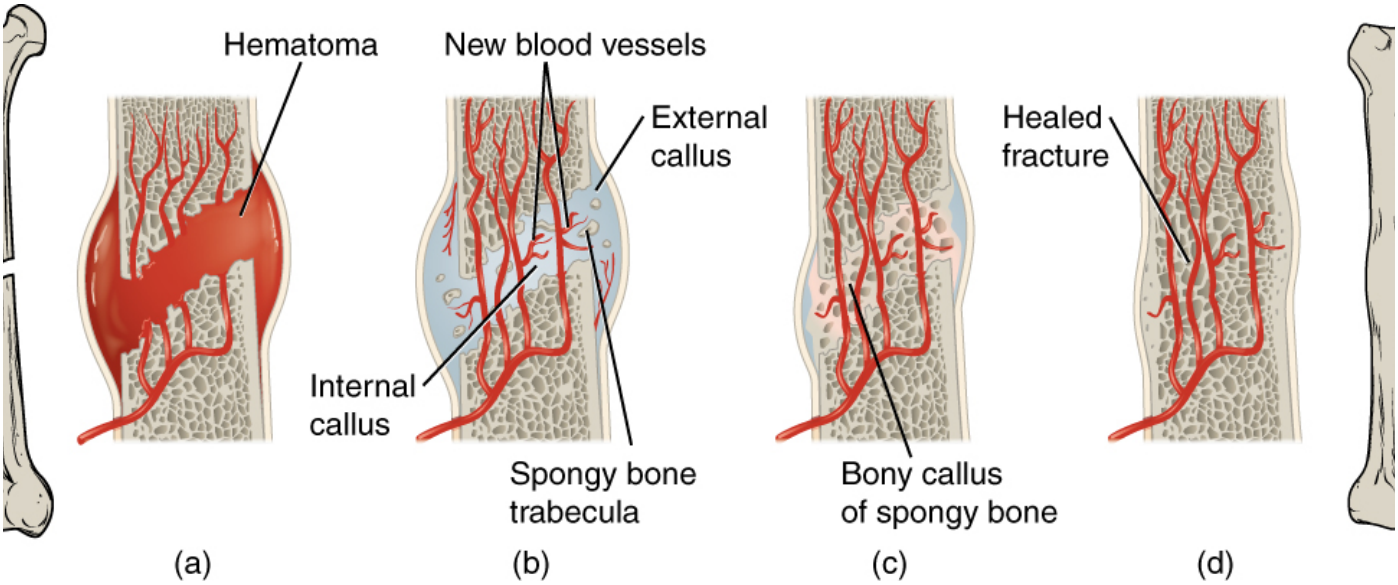

Figure $5.5.2$: Stages in Fracture Repair. The healing of a bone fracture follows a series of progressive steps: (a) A fracture hematoma forms. (b) Internal and external calli form. (c) Cartilage of the calli is replaced by trabecular bone. (d) Remodeling occurs. (Image credit: "Stages of Fracture Repair" by OpenStax is licensed under CC BY 3.0)

Within about 48 hours after the fracture, chondrocytes from the endosteum have created an **internal callus** (plural = calli) by secreting a fibrocartilaginous matrix between the two ends of the broken bone, while the periosteal chondrocytes and osteoblasts create an **external callus** of hyaline cartilage and bone, respectively, around the outside of the break (Figure $5.5.2.b$). This stabilizes the fracture.

Over the next several weeks, osteoclasts resorb the dead bone; osteogenic cells become active, divide, and differentiate into osteoblasts. The cartilage in the calli is replaced by trabecular bone via endochondral ossification (Figure $5.5.2.c$).

Eventually, the internal and external calli unite, compact bone replaces spongy bone at the outer margins of the fracture, and healing is complete. A slight swelling may remain on the outer surface of the bone, but quite often, that region undergoes remodeling (Figure $5.5.2$.d), and no external evidence of the fracture remains.

Concept Review

Fractured bones may be repaired by closed reduction or open reduction. Fractures are classified by their complexity, location, and other features. Common types of fractures are transverse, oblique, spiral, comminuted, impacted, greenstick, open (or compound), and closed (or simple). Healing of fractures begins with the formation of a hematoma, followed by internal and external calli. Osteoclasts resorb dead bone, while osteoblasts create new bone that replaces the cartilage in the calli. The calli eventually unite, remodeling occurs, and healing is complete.

Review Questions

Q. A fracture can be both _____.

A. open and closed

B. open and transverse

C. transverse and greenstick

D. greenstick and comminuted

Answer

Answer: B

Q. How can a fractured diaphysis release fat globules into the bloodstream?

A. The bone pierces fat stores in the skin.

B. The yellow marrow in the diaphysis is exposed and damaged.

C. The injury triggers the body to release fat from healthy bones.

D. The red marrow in the fractured bone releases fat to heal the fracture.

Answer

Answer: B

Q. In a compound fracture, _____.

A. the break occurs at an angle to the bone

B. the broken bone does not tear the skin

C. one fragment of broken bone is compressed into the other

D. broken bone pierces the skin

Answer

Answer: D

Q. The internal and external calli are replaced by _____.

A. hyaline cartilage

B. trabecular bone

C. osteogenic cells

D. osteoclasts

Answer

Answer: B

Q. The first type of bone to form during fracture repair is _____ bone.

A. compact

B. lamellar

C. spongy

D. dense

Answer

Answer: C

Critical Thinking Questions

Q. What is the difference between closed reduction and open reduction? In what type of fracture would closed reduction most likely occur? In what type of fracture would open reduction most likely occur?

Answer

A. In closed reduction, the broken ends of a fractured bone can be reset without surgery. Open reduction requires surgery to return the broken ends of the bone to their correct anatomical position. A partial fracture would likely require closed reduction. A compound fracture would require open reduction.

Q. In terms of origin and composition, what are the differences between an internal callus and an external callus?

Answer

A. The internal callus is produced by cells in the endosteum and is composed of a fibrocartilaginous matrix. The external callus is produced by cells in the periosteum and consists of hyaline cartilage and bone.

Glossary

closed reduction
: manual manipulation of a broken bone to set it into its natural position without surgery

external callus
: collar of hyaline cartilage and bone that forms around the outside of a fracture

fracture
: broken bone

fracture hematoma
: blood clot that forms at the site of a broken bone

internal callus
: fibrocartilaginous matrix, in the endosteal region, between the two ends of a broken bone

open reduction
: surgical exposure of a bone to reset a fracture

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5.6: Exercise, Nutrition, Hormones, and Bone Tissue

By the end of this section, you will be able to:

- Describe the effect exercise has on bone tissue
- List the nutrients that affect bone health
- Discuss the role those nutrients play in bone health
- Describe the effects of hormones on bone tissue

All of the organ systems of your body are interdependent, and the skeletal system is no exception. The food you take in via your digestive system and the hormones secreted by your endocrine system affect your bones. Even using your muscles to engage in exercise has an impact on your bones.

Exercise and Bone Tissue

During long space missions, astronauts can lose approximately 1 to 2 percent of their bone mass per month. This loss of bone mass is thought to be caused by the lack of mechanical stress on astronauts' bones due to the low gravitational forces in space. Lack of mechanical stress causes bones to lose mineral salts and collagen fibers, and thus strength. Similarly, mechanical stress stimulates the deposition of mineral salts and collagen fibers. The internal and external structure of a bone will change as stress increases or decreases so that the bone is an ideal size and weight for the amount of activity it endures. That is why people who exercise regularly have thicker bones than people who are more sedentary. It is also why a broken bone in a cast atrophies while its contralateral mate maintains its concentration of mineral salts and collagen fibers. Bones undergo remodeling as a result of forces (or lack of forces) placed on them.

Numerous, controlled studies have demonstrated that people who exercise regularly have greater bone density than those who are more sedentary. Any type of exercise will stimulate the deposition of more bone tissue, but resistance training has a greater effect than cardiovascular activities. Resistance training is especially important to slow down the eventual bone loss due to aging and for preventing osteoporosis.

Nutrition and Bone Tissue

The vitamins and minerals contained in the food we consume are important for all of our organ systems. However, there are certain nutrients that affect bone health.

Calcium and Vitamin D

You already know that calcium is a critical component of bone, especially in the form of calcium phosphate and calcium carbonate. Since the body cannot make calcium, it must be obtained from the diet. However, calcium cannot be absorbed from the small intestine without vitamin D. Therefore, intake of vitamin D is also critical to bone health. In addition to vitamin D's role in calcium absorption, it also plays a role in the reabsorption of calcium in the kidneys, though not as clearly understood, in bone remodeling.

Milk and other dairy foods are not the only sources of calcium. This important nutrient is also found in green leafy vegetables, broccoli, and intact salmon and canned sardines with their soft bones. Nuts, beans, seeds, and shellfish provide calcium in smaller quantities.

Except for fatty fish like salmon and tuna, or fortified milk or cereal, vitamin D is not found naturally in many foods. The action of sunlight on the skin triggers the body to produce its own vitamin D (Figure $5.6.1$), but many people, especially those of darker complexion and those living in northern latitudes where the sun's rays are not as strong, are deficient in vitamin D. In cases of deficiency, a doctor can prescribe a vitamin D supplement.

Figure $5.6.1$ shows a simplified version of vitamin D synthesis. As mentioned above, there are two major ways the human body can obtain vitamin D, either through sunlight or food. Once sunlight is absorbed by the skin, vitamin D is manufactured there and

can enter the bloodstream. If vitamin D is ingested through food and/or supplements, it is absorbed by the small intestine and enters the bloodstream. From the bloodstream vitamin D is delivered to either the liver or the kidneys. If vitamin D reaches the liver, it is converted into 25(OH)D (calcidiol), the primary form of circulating vitamin D. In the kidneys, vitamin D is transformed into 1,25(OH)D_2 (calcitriol), a biologically active form of vitamin D. Both forms of vitamin D then facilitate calcium absorption from the small intestine, calcium reabsorption from the kidneys, and the rebuilding of bone tissue.

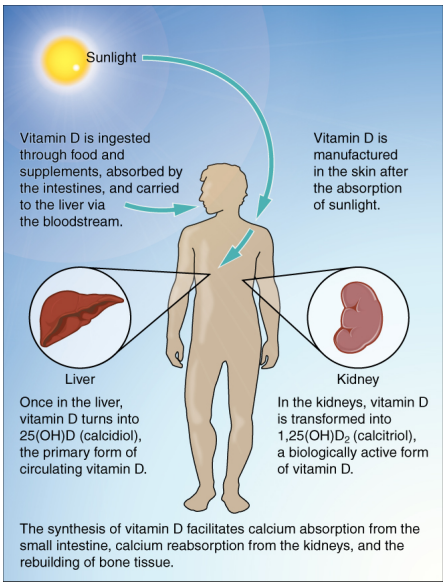

Figure 5.6.1: Synthesis of Vitamin D. Sunlight and food are sources of vitamin D. (Image credit: "Synthesis of Vitamin D" by OpenStax is licensed under CC BY 3.0)

Other Nutrients

Vitamin K also supports bone mineralization and may have a synergistic role with vitamin D in the regulation of bone growth. Green leafy vegetables are a good source of vitamin K. The minerals magnesium and fluoride may also play a role in supporting bone health. While magnesium is only found in trace amounts in the human body, more than 60 percent of it is in the skeleton, suggesting it plays a role in the structure of bone. Fluoride can displace the hydroxyl group in bone's hydroxyapatite crystals and form fluorapatite. Similar to its effect on dental enamel, fluorapatite helps stabilize and strengthen bone minerals. Fluoride can also enter spaces within hydroxyapatite crystals, thus increasing their density.

Omega-3 fatty acids have long been known to reduce inflammation in various parts of the body. Inflammation can interfere with the function of osteoblasts, so consuming omega-3 fatty acids, in the diet or in supplements, may also help enhance production of new osseous tissue. Table 5.6.1 summarizes the role of nutrients in bone health.

Table 5.6.1: Nutrients and Bone Health

Nutrient	Role in bone health
Calcium	Needed to make calcium phosphate and calcium carbonate, which form the hydroxyapatite crystals that give bone its hardness
Vitamin D	Needed for calcium absorption
Vitamin K	Supports bone mineralization; may have synergistic effect with vitamin D
Magnesium	Structural component of bone
Fluoride	Structural component of bone
Omega-3 fatty acids	Reduces inflammation that may interfere with osteoblast function

Hormones and Bone Tissue

The endocrine system produces and secretes hormones, many of which interact with the skeletal system. These hormones are involved in controlling bone growth, maintaining bone once it is formed, and remodeling it.

Hormones That Influence Osteoblasts and/or Maintain the Matrix

Several hormones are necessary for controlling bone growth and maintaining the bone matrix. The pituitary gland secretes growth hormone (GH), which, as its name implies, controls bone growth in several ways. It triggers chondrocyte proliferation in epiphyseal plates, resulting in the increasing length of long bones. GH also increases calcium retention, which enhances mineralization, and stimulates osteoblastic activity, which improves bone density.

GH is not alone in stimulating bone growth and maintaining osseous tissue. Thyroxine, a hormone secreted by the thyroid gland promotes osteoblastic activity and the synthesis of bone matrix. During puberty, the sex hormones (estrogen from the ovaries, testosterone from the testes) also come into play. They too promote osteoblastic activity and production of bone matrix, and in addition, are responsible for the growth spurt that often occurs during adolescence. They also promote the conversion of the epiphyseal plate to the epiphyseal line (i.e., cartilage to its bony remnant), thus bringing an end to the longitudinal growth of bones. Additionally, calcitriol, the active form of vitamin D, is produced by the kidneys and stimulates the absorption of calcium and phosphate from the digestive tract.

AGING AND THE...

Skeletal System

Osteoporosis is a disease characterized by a decrease in bone mass that occurs when the rate of bone resorption exceeds the rate of bone formation, a common occurrence as the body ages. Notice how this is different from Paget's disease. In Paget's disease, new bone is formed in an attempt to keep up with the resorption by the overactive osteoclasts, but that new bone is produced haphazardly. In fact, when a physician is evaluating a patient with thinning bone, they will test for osteoporosis and *Paget's disease* (as well as other diseases). Osteoporosis does not have the elevated blood levels of alkaline phosphatase found in Paget's disease.

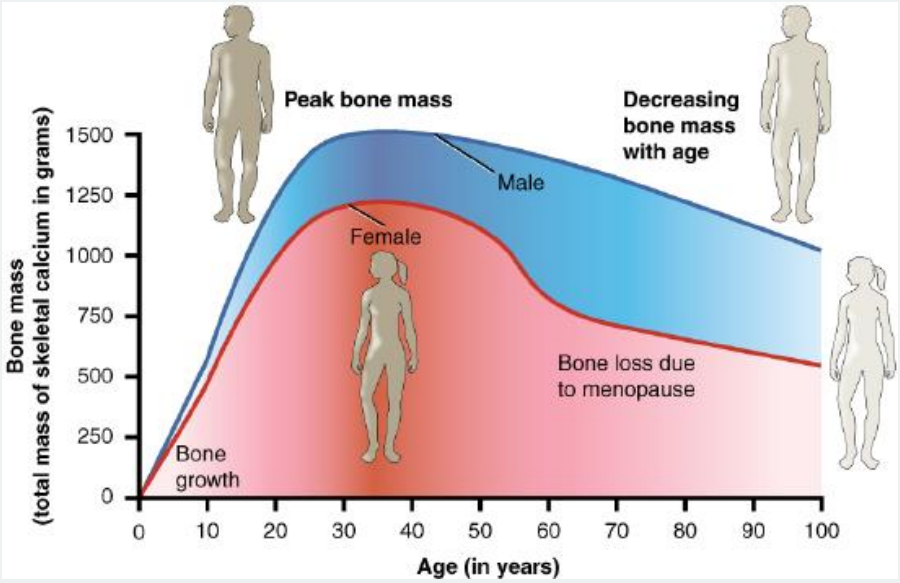

Figure 5.6.2: Graph Showing Relationship Between Age and Bone Mass. Bone density peaks at about 30 years of age. Females lose bone mass more rapidly than males. (Image credit: "Age and Bone Mass" by OpenStax is licensed under CC BY 3.0)

While osteoporosis can involve any bone, it most commonly affects the proximal ends of the femur, vertebra, and wrist. As a result of the loss of bone density, the osseous tissue may not provide adequate support for everyday functions, and something as simple as a sneeze can cause a vertebral fracture. When an elderly person falls and breaks a hip (really, the femur), it is very likely the femur that broke first, which resulted in the fall. Histologically, osteoporosis is characterized by a reduction in the thickness of compact bone and the number and size of trabeculae in cancellous bone.

Figure 5.6.2 shows bone mass (total mass of skeletal calcium in grams) peaks around 30 years of age for both males and females. Females lose bone mass more quickly than males starting at about 50 years of age. This occurs because 50 is the approximate age at which females go through menopause. Not only do their menstrual periods lessen and eventually cease, but their ovaries reduce in size and then cease the production of estrogen, a hormone that promotes osteoblastic activity and production of bone matrix. Thus, osteoporosis is more common in females than in males, but males can develop it, too. Anyone with a family history of osteoporosis has a greater risk of developing the disease, so the best treatment is prevention, which should start with a childhood diet that includes adequate intake of calcium and vitamin D and a lifestyle that includes weight-bearing exercise. These actions, as discussed above, are important in building bone mass. Promoting proper nutrition and weight-bearing exercise early in life can maximize bone mass before the age of 30, thus reducing the risk of osteoporosis.

For many elderly people, a hip fracture can be life threatening. The fracture itself may not be serious, but the immobility that comes during the healing process can lead to the formation of blood clots that can lodge in the capillaries of the lungs, resulting in respiratory failure; pneumonia due to the lack of poor air exchange that accompanies immobility; pressure sores (bed sores) that allow pathogens to enter the body and cause infections; and urinary tract infections from catheterization.

Current treatments for managing osteoporosis include bisphosphonates (the same medications often used in Paget's disease), calcitonin, and estrogen (for women only). Minimizing the risk of falls, for example, by removing tripping hazards, is also an important step in managing the potential outcomes from the disease.

Hormones That Influence Osteoclasts

Bone modeling and remodeling require osteoclasts to resorb unneeded, damaged, or old bone, and osteoblasts to lay down new bone. Two hormones that affect the osteoclasts are parathyroid hormone (PTH) and calcitonin. These two hormones are released in response to blood calcium levels that are too low or too high and their effects are targeted at maintaining homeostatic blood calcium.

PTH stimulates osteoclast proliferation and activity. As a result, calcium is released from the bones into the circulation, thus increasing the calcium ion concentration in the blood. PTH also promotes the reabsorption of calcium by the kidney tubules, which can affect calcium homeostasis (see below).

The small intestine is also affected by PTH, albeit indirectly. Because another function of PTH is to stimulate the synthesis of vitamin D, and because vitamin D promotes intestinal absorption of calcium, PTH indirectly increases calcium uptake by the small intestine. Calcitonin, a hormone secreted by the thyroid gland, has some effects that counteract those of PTH. Calcitonin inhibits osteoclast activity and stimulates calcium uptake by the bones, thus reducing the concentration of calcium ions in the blood. As evidenced by their opposing functions in maintaining calcium homeostasis, PTH and calcitonin are generally *not* secreted at the same time. Table 5.6.2 summarizes the hormones that influence the skeletal system.

Table 5.6.2: Hormones That Affect the Skeletal System

Hormone	Role
Growth hormone	Increases length of long bones, enhances mineralization, and improves bone density
Thyroxine	Stimulates bone growth and promotes synthesis of bone matrix
Sex hormones	Promote osteoblastic activity and production of bone matrix; responsible for adolescent growth spurt; promote conversion of epiphyseal plate to epiphyseal line
Calcitriol	Stimulates absorption of calcium and phosphate from digestive tract
Parathyroid hormone	Stimulates osteoclast proliferation and resorption of bone by osteoclasts; promotes reabsorption of calcium by kidney tubules; indirectly increases calcium absorption by small intestine

Hormone	Role
Calcitonin	Inhibits osteoclast activity and stimulates calcium uptake by bones

Concept Review

Mechanical stress stimulates the deposition of mineral salts and collagen fibers within bones. Calcium, the predominant mineral in bone, cannot be absorbed from the small intestine if vitamin D is lacking. Vitamin K supports bone mineralization and may have a synergistic role with vitamin D. Magnesium and fluoride, as structural elements, play a supporting role in bone health. Omega-3 fatty acids reduce inflammation and may promote production of new osseous tissue. Growth hormone increases the length of long bones, enhances mineralization, and improves bone density. Thyroxine stimulates bone growth and promotes the synthesis of bone matrix. The sex hormones (estrogen from the ovaries, testosterone from the testes) promote osteoblastic activity and the production of bone matrix, are responsible for the adolescent growth spurt, and promote closure of the epiphyseal plates. Osteoporosis is a disease characterized by decreased bone mass that is common in aging adults. Calcitriol stimulates the digestive tract to absorb calcium and phosphate. Parathyroid hormone (PTH) stimulates osteoclast proliferation and resorption of bone by osteoclasts. Vitamin D plays a synergistic role with PTH in stimulating the osteoclasts. Additional functions of PTH include promoting reabsorption of calcium by kidney tubules and indirectly increasing calcium absorption from the small intestine. Calcitonin inhibits osteoclast activity and stimulates calcium uptake by bones.

Review Questions

Q. Calcium cannot be absorbed from the small intestine if _____ is lacking.

A. vitamin D

B. vitamin K

C. calcitonin

D. fluoride

Answer

Answer: A

Q. Which one of the following foods is best for bone health?

A. carrots

B. liver

C. leafy green vegetables

D. oranges

Answer

Answer: C

Q. Which of the following hormones are responsible for the adolescent growth spurt?

A. estrogen and testosterone

B. calcitonin and calcitriol

C. growth hormone and parathyroid hormone

D. thyroxine and progesterone

Answer

Answer: A

Q. With respect to their direct effects on osseous tissue, which pair of hormones has actions that oppose each other?

A. estrogen and testosterone

B. calcitonin and calcitriol

C. estrogen and progesterone

D. calcitonin and parathyroid hormone

Answer

Answer: D

Critical Thinking Questions

Q. If you were a dietician who had a young female patient with a family history of osteoporosis, what foods would you suggest she include in her diet? Why?

Answer

A. Since maximum bone mass is achieved by age 30, I would want this patient to have adequate calcium and vitamin D in her diet. To do this, I would recommend ingesting milk and other dairy foods, green leafy vegetables, and intact canned sardines so she receives sufficient calcium. Intact salmon would be a good source for calcium and vitamin D. Other fatty fish would also be a good vitamin D source.

Q. During the early years of space exploration our astronauts, who had been floating in space, would return to earth showing significant bone loss dependent on how long they were in space. Discuss how this might happen and what could be done to alleviate this condition.

Answer

A. Astronauts floating in space were not exerting significant pressure on their bones; they were “weightless.” Without the force of gravity exerting pressure on the bones, bone mass was lost. To alleviate this condition, astronauts now do resistive exercise designed to apply forces to the bones and thus help keep them healthy.

Glossary

osteoporosis
: disease characterized by a decrease in bone mass; occurs when the rate of bone resorption exceeds the rate of bone formation, a common occurrence as the body ages

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5.7: Bone Classification

By the end of this section, you will be able to:

- Classify bones according to their shapes
- Describe the function of each category of bones

The 206 bones that compose the adult skeleton are divided into five categories based on their shapes (Figure 5.7.1). Their shapes and their functions are related such that each categorical shape of bone has a distinct function.

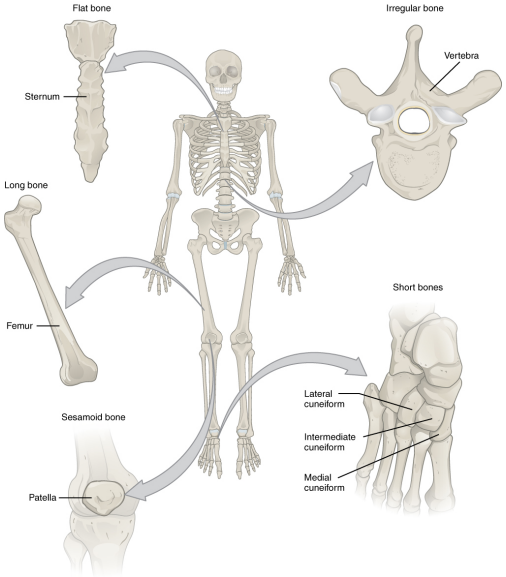

Figure 5.7.1: Classifications of Bones. Bones are classified according to their shape. (Image credit: "Bone Classification" by OpenStax is licensed under CC BY 3.0)

Long Bones

A **long bone** is one that is cylindrical in shape, being longer than it is wide. Keep in mind, however, that the term describes the shape of a bone, not its size. Long bones are found in the arms (humerus, ulna, radius) and legs (femur, tibia, fibula), as well as in the hands (metacarpals, phalanges) and feet (metatarsals, phalanges). Long bones function as levers; they move when muscles contract.

Short Bones

A **short bone** is one that is cube-like in shape, being approximately equal in length, width, and thickness. The only short bones in the human skeleton are in the carpals of the wrists and the tarsals, such as the lateral cuneiform, intermediate cuneiform, and medial cuneiform, of the ankles. Short bones provide stability and support as well as some limited motion.

Flat Bones

The term "**flat bone**" is somewhat of a misnomer because, although a flat bone is typically thin, it is also often curved. Examples include the cranial (skull) bones, the scapulae (shoulder blades), the sternum (breastbone), and the ribs. Flat bones serve as points of attachment for muscles and often protect internal organs.

Irregular Bones

An **irregular bone** is one that does not have any easily characterized shape and therefore does not fit any other classification. These bones tend to have more complex shapes, like the vertebrae that support the spinal cord and protect it from compressive forces. Many facial bones, particularly the ones containing sinuses, are classified as irregular bones. While most irregular bones function to protect internal organs, because each is irregular in its own way, there is no one general function that fits this class of bones.

Sesamoid Bones

A **sesamoid bone** is a small, round bone that, as the name suggests, is shaped like a sesame seed. These bones form in tendons (the sheaths of tissue that connect bones to muscles) where a great deal of pressure is generated in a joint. The sesamoid bones protect tendons by helping them overcome compressive forces. Sesamoid bones vary in number and placement from person to person but are typically found in tendons associated with the feet, hands, and knees. The patellae (singular = patella) are the only sesamoid bones found in common with every person. Table 5.7.1 reviews bone classifications with their associated features, functions, and examples.

Table 5.7.1: Bone Classifications

Bone classification	Features	Function(s)	Examples
Long	Cylinder-like shape, longer than it is wide	Leverage	Femur, tibia, fibula, metatarsals, humerus, ulna, radius, metacarpals, phalanges
Short	Cube-like shape, approximately equal in length, width, and thickness	Provide stability, support, while allowing for some motion	Carpals, tarsals
Flat	Thin and curved	Points of attachment for muscles; protectors of internal organs	Sternum, ribs, scapulae, cranial bones
Irregular	Complex shape	Protect internal organs	Vertebrae, facial bones
Sesamoid	Small and round; embedded in tendons	Protect tendons from compressive forces	Patellae

Concept Review

Bones can be classified according to their shapes. Long bones, such as the femur, are longer than they are wide. Short bones, such as the carpals, are approximately equal in length, width, and thickness. Flat bones are thin, but are often curved, such as the ribs. Irregular bones such as those of the face have no characteristic shape. Sesamoid bones, such as the patellae, are small and round, and are located in tendons.

Review Questions

Q. Most of the bones of the arms and hands are long bones; however, the bones in the wrist are categorized as _____.

A. flat bones

B. short bones

C. sesamoid bones

D. irregular bones

Answer

Answer: B

Q. Sesamoid bones are found embedded in _____.

A. joints

B. muscles

C. ligaments

D. tendons

Answer

Answer: D

Q. Bones that surround the spinal cord are classified as _____ bones.

A. irregular

B. sesamoid

C. flat

D. short

Answer

Answer: A

Q. Which category of bone is among the most numerous in the skeleton?

A. long bone

B. sesamoid bone

C. short bone

D. flat bone

Answer

Answer: A

Q. Long bones enable body movement by acting as a _____.

A. counterweight

B. resistive force

C. lever

D. fulcrum

Answer

Answer: C

Critical Thinking Questions

Q. What are the structural and functional differences between a tarsal and a metatarsal?

Answer

A. Structurally, a tarsal is a short bone, meaning its length, width, and thickness are about equal, while a metatarsal is a long bone whose length is greater than its width. Functionally, the tarsal provides limited motion, while the metatarsal acts as a lever.

Q. What are the structural and functional differences between the femur and the patella?

Answer

A. Structurally, the femur is a long bone, meaning its length is greater than its width, while the patella, a sesamoid bone, is small and round. Functionally, the femur acts as a lever, while the patella protects the patellar tendon from compressive forces.

Glossary

flat bone
thin and curved bone; serves as a point of attachment for muscles and protects internal organs

irregular bone
bone of complex shape; protects internal organs from compressive forces

long bone
cylinder-shaped bone that is longer than it is wide; functions as a lever

sesamoid bone
small, round bone embedded in a tendon; protects the tendon from compressive forces

short bone
cube-shaped bone that is approximately equal in length, width, and thickness; provides limited motion

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6: AXIAL SKELETON

6.1: Introduction to the Skeleton System
6.2: Divisions of the Skeletal System
6.3: The Skull
6.4: The Vertebral Column
6.5: The Thoracic Cage
6.6: Embryonic Development of the Axial Skeleton

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6.1: Introduction to the Skeleton System

Chapter Learning Objectives

After studying this chapter, you will be able to:

- Describe the functions of the skeletal system and define its two major subdivisions
- Identify the bones and bony structures of the skull, the cranial suture lines, the cranial fossae, and the openings in the skull
- Discuss the vertebral column and regional variations in its bony components and curvatures
- Describe the components of the thoracic cage
- Discuss the embryonic development of the axial skeleton

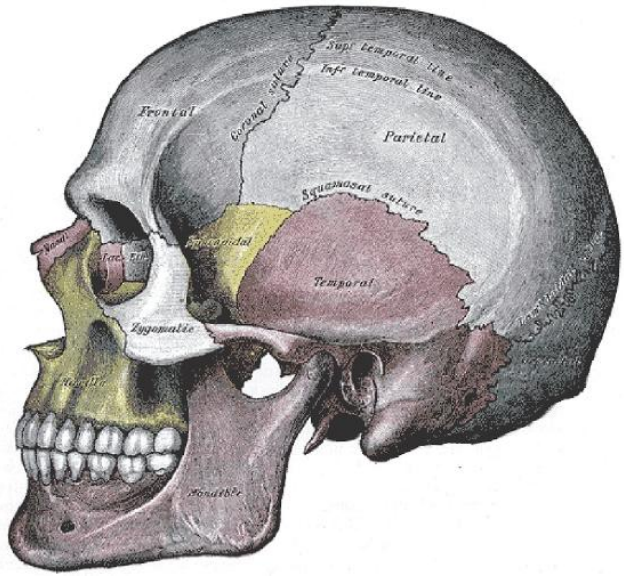

Figure 6.1.1: Lateral View of the Human Skull. (Image credit: "Lateral View of Skull-01" by OpenStax is licensed under CC BY 4.0)

The skeletal system forms the rigid internal framework of the body. It consists of the bones, cartilages, and ligaments. Bones support the weight of the body, allow for body movements, and protect internal organs. Cartilage provides flexible strength and support for body structures such as the thoracic cage, the external ear, and the trachea and larynx. At joints of the body, cartilage can also unite adjacent bones or provide cushioning between them. Ligaments are the strong connective tissue bands that hold the bones at a moveable joint together and serve to prevent excessive movements of the joint that would result in injury. The skeleton is moved by the muscles of the body, which are firmly attached to bones, often via connective tissue structures called tendons. As muscles contract, they pull on the bones to produce movements of the body. Thus, without a skeleton, you would not be able to stand, run, or even feed yourself!

Each bone of the body serves a particular function, and therefore bones vary in size, shape, and strength based on these functions. For example, the bones of the lower back and lower limb are thick and strong to support your body weight. Similarly, the size of a bony landmark that serves as a muscle attachment site on an individual bone is related to the strength of this muscle. Muscles can apply very strong pulling forces to the bones of the skeleton. To resist these forces, bones have enlarged bony landmarks at sites where powerful muscles attach. This means that not only the size of a bone, but also its shape, is related to its function. For this reason, the identification of bony landmarks is important during your study of the skeletal system.

Bones are also dynamic organs that can modify their strength and thickness in response to changes in muscle strength or body weight. Thus, muscle attachment sites on bones will thicken if you begin a workout program that increases muscle strength. Similarly, the walls of weight-bearing bones will thicken if you gain body weight or begin pounding the pavement as part of a new running regimen. In contrast, a reduction in muscle strength or body weight will cause bones to become thinner. This may happen during a prolonged hospital stay, following limb immobilization in a cast, or going into the weightlessness of outer space. Even a

change in diet, such as eating only soft food due to the loss of teeth, will result in a noticeable decrease in the size and thickness of the jaw bones.

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6.2: Divisions of the Skeletal System

By the end of this section, you will be able to:

- Distinguish between the axial skeleton and appendicular skeleton
- Discuss the functions of the axial skeleton and appendicular skeleton
- Define the axial skeleton and its components
- Define the appendicular skeleton and its components

The skeletal system includes all of the bones, cartilages, and ligaments of the body that support and give shape to the body and body structures. The **skeleton** consists of the bones of the body. For adults, there are 206 bones in the skeleton. Younger individuals have higher numbers of bones because some bones fuse together during childhood and adolescence to form an adult bone. The primary functions of the skeleton are to provide a rigid, internal structure that can support the weight of the body against the force of gravity, and to provide a structure upon which muscles can act to produce movements of the body. The lower portion of the skeleton is specialized for stability during walking or running. In contrast, the upper skeleton has greater mobility and ranges of motion, features that allow you to lift and carry objects or turn your head and trunk.

In addition to providing for support and movements of the body, the skeleton has protective and storage functions. It protects the internal organs, including the brain, spinal cord, heart, lungs, and pelvic organs. The bones of the skeleton serve as the primary storage site for important minerals such as calcium and phosphate. The bone marrow found within bones stores fat and houses the blood-cell producing tissue of the body.

The skeleton is subdivided into two major divisions—the axial and appendicular.

The Axial Skeleton

The **axial skeleton** forms the vertical, central axis of the body and includes all bones of the head, neck, chest, and back (Figure 6.2.1). It serves to protect the brain, spinal cord, heart, and lungs. It also serves as the attachment site for muscles that move the head, neck, and back, and for muscles that act across the shoulder and hip joints to move their corresponding limbs.

The axial skeleton of the adult consists of 80 bones, including the **skull**, the **vertebral column**, and the **thoracic cage**. The skull has two main divisions, the cranial portion and the facial portion, and is formed by 22 bones. Also associated with the head are an additional seven bones, including the **hyoid bone** and the **ear ossicles** (three small bones found in each middle ear). The vertebral column consists of 24 bones, each called a **vertebra**, plus the **sacrum** and **coccyx**. The thoracic cage includes the 12 pairs of **ribs**, and the **sternum**, the flattened bone of the anterior chest.

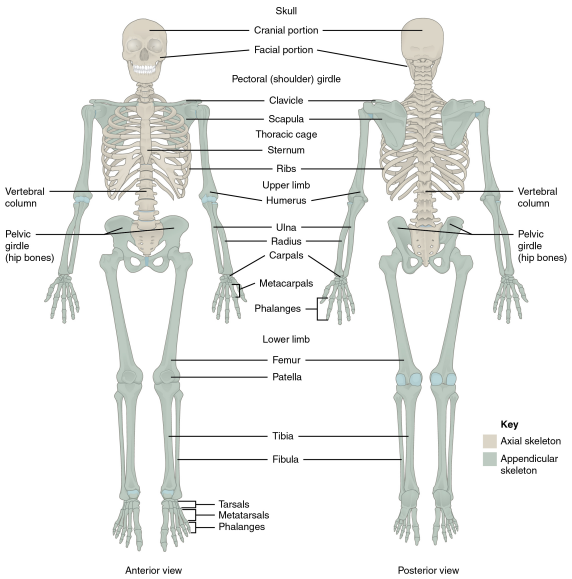

Figure 6.2.1: Axial and Appendicular Skeleton. The axial skeleton supports the head, neck, back, and chest and thus forms the vertical axis of the body. It consists of the skull, vertebral column (including the sacrum and coccyx), and the thoracic cage, formed by the ribs and sternum. The appendicular skeleton is made up of all bones of the upper and lower limbs. (Image credit: "Axial Skeleton" by OpenStax is licensed under CC BY 3.0)

The Appendicular Skeleton

The **appendicular skeleton** includes all bones of the upper and lower limbs, plus the bones that attach each limb to the axial skeleton. There are 126 bones in the appendicular skeleton of an adult. The bones that attach the upper limbs to the axial skeleton, include the clavicle and scapula, and are collectively known as the pectoral (shoulder) girdle. Bones of the upper limb include the humerus, ulna, radius, carpals, metacarpals and phalanges. The pelvic girdle, which attaches the lower limbs to the axial skeleton, is made up of the hip bones (coxae; singular coxa). Bones of the lower limb include the femur, patella, tibia, fibula, tarsals, metatarsals, and phalanges. The bones of the appendicular skeleton serve as attachment sites for muscles that move the appendages. The bones of the lower limb are structured to bear the weight of the body as well. The bones of the appendicular skeleton are covered in more detail in a separate chapter.

Concept Review

The skeletal system includes all of the bones, cartilages, and ligaments of the body. It serves to support the body, protect the brain and other internal organs, and provides a rigid structure upon which muscles can pull to generate body movements. It also stores fat and the tissue responsible for the production of blood cells. The skeleton is subdivided into two parts. The axial skeleton forms a vertical axis that includes the head, neck, back, and chest. It has 80 bones and consists of the skull, vertebral column, and thoracic cage. The adult vertebral column consists of 24 vertebrae plus the sacrum and coccyx. The thoracic cage is formed by 12 pairs of ribs and the sternum. The appendicular skeleton consists of 126 bones in the adult and includes all of the bones of the upper and lower limbs plus the bones that anchor each limb to the axial skeleton.

Review Questions

Q. Which of the following is part of the axial skeleton?

A. shoulder bones

B. thigh bone

C. foot bones

D. vertebral column

Answer

Answer: D

Q. Which of the following is a function of the axial skeleton?

A. allows for movement of the wrist and hand

B. protects nerves and blood vessels at the elbow

C. supports trunk of body

D. allows for movements of the ankle and foot

Answer

Answer: C

Q. The axial skeleton _____.

A. consists of 126 bones

B. forms the vertical axis of the body

C. includes all bones of the body trunk and limbs

D. includes only the bones of the lower limbs

Answer

Answer: B

Critical Thinking Question

Q. Define the two divisions of the skeleton.

Answer

A. The axial skeleton forms the vertical axis of the body and includes the bones of the head, neck, back, and chest of the body. It consists of 80 bones that include the skull, vertebral column, and thoracic cage. The appendicular skeleton consists of 126 bones and includes all bones of the upper and lower limbs.

Q. Discuss the functions of the axial skeleton.

Answer

A. The axial skeleton supports the head, neck, back, and chest of the body and allows for movements of these body regions. It also gives bony protections for the brain, spinal cord, heart, and lungs; stores fat and minerals; and houses the blood-cell producing tissue.

Glossary

appendicular skeleton
all bones of the upper and lower limbs, plus the girdle bones that attach each limb to the axial skeleton

axial skeleton
central, vertical axis of the body, including the skull, vertebral column, and thoracic cage

coccyx
small bone located at inferior end of the adult vertebral column that is formed by the fusion of four coccygeal

vertebrae; also referred to as the “tailbone”

ear ossicles
three small bones located in the middle ear cavity that serve to transmit sound vibrations to the inner ear

hyoid bone
small, U-shaped bone located in upper neck that does not contact any other bone

ribs
thin, curved bones of the chest wall

sacrum
single bone located near the inferior end of the adult vertebral column that is formed by the fusion of five sacral vertebrae; forms the posterior portion of the pelvis

skeleton
bones of the body

skull
bony structure that forms the head, face, and jaws, and protects the brain; consists of 22 bones

sternum
flattened bone located at the center of the anterior chest

thoracic cage
consists of 12 pairs of ribs and sternum

vertebra
individual bone in the neck and back regions of the vertebral column

vertebral column
entire sequence of bones that extend from the skull to the tailbone

Contributors and Attributions

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6.3: The Skull

By the end of this section, you will be able to:

- List and identify the bones of the brain case and face
- Locate the major suture lines of the skull and name the bones associated with each
- Locate and define the boundaries of the anterior, middle, and posterior cranial fossae, the temporal fossa, and infratemporal fossa
- Define the paranasal sinuses and identify the location of each
- Name the bones that make up the walls of the orbit and identify the openings associated with the orbit
- Identify the bones and structures that form the nasal septum and nasal conchae, and locate the hyoid bone
- Identify the bony openings of the skull

The **cranium** (skull) is the skeletal structure of the head that supports the face and protects the brain. It is subdivided into the **facial bones** and the **brain case**, or cranial vault (Figure 6.3.1). The facial bones underlie the facial structures, form the nasal cavity, enclose the eyeballs, and support the teeth of the upper and lower jaws. The rounded brain case surrounds and protects the brain and houses the middle and inner ear structures.

In the adult, the skull consists of 22 individual bones, 21 of which are immobile and united into a single unit. The 22nd bone is the **mandible** (lower jaw), which is the only moveable bone of the skull.

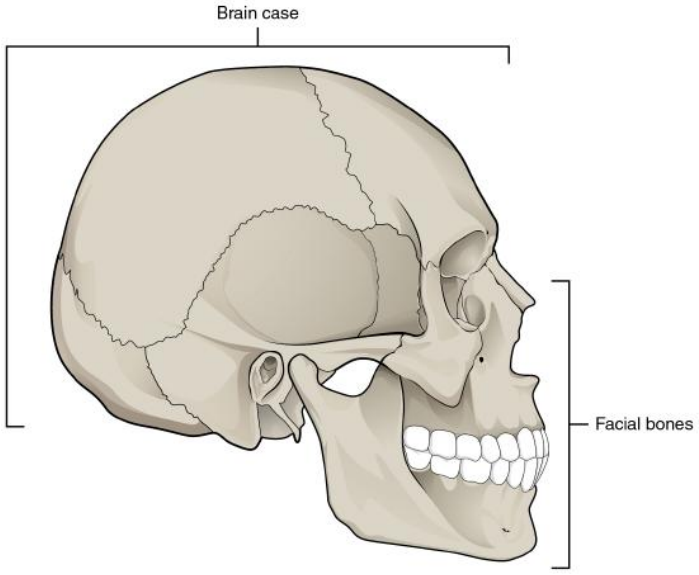

Figure 6.3.1: Parts of the Skull. The skull consists of the rounded brain case that houses the brain and the facial bones that form the upper and lower jaws, nose, orbits, and other facial structures. (Image credit: "Parts of the Skull" by OpenStax is licensed under CC BY 3.0)

Interactive Link

The Skull

QR Code representing a URL

Watch this video to view a rotating and exploded skull, with color-coded bones. Which bone (yellow) is centrally located and joins with most of the other bones of the skull?

Answer

Answer: The sphenoid bone joins with most other bones of the skull. It is centrally located, where it forms portions

of the rounded brain case and cranial base.

Anterior View of Skull

The anterior skull consists of the facial bones and provides the bony support for the eyes and structures of the face. This view of the skull seen in Figure 6.3.2 is dominated by the forehead, formed mainly by the **frontal bone**, and the openings of the orbits and the nasal cavity. Also seen are the upper and lower jaws, with their respective teeth.

The **orbit** is the bony socket that houses the eyeball and muscles that move the eyeball or open the upper eyelid. The upper margin of the anterior orbit is the **supraorbital margin**. Located near the midpoint of the supraorbital margin is a small opening called the **supraorbital foramen**. This provides for passage of a sensory nerve to the skin of the forehead. Below the orbit is the **infraorbital foramen**, which is the point of emergence for a sensory nerve that innervates the anterior face below the orbit.

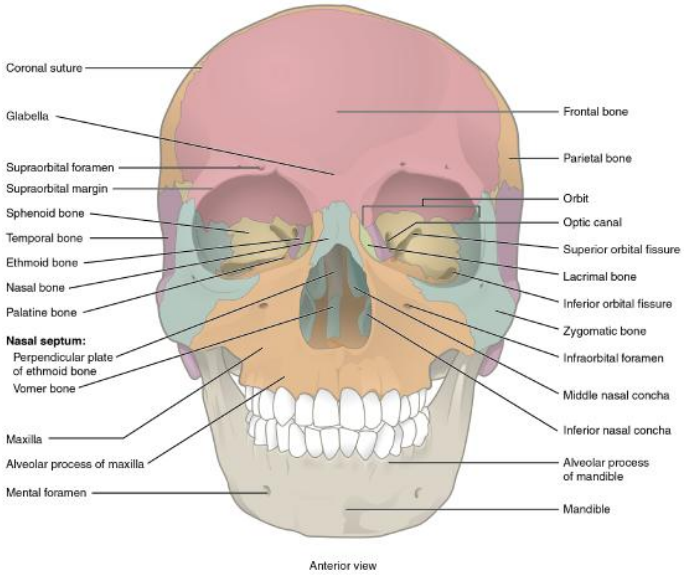

Figure 6.3.2: Anterior View of Skull. An anterior view of the skull shows the bones that form the forehead, orbits (eye sockets), nasal cavity, nasal septum, and upper and lower jaws. (Image credit: "Skull" by OpenStax is licensed under CC BY 3.0)

Inside the nasal area of the skull, the **nasal cavity** is divided into halves by the **nasal septum**. The upper portion of the nasal septum is formed by the **perpendicular plate of the ethmoid bone** and the lower portion is formed by the **vomer bone**. Each side of the nasal cavity is triangular in shape, with a broad inferior space that narrows superiorly. When looking into the nasal cavity from the front of the skull, two bony plates are seen projecting from each lateral wall. The larger of these is the **inferior nasal concha**, an independent bone of the skull. Two ridges are located just above the inferior concha in the upper nasal cavity: the **middle nasal concha** and **superior nasal concha**, although the superior concha is much smaller and out of sight in the articulated skull. The middle and superior nasal conchae are parts of the labyrinth of the ethmoid bone, also called the lateral mass due to its position lateral to the perpendicular plate.

Lateral View of Skull

A view of the lateral skull is dominated by the large, rounded brain case above and the upper and lower jaws with their teeth below (Figure 6.3.3). Separating these areas is the bridge of bone called the zygomatic arch. The **zygomatic arch** is the bony arch on the side of skull that spans from the area of the cheek to just above the ear canal. It is formed by the junction of two bony processes: a short anterior component, the **temporal process of the zygomatic bone** (the cheekbone) and a longer posterior portion, the **zygomatic process of the temporal bone**, extending forward from the temporal bone. Thus the temporal process (anteriorly) and the zygomatic process (posteriorly) join together, like the two ends of a drawbridge, to form the zygomatic arch. One of the major muscles that pulls the mandible upward during biting and chewing arises from the zygomatic arch.

On the lateral side of the brain case, above the level of the zygomatic arch, is a shallow space called the **temporal fossa**. Below the level of the zygomatic arch and deep to the vertical portion of the mandible is another space called the **infratemporal fossa**. Both the temporal fossa and infratemporal fossa contain muscles that act on the mandible during chewing.

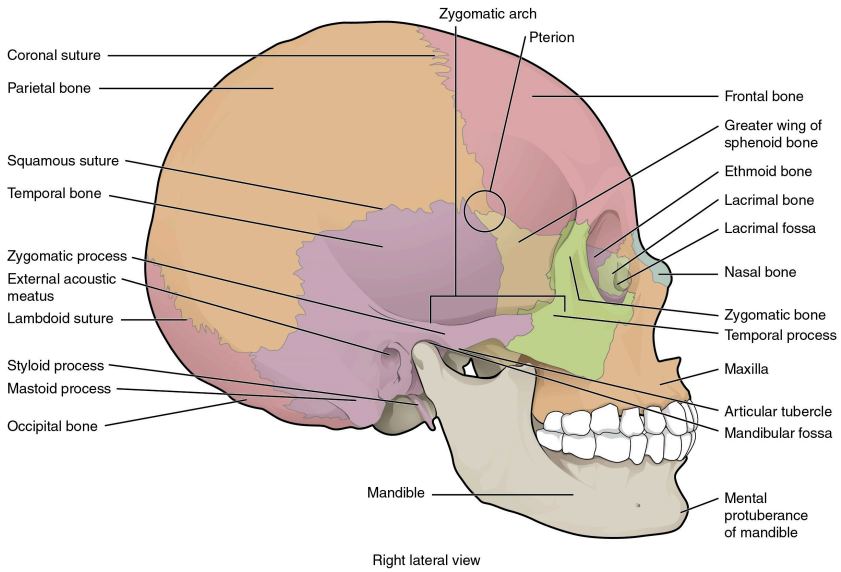

Figure 6.3.3: Lateral View of Skull. The lateral skull shows the large rounded brain case, zygomatic arch, and the upper and lower jaws. The zygomatic arch is formed jointly by the zygomatic process of the temporal bone and the temporal process of the zygomatic bone. The shallow space above the zygomatic arch is the temporal fossa. The space inferior to the zygomatic arch and deep to the posterior mandible is the infratemporal fossa. (Image credit: "Lateral View of Skull" by Whitney Menefee is licensed under CC BY 4.0 / A derivative from the original work)

Bones of the Brain Case

The brain case contains and protects the brain. The interior space that is almost completely occupied by the brain is called the **cranial cavity**. This cavity is enclosed superiorly by the rounded top of the skull, which is called the **calvaria** (skullcap), and the lateral and posterior sides of the skull. The floor of the brain case is referred to as the base of the skull. The brain case consists of eight bones. These include the paired parietal and temporal bones, plus the unpaired frontal, occipital, sphenoid, and ethmoid bones.

Parietal Bone

The **parietal bone** forms most of the upper lateral side wall of the skull (parietal = "wall") (Figure 6.3.3). These are paired bones, with the right and left parietal bones joining together at the top of the skull. Each parietal bone is also bordered anteriorly by the frontal bone, inferiorly by the temporal bone, and posteriorly by the occipital bone.

Temporal Bone

The **temporal bone** forms the lower lateral side of the skull (Figure 6.3.3). Common wisdom has it that the temporal bone (temporal = “time”) is so named because this area of the head (the temple) is where hair typically first turns gray, indicating the passage of time.

The temporal bone is subdivided into several regions (Figure 6.3.4). The flattened, upper portion is the **squamous portion of the temporal bone**. Below this area and projecting anteriorly is the **zygomatic process** of the temporal bone, which forms the posterior portion of the zygomatic arch. Posteriorly is the **mastoid portion of the temporal bone**. Projecting inferiorly from this region is a large prominence, the **mastoid process**, which serves as a muscle attachment site. The mastoid process can easily be felt on the side of the head just behind your earlobe. On the interior of the skull, the petrous portion of each temporal bone forms the prominent, diagonally oriented **petrous ridge** in the floor of the cranial cavity (Figure 6.3.5.b). Located inside each petrous ridge are small cavities that house the structures of the middle and inner ears.

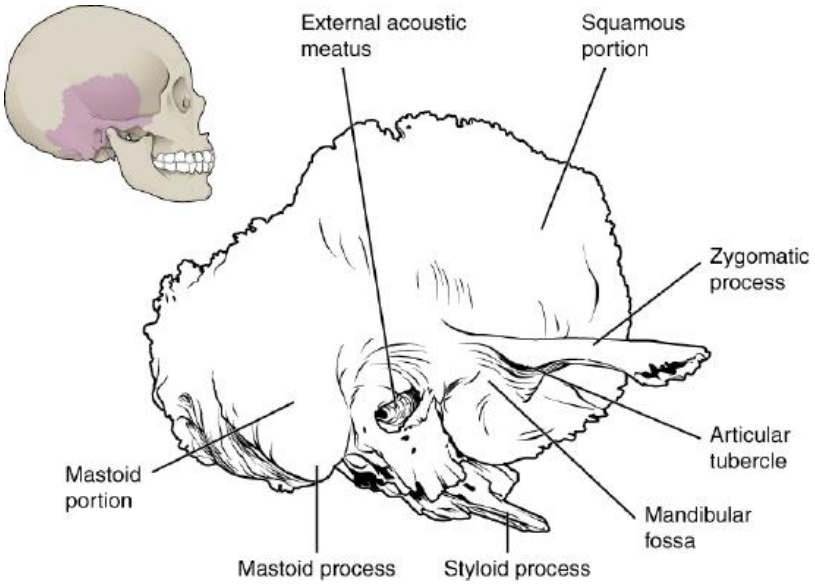

Figure 6.3.4: Temporal Bone. A lateral view of the isolated temporal bone shows the squamous, mastoid, and zygomatic portions of the temporal bone. (Image credit: "Temporal Bone" by OpenStax is licensed under CC BY 3.0)

Important landmarks of the temporal bone, as seen in Figures 6.3.4 and 6.3.5, include the following:

- **External acoustic meatus** (ear canal) - This is the large opening on the lateral side of the skull that is associated with the ear.
- **Internal acoustic meatus** - This opening is located inside the cranial cavity, on the medial side of the petrous ridge. It connects to the middle and inner ear cavities of the temporal bone.
- **Mandibular fossa** - This is the deep, oval-shaped depression located on the external base of the skull, just in front of the external acoustic meatus. The mandible (lower jaw) joins with the skull at this site as part of the temporomandibular joint, which allows for movements of the mandible during opening and closing of the mouth.
- **Articular tubercle** - The smooth ridge located immediately anterior to the mandibular fossa. Both the articular tubercle and mandibular fossa contribute to the temporomandibular joint, the joint that provides for movements between the temporal bone of the skull and the mandible.
- **Styloid process** - Posterior to the mandibular fossa on the external base of the skull is an elongated, downward bony projection called the styloid process, so named because of its resemblance to a stylus (a pen or writing tool). This structure serves as an attachment site for several small muscles and for a ligament that supports the hyoid bone of the neck.
- **Stylomastoid foramen** - This small opening is located between the styloid process and mastoid process. This is the point of exit for the cranial nerve that supplies the facial muscles.
- **Carotid canal** - The carotid canal is a zig-zag shaped tunnel that provides passage through the base of the skull for one of the major arteries that supplies the brain. Its entrance is located on the outside base of the skull, anteromedial to the styloid process. The canal then runs anteromedially within the bony base of the skull, and then turns upward to its exit in the floor of the middle cranial cavity, above the foramen lacerum.

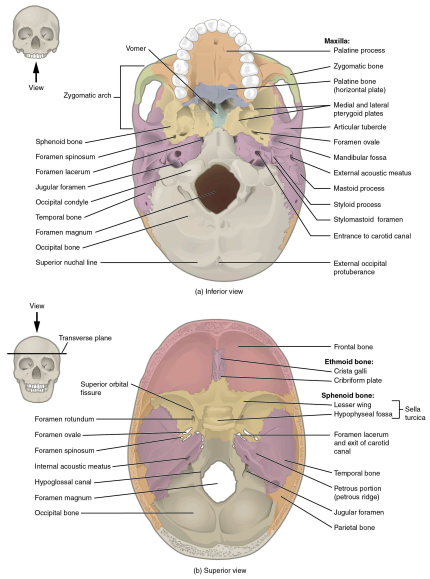

Figure 6.3.5: External and Internal Views of Base of Skull. (a) The hard palate is formed anteriorly by the palatine processes of the maxilla bones and posteriorly by the horizontal plate of the palatine bones. (b) The complex floor of the cranial cavity is formed by the frontal, ethmoid, sphenoid, temporal, and occipital bones. The lesser wing of the sphenoid bone separates the anterior and middle cranial fossae. The petrous ridge (petrous portion of temporal bone) separates the middle and posterior cranial fossae. (Image credit: "Superior-Inferior View of Skull" by Whitney Menefee is licensed under CC BY 4.0 / A derivative from the original work)

Frontal Bone

The **frontal bone** is the single bone that forms the forehead. It has two main parts, the squamous part, which forms the large, flat, superior portion of the bone, and the orbit part. At its anterior midline, between the eyebrows, there is a slight depression called the **glabella** (Figure 6.3.2). The frontal bone also forms the **supraorbital margin** of the orbit. Near the middle of this margin, is the **supraorbital foramen**, the opening that provides passage for a sensory nerve to the forehead. The frontal bone is thickened just above each supraorbital margin, forming rounded brow ridges known as the superciliary arches. These are located just behind your eyebrows and vary in size among individuals, although they are generally larger in males. Inside the cranial cavity, the frontal bone extends posteriorly. This flattened region forms both the roof of the orbit below and part of the floor of the cranial cavity above (Figure 6.3.5.*b*).

Occipital Bone

The **occipital bone** is the single bone that forms the posterior skull and posterior base of the cranial cavity (Figure 6.3.6; see also Figure 6.3.5). On its superficial surface, at the posterior midline, is a small protrusion called the **external occipital protuberance**, which serves as an attachment site for a ligament of the posterior neck. Lateral to either side of this bump is a **superior nuchal line** (nuchal = “nape” or “posterior neck”). The nuchal lines represent the most superior point at which muscles of the neck attach to the skull, with only the scalp covering the skull above these lines. On the base of the skull, the occipital bone contains the large opening of the **foramen magnum**, which allows for passage of the spinal cord as it exits the skull. Superfically, on either side of the foramen magnum is an oval-shaped **occipital condyle**. These condyles form joints with the first cervical vertebra and thus support the skull on top of the vertebral column.

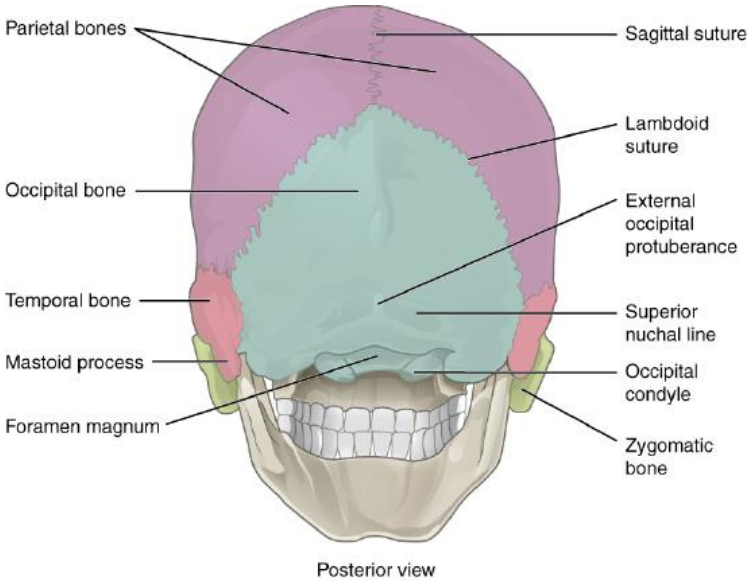

Figure 6.3.6: Posterior View of Skull. This view of the posterior skull shows attachment sites for muscles and joints that support the skull. (Image credit: "Posterior View Skull" by OpenStax is licensed under CC BY 3.0)

Sphenoid Bone

The **sphenoid bone** is a single, complex bone of the central skull (Figure 6.3.7). It serves as a "keystone" bone, because it joins with almost every other bone of the skull. The sphenoid forms much of the base of the central skull (Figure 6.3.5) and also extends laterally to contribute to the sides of the skull (Figure 6.3.3). Inside the cranial cavity, the right and left lesser wings of the sphenoid bone, which resemble the wings of a flying bird, form the lip of a prominent ridge that marks the boundary between the anterior and middle cranial fossae, depressions in the floor of the cranial cavity (discussed later in this section). The **sella turcica** ("Turkish saddle") is located at the midline, on the **body of the sphenoid bone**. This bony region of the sphenoid bone is named for its resemblance to the horse saddles used by the Ottoman Turks, with a high back and a tall front. The rounded depression in the floor of the sella turcica is the **hypophyseal (pituitary) fossa**, which houses the pea-sized pituitary (hypophyseal) gland. The **greater wings of the sphenoid bone** extend laterally to either side away from the sella turcica, where they form the anterior floor of the middle cranial fossa. The greater wing is best seen on the outside of the lateral skull, where it forms a rectangular area immediately anterior to the squamous portion of the temporal bone.

On the inferior aspect of the skull, each half of the sphenoid bone forms two thin, vertically oriented bony plates. These are the **medial pterygoid plate** and **lateral pterygoid plate** (pterygoid = "wing-shaped"). The right and left medial pterygoid plates form the posterior, lateral walls of the nasal cavity. The somewhat larger lateral pterygoid plates serve as attachment sites for chewing muscles that fill the infratemporal space and act on the mandible.

The sphenoid bone has several openings for the passage of blood vessels and cranial nerves, which include:

- **Optic canal**—This opening is located at the anterior lateral corner of the sella turcica. It provides for passage of the optic nerve into the orbit.
- **Superior orbital fissure**—This large, irregular opening into the posterior orbit is located on the anterior wall of the middle cranial fossa, lateral to the optic canal and under the projecting margin of the lesser wing of the sphenoid bone. Nerves to the eyeball and associated muscles, and sensory nerves to the forehead pass through this opening.
- **Foramen rotundum**—This rounded opening (rotundum = "round") is located in the floor of the middle cranial fossa, just inferior to the superior orbital fissure. It is the exit point for a major sensory nerve that supplies the cheek, nose, and upper teeth.
- **Foramen ovale of the middle cranial fossa**—This large, oval-shaped opening in the floor of the middle cranial fossa provides passage for a major sensory nerve to the lateral head, cheek, chin, and lower teeth.
- **Foramen spinosum**—This small opening, located posterior-lateral to the foramen ovale, is the entry point for an important artery that supplies the covering layers surrounding the brain. The branching pattern of this artery forms readily visible grooves on the internal surface of the skull and these grooves can be traced back to their origin at the foramen spinosum.
- **Carotid canal**—This is the zig-zag passageway through which a major artery to the brain enters the skull. The entrance to the carotid canal is located on the inferior aspect of the skull, anteromedial to the styloid process (see Figure 6.3.6.*a*). From here,

the canal runs anteromedially within the bony base of the skull. Just above the foramen lacerum, the carotid canal opens into the middle cranial cavity, near the posterior-lateral base of the sella turcica.

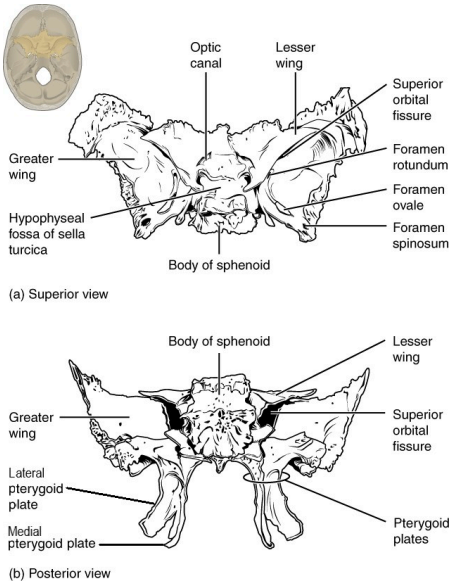

Figure 6.3.7: Sphenoid Bone. Shown in isolation in (a) superior and (b) posterior views, the sphenoid bone is a single midline bone that forms the anterior walls and floor of the middle cranial fossa. It has a pair of lesser wings and a pair of greater wings. The sella turcica surrounds the hypophyseal fossa. Projecting downward are the medial and lateral pterygoid plates. The sphenoid has multiple openings for the passage of nerves and blood vessels, including the optic canal, superior orbital fissure, foramen rotundum, foramen ovale, and foramen spinosum. (Image credit: "Sphenoid Bone" by Whitney Menefee is licensed under CC BY 4.0 / A derivative from the original work)

Ethmoid Bone

The **ethmoid bone** is a single, midline bone that forms the roof and lateral walls of the upper nasal cavity, the upper portion of the nasal septum, and contributes to the medial wall of the orbit (Figure 6.3.8 and Figure 6.3.9). On the interior of the skull, the ethmoid also forms a portion of the floor of the anterior cranial cavity (see Figure 6.3.5.*b*).

Within the nasal cavity, the **perpendicular plate** of the ethmoid bone forms the upper portion of the nasal septum. The ethmoid bone also forms the lateral walls of the upper nasal cavity. Extending from each lateral wall are the **superior nasal concha** and **middle nasal concha**, which are thin, curved projections that extend into the nasal cavity (Figure 6.3.10). The superior and middle nasal conchae, along with the bone surrounding the honeycomb of hollowed sinuses collectively called the **ethmoid air cells**, compose a region called the ethmoidal labyrinth (for the maze-like appearance created by the air cells inside the bone) or the lateral mass (for its position lateral to the perpendicular plate).

In the cranial cavity, the ethmoid bone forms a small area at the midline in the floor of the anterior cranial fossa. This region also forms the narrow roof of the underlying nasal cavity. This portion of the ethmoid bone consists of two parts, the crista galli and cribriform plates. The **crista galli** (“rooster’s comb or crest”) is a small upward bony projection located at the midline. It functions as an anterior attachment point for one of the connective tissue covering layers of the brain. To either side of the crista galli is the **cribriform plate** (cribrum = “sieve”), a small, flattened area with numerous small openings termed olfactory foramina. Small nerve branches from the olfactory (smell) areas of the nasal cavity pass through these openings to enter the brain.

The lateral portions of the ethmoid bone are located between the orbit and upper nasal cavity, and thus form the lateral nasal cavity wall and a portion of the medial orbit wall. Located inside this portion of the ethmoid bone are several small, air-filled spaces that are part of the paranasal sinus system of the skull.

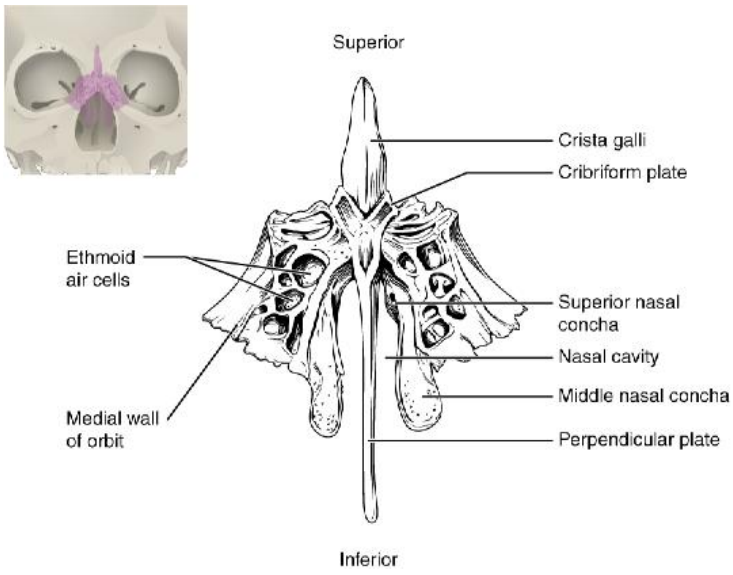

Figure 6.3.8: Ethmoid Bone. The unpaired ethmoid bone is located at the midline within the central skull. It has an upward projection, the crista galli, and a downward projection, the perpendicular plate, which forms the upper nasal septum. The cribriform plates form both the roof of the nasal cavity and a portion of the anterior cranial fossa floor. The lateral sides of the ethmoid bone form the lateral walls of the upper nasal cavity, part of the medial orbit wall, and give rise to the superior and middle nasal conchae. The ethmoid bone also contains the ethmoid air cells. (Image credit: "Ethmoid Bone" by OpenStax is licensed under CC BY 3.0)

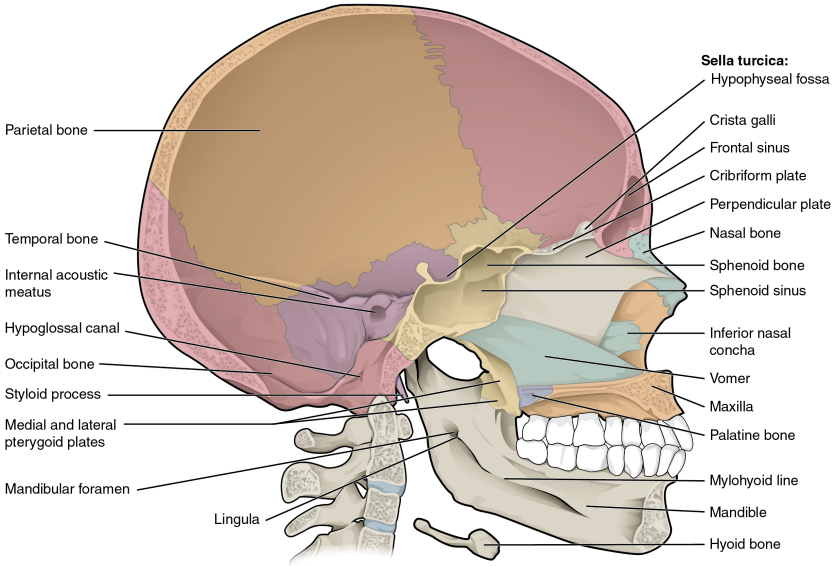

Figure 6.3.9: Sagittal Section of Skull. This midline view of the sagittally sectioned skull shows the nasal septum. (Image credit: "Sagittal Section of Skull" by OpenStax is licensed under CC BY 3.0)

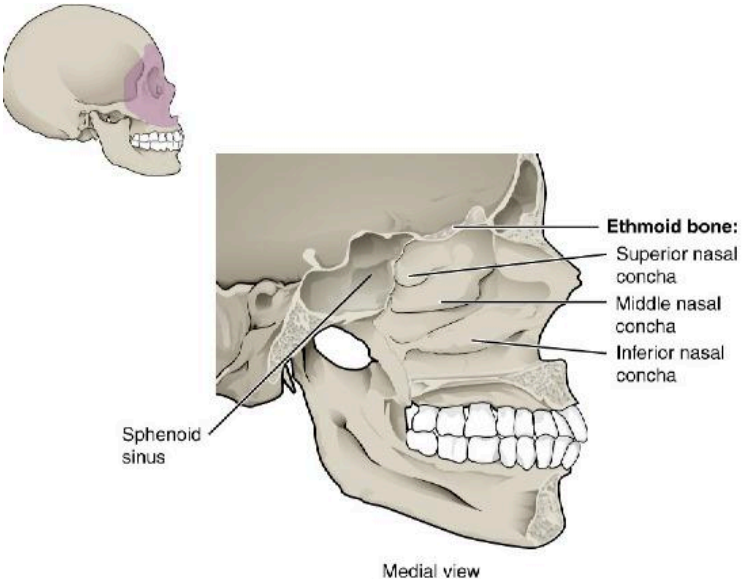

Figure 6.3.10: Lateral Wall of Nasal Cavity. The three nasal conchae are curved bones that project from the lateral walls of the nasal cavity. The superior nasal concha and middle nasal concha are parts of the ethmoid bone. The inferior nasal concha is an independent bone of the skull. (Image credit: "Nasal Cavity" by Whitney Menefee is licensed under CC BY 4.0 / A derivative from the original work)

Cranial Fossae

Recall that the floor of the brain case (floor of the cranial cavity) is referred to as the base of the skull. This is a complex area that varies in depth and has numerous openings for the passage of cranial nerves, blood vessels, and the spinal cord. Inside the skull, the base is subdivided into three large spaces, called the **anterior cranial fossa**, **middle cranial fossa**, and **posterior cranial fossa** (fossa = "trench or ditch") (Figure 6.3.11). From anterior to posterior, the fossae (singular = fossa) increase in depth. Since the brain occupies these areas, the shape of each conforms to the shape of the brain regions that it contains. Each cranial fossa has anterior and posterior boundaries and is divided at the midline into right and left areas by a significant bony structure or opening.

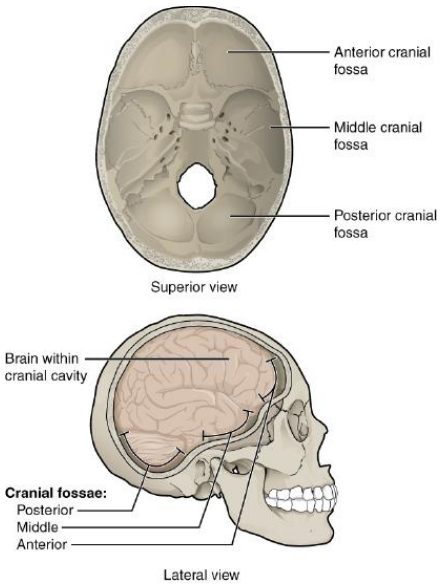

Figure 6.3.11: Cranial Fossae. The bones of the brain case surround and protect the brain, which occupies the cranial cavity. The base of the brain case, which forms the floor of cranial cavity, is subdivided into the shallow anterior cranial fossa, the middle cranial fossa, and the deep posterior cranial fossa. (Image credit: "Cranial Fossae" by OpenStax is licensed under CC BY 3.0)

Anterior Cranial Fossa

The anterior cranial fossa is the most anterior and the shallowest of the three cranial fossae. It overlies the orbits and contains the frontal lobes of the brain. Anteriorly, the anterior fossa is bounded by the frontal bone, which also forms the majority of the floor for this space. The lesser wings of the sphenoid bone form the prominent ledge that marks the boundary between the anterior and middle cranial fossae. Located in the floor of the anterior cranial fossa at the midline is a portion of the ethmoid bone, consisting of the upward projecting crista galli and to either side of this, the cribriform plates.

Middle Cranial Fossa

The middle cranial fossa is deeper and situated posterior to the anterior fossa. It extends from the lesser wings of the sphenoid bone anteriorly, to the petrous ridges (petrous portion of the temporal bones) posteriorly. The large, diagonally positioned petrous ridges give the middle cranial fossa a butterfly shape, making it narrow at the midline and broad laterally. The temporal lobes of the brain occupy this fossa. The middle cranial fossa is divided at the midline by the upward bony prominence of the sella turcica, a part of the sphenoid bone. The middle cranial fossa has several openings for the passage of blood vessels and cranial nerves, most of which are found in the sphenoid bone (Figure $6.3.5$). Other openings in the middle cranial fossa are as follows:

- **Inferior orbital fissure** - This opening is found on the floor of the orbit between the sphenoid, maxillary, and zygomatic bones. Traveling through this fissure are nerves that provide sensory information to the skin that covers the temporal and zygomatic bones and that regulate blood flow to the nasal mucosa, allowing for the warming/cooling of air in the nasal cavity. This fissure also allows for the passage of blood vessels.
- **Foramen lacerum** - This irregular opening is located in the base of the skull, immediately inferior to the exit of the carotid canal. This opening is an artifact of the dry skull, because in life it is completely filled with cartilage. All the openings of the skull that provide for passage of nerves or blood vessels have smooth margins; the word lacerum ("ragged" or "torn") tells us that this opening has ragged edges and thus nothing passes through it.

Posterior Cranial Fossa

The posterior cranial fossa is the most posterior and deepest portion of the cranial cavity. It contains the cerebellum of the brain. The posterior fossa is bounded anteriorly by the petrous ridges, while the occipital bone forms the floor and posterior wall. It is divided at the midline by the large foramen magnum ("great aperture"), the opening that provides for passage of the spinal cord.

Located on the medial wall of the petrous ridge in the posterior cranial fossa is the internal acoustic meatus (see Figure $6.3.9$). This opening provides for passage of the nerve from the hearing and equilibrium organs of the inner ear, and the nerve that supplies the muscles of the face. Located at the anterior-lateral margin of the foramen magnum is the **hypoglossal canal**. These emerge on the inferior aspect of the skull at the base of the occipital condyle and provide passage for an important nerve to the tongue.

Immediately inferior to the internal acoustic meatus is the large, irregularly shaped **jugular foramen** (see Figure $6.3.6.a$). Several cranial nerves from the brain exit the skull via this opening. It is also the exit point through the base of the skull for all the venous return blood leaving the brain. The venous structures that carry blood inside the skull form large, curved grooves on the inner walls of the posterior cranial fossa, which terminate at each jugular foramen.

Sutures of the Skull

A **suture** is an immobile joint between adjacent bones of the skull. The narrow gap between the bones is filled with dense irregular connective tissue that unites the bones. The long sutures located between the bones of the brain case are not straight, but instead follow irregular, tightly twisting paths. These twisting lines serve to tightly interlock the adjacent bones, thus adding strength to the skull for brain protection.

Figure $6.3.12$ shows the major sutures of the skull. The two suture lines seen on the top of the skull are the coronal and sagittal sutures. The **coronal suture** runs from side to side across the skull, within the coronal plane of section. It joins the frontal bone to the right and left parietal bones. The **sagittal suture** extends posteriorly from the coronal suture, running along the midline at the top of the skull in the sagittal plane of section. It unites the right and left parietal bones. On the posterior skull, the sagittal suture terminates by joining the lambdoid suture. The **lambdoid suture** extends downward and laterally to either side away from its junction with the sagittal suture. The lambdoid suture joins the occipital bone to the right and left parietal and temporal bones.

This suture is named for its upside-down "V" shape, which resembles the capital letter version of the Greek letter lambda (Λ). The **squamous suture** is located on the lateral skull. It unites the squamous portion of the temporal bone with the parietal bone. At the intersection of four bones is the **pterion**, a small, capital-H-shaped suture line region that unites the frontal bone, parietal bone, squamous portion of the temporal bone, and greater wing of the sphenoid bone. It is the weakest part of the skull. The pterion is located approximately two finger widths above the zygomatic arch and a thumb's width posterior to the upward portion of the zygomatic bone.

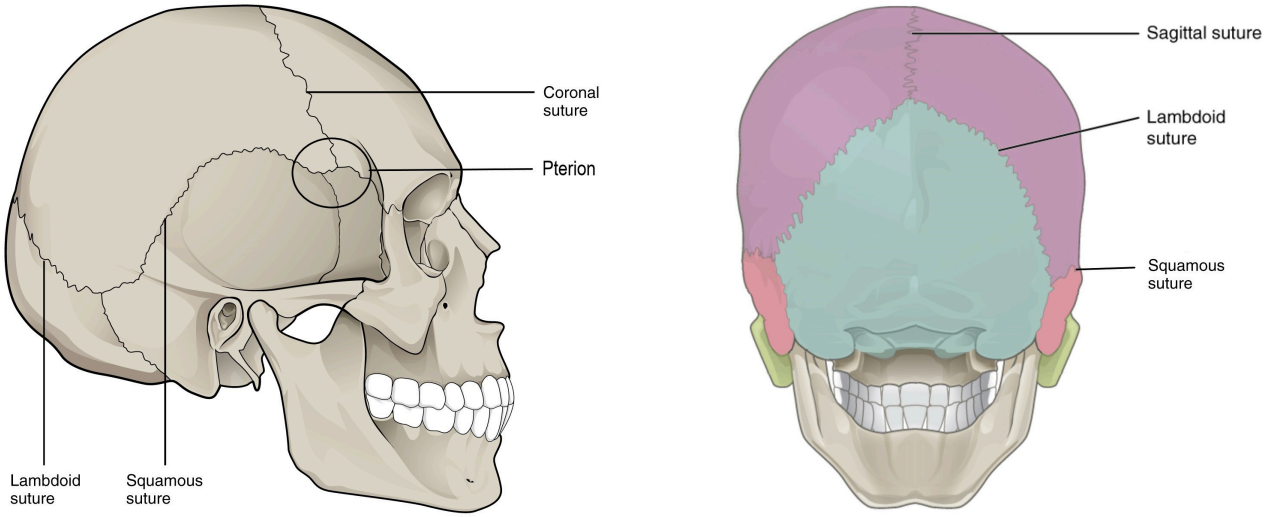

Figure 6.3.12: Sutures of the Skull. Sutures represent the immovable joints found between skull bones.(a) A lateral view of the skull shows the coronal, squamous, and lambdoid sutures, as well as the pterion. (b) A posterior view shows the sagittal, lambdoid, and squamous sutures. ("Sutures of the Skull" by Whitney Menefee is licensed under CC BY 4.0 / A derivative from the original work and original work)

DISORDERS OF THE...

Skeletal System

Head and traumatic brain injuries are major causes of immediate death and disability, with bleeding and infections as possible additional complications. According to the Centers for Disease Control and Prevention (2010), approximately 30 percent of all injury-related deaths in the United States are caused by head injuries. The majority of head injuries involve falls. They are most common among young children (ages 0–4 years), adolescents (15–19 years), and the elderly (over 65 years). Additional causes vary, but prominent among these are automobile and motorcycle accidents.

Strong blows to the brain-case portion of the skull can produce fractures. These may result in bleeding inside the skull with subsequent injury to the brain. The most common is a linear skull fracture, in which fracture lines radiate from the point of impact. Other fracture types include a comminuted fracture, in which the bone is broken into several pieces at the point of impact, or a depressed fracture, in which the fractured bone is pushed inward. In a contrecoup (counterblow) fracture, the bone at the point of impact is not broken, but instead a fracture occurs on the opposite side of the skull. Fractures of the occipital bone at the base of the skull can occur in this manner, producing a basilar fracture that can damage the artery that passes through the carotid canal.

A blow to the lateral side of the head may fracture the bones of the pterion. The pterion is an important clinical landmark because located immediately deep to it on the inside of the skull is a major branch of an artery that supplies the skull and covering layers of the brain. If the underlying artery is damaged, bleeding can cause the formation of a hematoma (collection of blood) between the brain and interior of the skull. As blood accumulates, it will put pressure on the brain. Symptoms associated with a hematoma may not be apparent immediately following the injury, but if untreated, blood accumulation will exert increasing pressure on the brain and can result in death within a few hours.

Facial Bones of the Skull

The facial bones of the skull form the upper and lower jaws, the nose, nasal cavity and nasal septum, and the orbit. The facial bones include 14 bones, with six paired bones and two unpaired bones. The paired bones are the maxilla, palatine, zygomatic, nasal, lacrimal, and inferior nasal conchae bones. The unpaired bones are the vomer and mandible bones. Although classified with the brain-case bones, the ethmoid bone also contributes to the nasal septum and the walls of the nasal cavity and orbit.

Maxillary Bone

The **maxillary bone**, often referred to simply as the maxilla (plural = maxillae), is one of a pair that together form the upper jaw, much of the hard palate, the medial floor of the orbit, and the lateral base of the nose (see Figure $6.3.2$). The curved, inferior margin of the maxillary bone that forms the upper jaw and contains the upper teeth is the **alveolar process of the maxilla** (Figure $6.3.13$). Each tooth is anchored into a deep socket called an alveolus. On the anterior maxilla, just below the orbit, is the **infraorbital foramen**. This is the point of exit for a sensory nerve that supplies the nose, upper lip, and anterior cheek. On the inferior skull, the **palatine process** from each maxillary bone can be seen joining together at the midline to form the anterior three-quarters of the hard palate (see Figure $6.3.5.a$). The **hard palate** is the bony plate that forms the roof of the mouth and floor of the nasal cavity, separating the oral and nasal cavities. On the lateral side of each maxillary bone is the **zygomatic process of the maxilla**, which is where the maxilla articulates (connects) with the zygomatic bone. The posterior side of this structure also forms a portion of the infratemporal fossa.

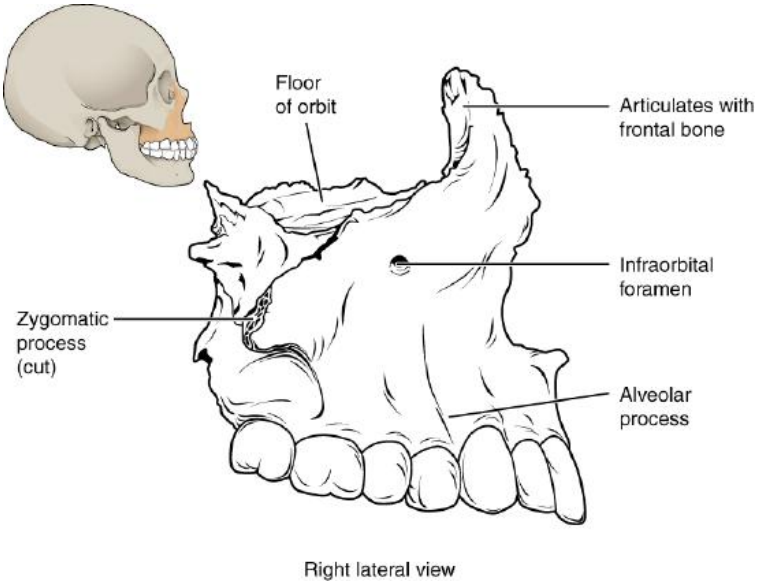

Figure $6.3.13$: Maxillary Bone. The maxillary bone forms the upper jaw and supports the upper teeth. Each maxilla also forms the lateral floor of each orbit and the majority of the hard palate. (Image credit: "Maxilla" by OpenStax is licensed under CC BY 3.0)

Palatine Bone

The **palatine bone** is one of a pair of irregularly shaped bones that contribute small areas to the lateral walls of the nasal cavity and the medial wall of each orbit. The largest region of each of the palatine bone is the **horizontal plate**. The plates from the right and left palatine bones join together at the midline to form the posterior quarter of the hard palate (see Figure $6.3.5.a$). Thus, the palatine bones are best seen in an inferior view of the skull and hard palate.

HOMEOSTATIC IMBALANCES

Cleft Lip and Cleft Palate

During embryonic development, the right and left maxilla bones come together at the midline to form the upper jaw. At the same time, the muscle and skin overlying these bones join together to form the upper lip. Inside the mouth, the palatine processes of the maxilla bones, along with the horizontal plates of the right and left palatine bones, join together to form the hard palate. If an error occurs in these developmental processes, a birth defect of cleft lip or cleft palate may result.

Cleft lip is a common development defect that affects approximately 1:1000 births, most of which are male. This defect involves a partial or complete failure of the right and left portions of the upper lip to fuse together, leaving a cleft (gap).

A more severe developmental defect is cleft palate, which affects the hard palate. The hard palate is the bony structure that separates the nasal cavity from the oral cavity. It is formed during embryonic development by the midline fusion of the horizontal plates from the right and left palatine bones and the palatine processes of the maxilla bones. Cleft palate affects approximately 1:2500 births and is more common in females. It results from a failure of the two halves of the hard palate to completely come together and fuse at the midline, thus leaving a gap between them. This gap allows for communication between the nasal and oral cavities. In severe cases, the bony gap continues into the anterior upper jaw where the alveolar processes of the maxilla bones also do not properly join together above the front teeth. If this occurs, a cleft lip will also be seen. Because of the communication between the oral and nasal cavities, a cleft palate makes it very difficult for an infant to generate the suckling needed for nursing, thus leaving the infant at risk for malnutrition. Surgical repair is required to correct cleft palate defects.

Zygomatic Bone

The **zygomatic bone** is also known as the cheekbone. Each of the paired zygomatic bones forms much of the lateral wall of the orbit and the lateral-inferior margins of the anterior orbital opening (Figure 6.3.2). The short **temporal process of the zygomatic bone** projects posteriorly, where it forms the anterior portion of the **zygomatic arch** (Figure 6.3.3).

Nasal Bone

The **nasal bone** is one of two small bones that articulate (join) with each other to form the bony base (bridge) of the nose. They also support the cartilages that form the lateral walls of the nose (Figure 6.3.9). These are the bones that are damaged when the nose is broken.

Lacrimal Bone

Each **lacrimal bone** is a small, rectangular bone that forms the anterior, medial wall of the orbit (Figure 6.3.2 and Figure 6.3.3). The anterior portion of the lacrimal bone forms a shallow depression called the **lacrimal fossa**, and extending inferiorly from this is the **nasolacrimal canal**. The lacrimal fluid (tears of the eye), which serves to maintain the moist surface of the eye, drains at the medial corner of the eye into the nasolacrimal canal. This duct then extends downward to open into the nasal cavity, behind the inferior nasal concha. In the nasal cavity, the lacrimal fluid normally drains posteriorly, but with an increased flow of tears due to crying or eye irritation, some fluid will also drain anteriorly, thus causing a runny nose.

Inferior Nasal Conchae

The right and left **inferior nasal conchae** form a curved bony plate that projects into the nasal cavity space from the lower lateral wall (Figure 6.3.9 and Figure 6.3.11). The inferior concha is the largest of the nasal conchae and can easily be seen when looking into the anterior opening of the nasal cavity.

Vomer Bone

The unpaired **vomer bone**, often referred to simply as the vomer, is triangular-shaped and forms the posterior-inferior part of the nasal septum (see Figure 6.3.9). The vomer is best seen when looking from behind into the posterior openings of the nasal cavity (see Figure 6.3.5.a). In this view, the vomer is seen to form the entire height of the nasal septum. A much smaller portion of the vomer can also be seen when looking into the anterior opening of the nasal cavity.

Mandible

The **mandible** forms the lower jaw and is the only moveable bone of the skull. At the time of birth, the mandible consists of paired right and left bones, but these fuse together during the first year to form the single U-shaped mandible of the adult skull. Each side of the mandible consists of a horizontal body and posteriorly, a vertically oriented **ramus of the mandible** (ramus = "branch"). The outside margin of the mandible, where the body and ramus come together is called the **angle of the mandible** (Figure 6.3.14).

The ramus on each side of the mandible has two upward-going bony projections. The more anterior projection is the flattened **coronoid process of the mandible**, which provides attachment for one of the biting muscles. The posterior projection is the **condylar process of the mandible**, which is topped by the oval-shaped **condyle**. The condyle of the mandible articulates (joins) with the mandibular fossa and articular tubercle of the temporal bone. Together these articulations form the temporomandibular joint, which allows for opening and closing of the mouth (see Figure 6.3.3). The broad U-shaped curve located between the coronoid and condylar processes is the **mandibular notch**.

Important landmarks of the mandible, as seen in Figure 6.3.14, include the following:

- **Alveolar process of the mandible -**This is the upper border of the mandibular body and serves to anchor the lower teeth.
- **Mental protuberance -**The forward projection from the inferior margin of the anterior mandible that forms the chin (mental = "chin").
- **Mental foramen -** The opening located on each side of the anterior-lateral mandible, which is the exit site for a sensory nerve that supplies the chin.
- **Mylohyoid line -**This bony ridge extends along the inner aspect of the mandibular body (see also Figure 6.3.9). The muscle that forms the floor of the oral cavity attaches to the mylohyoid lines on both sides of the mandible.
- **Mandibular foramen -**This opening is located on the medial side of the ramus of the mandible. The opening leads into a tunnel that runs down the length of the mandibular body. The sensory nerve and blood vessels that supply the lower teeth enter the mandibular foramen and then follow this tunnel. Thus, to numb the lower teeth prior to dental work, the dentist must inject anesthesia into the lateral wall of the oral cavity at a point prior to where this sensory nerve enters the mandibular foramen.
- **Lingula -**This small flap of bone is named for its shape (lingula = "little tongue"). It is located immediately next to the mandibular foramen, on the medial side of the ramus. A ligament that anchors the mandible during opening and closing of the mouth extends down from the base of the skull and attaches to the lingula.

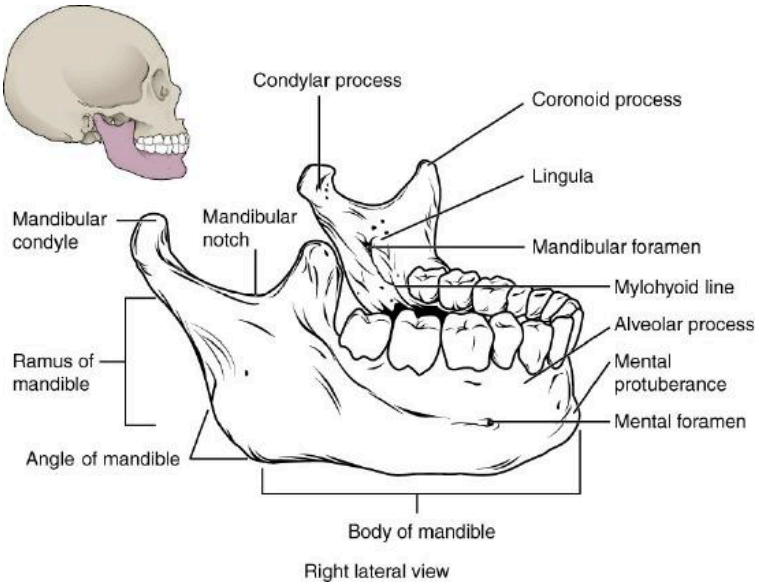

Figure 6.3.14: Isolated Mandible. The mandible is the only moveable bone of the skull. (Image Credit: "Mandible" by Whitney Menefee is licensed under CC BY 4.0 / A derivative from the original work)

The Orbit

The orbit is the bony socket that houses the eyeball and contains the muscles that move the eyeball or open the upper eyelid.

Each orbit is cone-shaped, with a narrow posterior region that widens toward the large anterior opening. To help protect the eye, the bony margins of the anterior opening are thickened and somewhat constricted. The medial walls of the two orbits are parallel to each other but each lateral wall diverges away from the midline at a 45° angle. This divergence provides greater lateral peripheral vision.

The walls of each orbit include contributions from seven skull bones (Figure 6.3.15). The frontal bone forms the roof and the zygomatic bone forms the lateral wall and lateral floor. The medial floor is primarily formed by the maxilla, with a small contribution from the palatine bone. The ethmoid bone and lacrimal bone make up much of the medial wall and the sphenoid bone forms the posterior orbit.

At the posterior apex of the orbit is the opening of the **optic canal** in the sphenoid bone, which allows for passage of the optic nerve from the retina to the brain. Lateral to this is the elongated and irregularly shaped **superior orbital fissure**, also in the sphenoid bone, which provides passage for the artery that supplies the eyeball, sensory nerves, and the nerves that supply the muscles involved in eye movements.

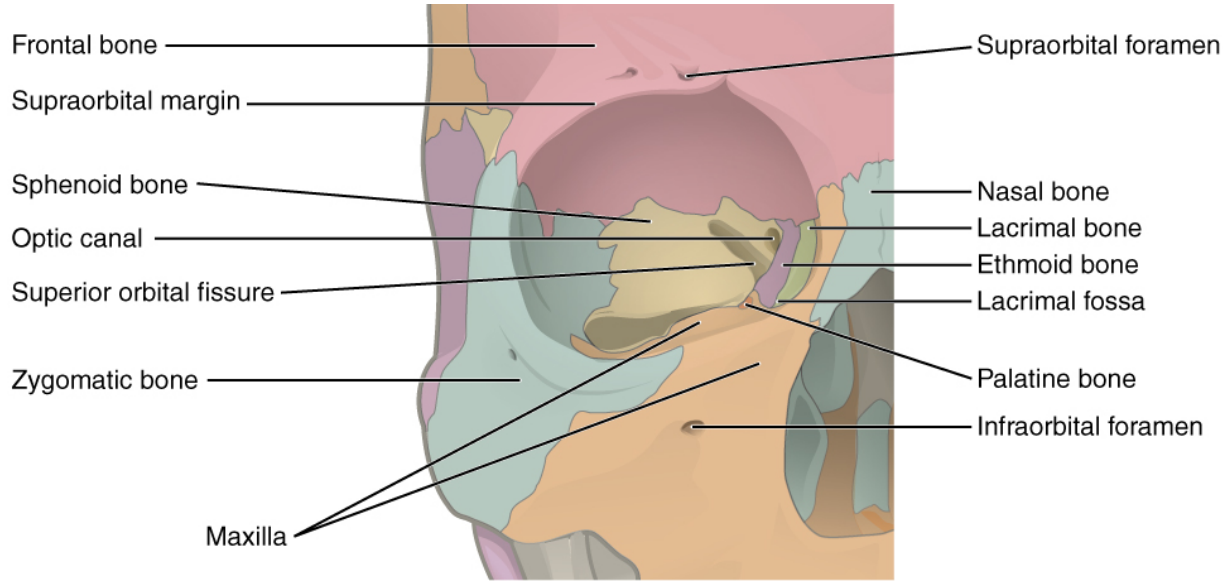

Figure 6.3.15: Bones of the Orbit. Seven skull bones contribute to the walls of the orbit. Opening into the posterior orbit from the cranial cavity are the optic canal and superior orbital fissure. (Image credit: "Bones Forming Orbit" by OpenStax is licensed under CC BY 3.0)

The Nasal Septum and Nasal Conchae

The **nasal septum** consists of both bone and cartilage components (Figure 6.3.16; see also Figure 6.3.9). The upper portion of the septum is formed by the perpendicular plate of the ethmoid bone. The lower and posterior parts of the septum are formed by the triangular-shaped vomer bone. In an anterior view of the skull, the perpendicular plate of the ethmoid bone is easily seen inside the nasal opening as the upper nasal septum, but only a small portion of the vomer is seen as the inferior septum. A better view of the vomer bone is seen when looking into the posterior nasal cavity with an inferior view of the skull, where the vomer forms the full height of the nasal septum. The anterior nasal septum is formed by the **septal cartilage**, a flexible plate that fills in the gap between the perpendicular plate of the ethmoid and vomer bones. This cartilage also extends outward into the nose where it separates the right and left nostrils. The septal cartilage is not found in the dry skull.

Attached to the lateral wall on each side of the nasal cavity are the superior, middle, and inferior **nasal conchae** (singular = concha), which are named for their positions (see Figure 6.3.11). These are bony plates that curve downward as they project into the space of the nasal cavity. They serve to swirl the incoming air, which helps to warm and moisturize it before the air moves into the delicate air sacs of the lungs. This also allows mucus, secreted by the tissue lining the nasal cavity, to trap incoming dust, pollen, bacteria, and viruses. The largest of the conchae is the inferior nasal concha, which is an independent bone of the skull. The middle concha and the superior conchae, which is the smallest, are both formed by the ethmoid bone. When looking into the anterior nasal opening of the skull, only the inferior and middle conchae can be seen. The small superior nasal concha is well hidden above and behind the middle concha.

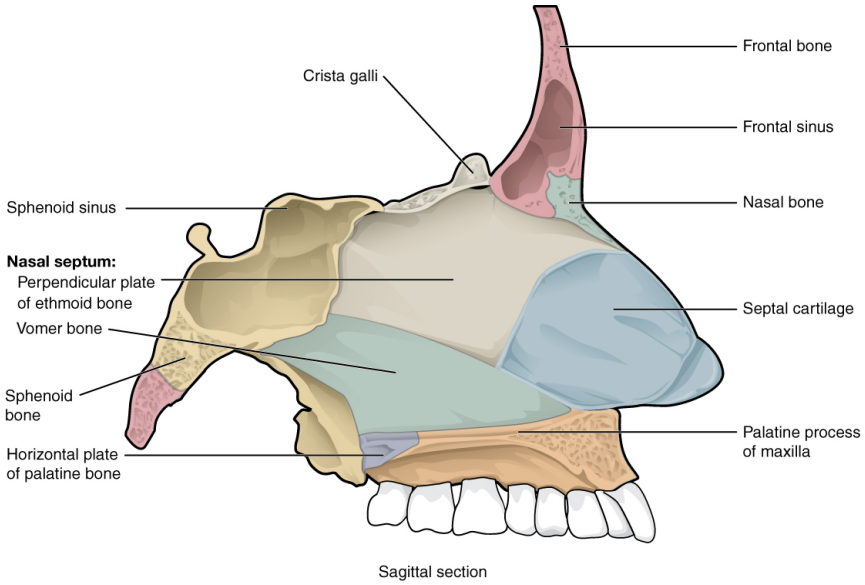

Figure 6.3.16: Nasal Septum. The nasal septum is formed by the perpendicular plate of the ethmoid bone and the vomer bone. The septal cartilage fills the gap between these bones and extends into the nose. (Image credit: "Bone of Nasal Cavity" by OpenStax is licensed under CC BY 3.0)

Paranasal Sinuses

The **paranasal sinuses** are hollow, air-filled spaces located within certain bones of the skull (Figure 6.3.17). All of the sinuses communicate with the nasal cavity (paranasal = “next to nasal cavity”) and are lined with nasal mucosa. They serve to reduce bone mass and thus lighten the skull, and they also add resonance to the voice. This second feature is most obvious when you have a cold or sinus congestion. These produce swelling of the mucosa and excess mucus production, which can obstruct the narrow passageways between the sinuses and the nasal cavity, causing your voice to sound different to yourself and others. This blockage can also allow the sinuses to fill with fluid, with the resulting pressure producing pain and discomfort.

The paranasal sinuses are named for the skull bone that each occupies. The **frontal sinus** is located just above the eyebrows, within the frontal bone (Figure 6.3.16). This irregular space may be divided at the midline into bilateral spaces, or these may be fused into a single sinus space. The frontal sinus is the most anterior of the paranasal sinuses. The largest sinus is the **maxillary sinus**. These are paired and located within the right and left maxillary bones, where they occupy the area just below the orbits. The maxillary sinuses are most commonly involved during sinus infections. Because their connection to the nasal cavity is located high on their medial wall, they are difficult to drain. The **sphenoid sinus** is a single, midline sinus. It is located within the body of the sphenoid bone, just anterior and inferior to the sella turcica, thus making it the most posterior of the paranasal sinuses. The lateral aspects of the ethmoid bone contain multiple small spaces separated by very thin bony walls. Each of these spaces is called an **ethmoid air cell**. These are located on both sides of the ethmoid bone, between the upper nasal cavity and medial orbit, just behind the superior nasal conchae.

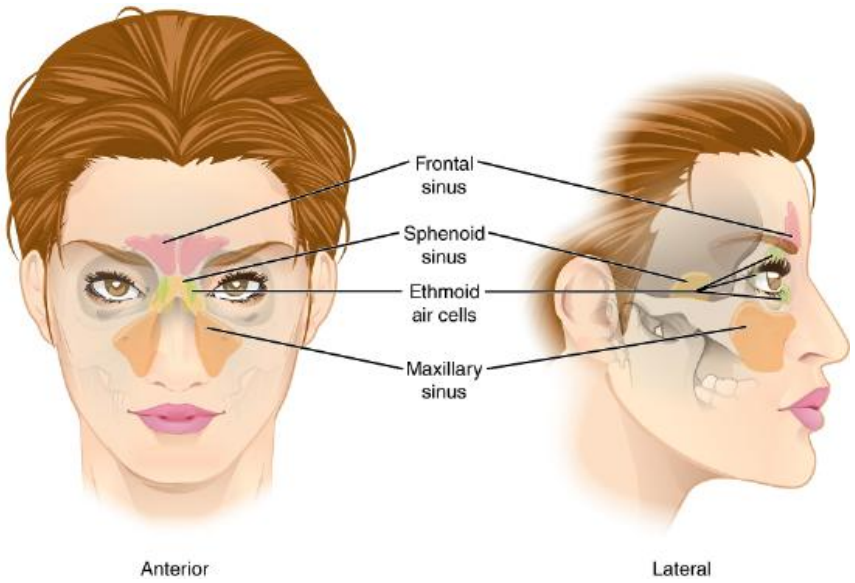

Figure 6.3.17: Paranasal Sinuses. The paranasal sinuses are hollow, air-filled spaces named for the skull bone that each occupies. The most anterior is the frontal sinus, located in the frontal bone above the eyebrows. The largest are the maxillary sinuses, located in the right and left maxillary bones below the orbits. The most posterior is the sphenoid sinus, located in the body of the sphenoid bone, under the sella turcica. The ethmoid air cells are multiple small spaces located in the right and left sides of the ethmoid bone, between the medial wall of the orbit and lateral wall of the upper nasal cavity. (Image credit: "Paranasal Sinuses" by OpenStax is licensed under CC BY 3.0)

Hyoid Bone

The **hyoid bone** is an independent bone that does not articulate (form a joint) any other bone and thus is not part of the skull. In fact, it is the only bone in the human body that does not articulate with another bone, making it unique. It is a small U-shaped bone located in the upper neck near the level of the inferior mandible, with the tips of the “U” pointing posteriorly. The hyoid serves as the base for the tongue above, and is attached to the larynx below and the pharynx posteriorly. The hyoid is held in position by a series of small muscles that attach to it either from above or below. These muscles act to move the hyoid up/down or forward/back. Movements of the hyoid are coordinated with movements of the tongue, larynx, and pharynx during swallowing and speaking.

Important landmarks of the hyoid bone, as seen in Figure 6.3.18, include:

- **Greater horn** - The larger, rough projection that forms the tip of the "U" shape and serves as a point of attachment for ligaments and several neck muscles.
- **Lesser horn** - A small, rough projection found on either side of the body that serves as a point of attachment for ligaments and muscles of the tongue.
- **Body of hyoid bone -** central portion of the hyoid bone that serves as an attachment point for neck and tongue muscles.

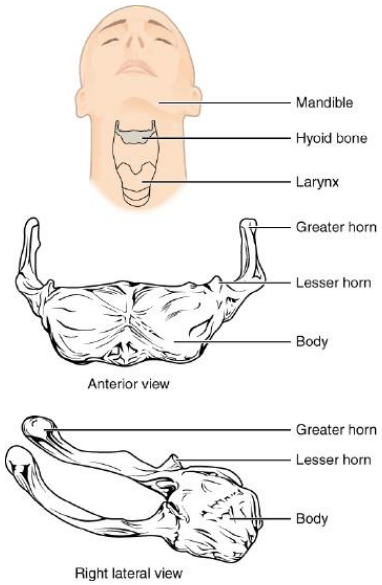

Figure 6.3.18: Hyoid Bone. The hyoid bone is located in the upper neck and does not join with any other bone. It provides attachments for muscles that act on the tongue, larynx, and pharynx. (Image credit: "Hyoid Bone" by OpenStax is licensed under CC BY 3.0)

Concept Review

The skull consists of the brain case and the facial bones. The brain case surrounds and protects the brain, which occupies the cranial cavity inside the skull. It consists of the rounded calvaria and a complex base. The brain case is formed by eight bones, the paired parietal and temporal bones plus the unpaired frontal, occipital, sphenoid, and ethmoid bones. The narrow gap between the bones is filled with dense, fibrous connective tissue that unites the bones. The sagittal suture joins the right and left parietal bones. The coronal suture joins the parietal bones to the frontal bone, the lamboid suture joins them to the occipital bone, and the squamous suture joins them to the temporal bone.

The facial bones support the facial structures and form the upper and lower jaws. These consist of 14 bones, with the paired maxillary, palatine, zygomatic, nasal, lacrimal, and inferior conchae bones and the unpaired vomer and mandible bones. The ethmoid bone also contributes to the formation of facial structures. The maxilla forms the upper jaw and the mandible forms the lower jaw. The maxilla also forms the larger anterior portion of the hard palate, which is completed by the smaller palatine bones that form the posterior portion of the hard palate.

The floor of the cranial cavity increases in depth from front to back and is divided into three cranial fossae. The anterior cranial fossa is located between the frontal bone and lesser wing of the sphenoid bone. A small area of the ethmoid bone, consisting of the crista galli and cribriform plates, is located at the midline of this fossa. The middle cranial fossa extends from the lesser wing of the sphenoid bone to the petrous ridge (petrous portion of temporal bone). The right and left sides are separated at the midline by the sella turcica, which surrounds the shallow hypophyseal fossa. Openings through the skull in the floor of the middle fossa include the optic canal and superior orbital fissure, which open into the posterior orbit, the foramen rotundum, foramen ovale, and foramen spinosum, and the exit of the carotid canal with its underlying foramen lacerum. The deep posterior cranial fossa extends from the petrous ridge to the occipital bone. Openings here include the large foramen magnum, plus the internal acoustic meatus, jugular foramina, and hypoglossal canals. Additional openings located on the external base of the skull include the stylomastoid foramen and the entrance to the carotid canal.

The anterior skull has the orbits that house the eyeballs and associated muscles. The walls of the orbit are formed by contributions from seven bones: the frontal, zygomatic, maxillary, palatine, ethmoid, lacrimal, and sphenoid. Located at the superior margin of the orbit is the supraorbital foramen, and below the orbit is the infraorbital foramen. The mandible has two openings, the mandibular foramen on its inner surface and the mental foramen on its external surface near the chin. The nasal conchae are bony projections from the lateral walls of the nasal cavity. The large inferior nasal concha is an independent bone, while the middle and superior conchae are parts of the ethmoid bone. The nasal septum is formed by the perpendicular plate of the ethmoid bone, the vomer bone, and the septal cartilage. The paranasal sinuses are air-filled spaces located within the frontal, maxillary, sphenoid, and ethmoid bones.

On the lateral skull, the zygomatic arch consists of two parts, the temporal process of the zygomatic bone anteriorly and the

zygomatic process of the temporal bone posteriorly. The temporal fossa is the shallow space located on the lateral skull above the level of the zygomatic arch. The infratemporal fossa is located below the zygomatic arch and deep to the ramus of the mandible.

The hyoid bone is located in the upper neck and does not join with any other bone. It is held in position by muscles and serves to support the tongue above, the larynx below, and the pharynx posteriorly.

Review Questions

Q. Which of the following is a bone of the brain case?

A. parietal bone

B. zygomatic bone

C. maxillary bone

D. lacrimal bone

Answer

Answer: A

Q. The lambdoid suture joins the parietal bone to the _____.

A. frontal bone

B. occipital bone

C. other parietal bone

D. temporal bone

Answer

Answer: B

Q. The middle cranial fossa _____.

A. is bounded anteriorly by the petrous ridge

B. is bounded posteriorly by the lesser wing of the sphenoid bone

C. is divided at the midline by a small area of the ethmoid bone

D. has the foramen rotundum, foramen ovale, and foramen spinosum

Answer

Answer: D

Q. The paranasal sinuses are _____.

A. air-filled spaces found within the frontal, maxilla, sphenoid, and ethmoid bones only

B. air-filled spaces found within all bones of the skull

C. not connected to the nasal cavity

D. divided at the midline by the nasal septum

Answer

Answer: A

Q. Parts of the sphenoid bone include the _____.

A. sella turcica

B. squamous portion

C. glabella

D. zygomatic process

Answer

Answer: A

Q. The bony openings of the skull include the _____.

A. carotid canal, which is located in the anterior cranial fossa

B. superior orbital fissure, which is located at the superior margin of the anterior orbit

C. mental foramen, which is located just below the orbit

D. hypoglossal canal, which is located in the posterior cranial fossa

Answer

Answer: D

Critical Thinking Questions

Q. Define and list the bones that form the brain case or support the facial structures.

Answer

A. The brain case is that portion of the skull that surrounds and protects the brain. It is subdivided into the rounded top of the skull, called the calvaria, and the base of the skull. There are eight bones that form the brain case. These are the paired parietal and temporal bones, plus the unpaired frontal, occipital, sphenoid, and ethmoid bones. The facial bones support the facial structures, and form the upper and lower jaws, nasal cavity, nasal septum, and orbit. There are 14 facial bones. These are the paired maxillary, palatine, zygomatic, nasal, lacrimal, and inferior nasal conchae bones, and the unpaired vomer and mandible bones.

Q. Identify the major sutures of the skull, their locations, and the bones united by each.

Answer

A. The coronal suture passes across the top of the anterior skull. It unites the frontal bone anteriorly with the right and left parietal bones. The sagittal suture runs at the midline on the top of the skull. It unites the right and left parietal bones with each other. The squamous suture is a curved suture located on the lateral side of the skull. It unites the squamous portion of the temporal bone to the parietal bone. The lambdoid suture is located on the posterior skull and has an inverted V-shape. It unites the occipital bone with the right and left parietal bones.

Q. Describe the anterior, middle, and posterior cranial fossae and their boundaries, and give the midline structure that divides each into right and left areas.

Answer

A. The anterior cranial fossa is the shallowest of the three cranial fossae. It extends from the frontal bone anteriorly to the lesser wing of the sphenoid bone posteriorly. It is divided at the midline by the crista galli and cribriform plates of the ethmoid bone. The middle cranial fossa is located in the central skull, and is deeper than the anterior fossa. The middle fossa extends from the lesser wing of the sphenoid bone anteriorly to the petrous ridge posteriorly. It is divided at the midline by the sella turcica. The posterior cranial fossa is the deepest fossa. It extends from the petrous ridge anteriorly to the occipital bone posteriorly. The large foramen magnum is located at the midline of the posterior fossa.

Q. Describe the parts of the nasal septum in both the dry and living skull.

Answer

A. There are two bony parts of the nasal septum in the dry skull. The perpendicular plate of the ethmoid bone forms the superior part of the septum. The vomer bone forms the inferior and posterior parts of the septum. In the living skull, the septal cartilage completes the septum by filling in the anterior area between the bony components and extending outward into the nose.

References

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Glossary

alveolar process of the mandible
upper border of mandibular body that contains the lower teeth

alveolar process of the maxilla
curved, inferior margin of the maxilla that supports and anchors the upper teeth

angle of the mandible
rounded corner located at outside margin of the body and ramus junction

anterior cranial fossa
shallowest and most anterior cranial fossa of the cranial base that extends from the frontal bone to the lesser wing of the sphenoid bone

articular tubercle
smooth ridge located on the inferior skull, immediately anterior to the mandibular fossa

body of the hyoid bone
central portion of the hyoid bone

body of the sphenoid bone
central portion of the sphenoid bone

brain case
portion of the skull that contains and protects the brain, consisting of the eight bones that form the cranial base and rounded upper skull

calvaria
(also, skullcap) rounded top of the skull

carotid canal
zig-zag tunnel providing passage through the base of the skull for the internal carotid artery to the brain; begins anteromedial to the styloid process and terminates in the middle cranial cavity, near the posterior-lateral base of the sella turcica

condylar process of the mandible
thickened upward projection from posterior margin of mandibular ramus

condyle
oval-shaped process located at the top of the condylar process of the mandible

coronal suture
joint that unites the frontal bone to the right and left parietal bones across the top of the skull

coronoid process of the mandible
flattened upward projection from the anterior margin of the mandibular ramus

cranial cavity
interior space of the skull that houses the brain

cranium
skull

cribriform plate
small, flattened areas with numerous small openings, located to either side of the midline in the floor of the anterior cranial fossa; formed by the ethmoid bone

crista galli
small upward projection located at the midline in the floor of the anterior cranial fossa; formed by the ethmoid bone

ethmoid air cell
one of several small, air-filled spaces located within the lateral sides of the ethmoid bone, between the orbit and upper nasal cavity

ethmoid bone
unpaired bone that forms the roof and upper, lateral walls of the nasal cavity, portions of the floor of the anterior cranial fossa and medial wall of orbit, and the upper portion of the nasal septum

external acoustic meatus
ear canal opening located on the lateral side of the skull

external occipital protuberance
small bump located at the midline on the posterior skull

facial bones
fourteen bones that support the facial structures and form the upper and lower jaws and the hard palate

foramen lacerum
irregular opening in the base of the skull, located inferior to the exit of carotid canal

foramen magnum
large opening in the occipital bone of the skull through which the spinal cord emerges and the vertebral arteries enter the cranium

foramen ovale of the middle cranial fossa
oval-shaped opening in the floor of the middle cranial fossa

foramen rotundum
round opening in the floor of the middle cranial fossa, located between the superior orbital fissure and foramen ovale

foramen spinosum
small opening in the floor of the middle cranial fossa, located lateral to the foramen ovale

frontal bone
unpaired bone that forms forehead, roof of orbit, and floor of anterior cranial fossa

frontal sinus
air-filled space within the frontal bone; most anterior of the paranasal sinuses

glabella
slight depression of frontal bone, located at the midline between the eyebrows

greater horn
larger, rough projection that forms the tip of the "U" shape of the hyoid bone

greater wings of sphenoid bone
lateral projections of the sphenoid bone that form the anterior wall of the middle cranial fossa and an area of the lateral skull

hard palate
bony structure that forms the roof of the mouth and floor of the nasal cavity, formed by the palatine process of the maxillary bones and the horizontal plate of the palatine bones

horizontal plate
medial extension from the palatine bone that forms the posterior quarter of the hard palate

hyoid bone
unpaired, u-shaped bone located in the upper neck

hypoglossal canal
paired openings that pass anteriorly from the anterior-lateral margins of the foramen magnum deep to the occipital condyles

hypophyseal (pituitary) fossa
shallow depression on top of the sella turcica that houses the pituitary (hypophyseal) gland

inferior nasal concha
one of the paired bones that project from the lateral walls of the nasal cavity to form the largest and most inferior of the nasal conchae

inferior orbital fissure
opening on the floor of the orbit between the sphenoid, maxillary, and zygomatic bones

infraorbital foramen
opening located on anterior skull, below the orbit

infratemporal fossa
space on lateral side of skull, below the level of the zygomatic arch and deep (medial) to the ramus of the mandible

internal acoustic meatus
opening into petrous ridge, located on the lateral wall of the posterior cranial fossa

jugular foramen
irregularly shaped opening located in the lateral floor of the posterior cranial cavity

lacrimal bone
paired bones that contribute to the anterior-medial wall of each orbit

lacrimal fossa
shallow depression in the anterior-medial wall of the orbit, formed by the lacrimal bone that gives rise to the nasolacrimal canal

lambdoid suture
inverted V-shaped joint that unites the occipital bone to the right and left parietal bones on the posterior skull

lateral pterygoid plate
paired, flattened bony projections of the sphenoid bone located on the inferior skull, lateral to the medial pterygoid plate

lesser horn
small, rough projection found on either side of the body of the hyoid bone

lesser wings of the sphenoid bone
lateral extensions of the sphenoid bone that form the bony lip separating the anterior and middle cranial fossae

lingula
small flap of bone located on the inner (medial) surface of mandibular ramus, next to the mandibular foramen

mandible
unpaired bone that forms the lower jaw bone; the only moveable bone of the skull

mandibular foramen
opening located on the inner (medial) surface of the mandibular ramus

mandibular fossa
oval depression located on the inferior surface of the skull

mandibular notch
large U-shaped notch located between the condylar process and coronoid process of the mandible

mastoid process
large bony prominence on the inferior, lateral skull, just behind the earlobe

mastoid portion of the temporal bone
posterior area of the temporal bone

maxillary bone
(also, maxilla) paired bones that form the upper jaw and anterior portion of the hard palate

maxillary sinus
air-filled space located with each maxillary bone; largest of the paranasal sinuses

medial pterygoid plate
paired, flattened bony projections of the sphenoid bone located on the inferior skull medial to the lateral pterygoid plate; form the posterior portion of the nasal cavity lateral wall

mental foramen
opening located on the anterior-lateral side of the mandibular body

mental protuberance
inferior margin of anterior mandible that forms the chin

middle cranial fossa
centrally located cranial fossa that extends from the lesser wings of the sphenoid bone to the petrous ridge

middle nasal concha
nasal concha formed by the ethmoid bone that is located between the superior and inferior conchae

mylohyoid line
bony ridge located along the inner (medial) surface of the mandibular body

nasal bone
paired bones that form the base of the nose

nasal cavity
opening through skull for passage of air

nasal conchae
curved bony plates that project from the lateral walls of the nasal cavity; include the superior and middle nasal conchae, which are parts of the ethmoid bone, and the independent inferior nasal conchae bone

nasal septum
: flat, midline structure that divides the nasal cavity into halves, formed by the perpendicular plate of the ethmoid bone, vomer bone, and septal cartilage

nasolacrimal canal
: passage for drainage of tears that extends downward from the medial-anterior orbit to the nasal cavity, terminating behind the inferior nasal conchae

occipital bone
: unpaired bone that forms the posterior portions of the brain case and base of the skull

occipital condyle
: paired, oval-shaped bony knobs located on the inferior skull, to either side of the foramen magnum

optic canal
: opening spanning between middle cranial fossa and posterior orbit

orbit
: bony socket that contains the eyeball and associated muscles

palatine bone
: paired bones that form the posterior quarter of the hard palate and a small area in floor of the orbit

palatine process
: medial projection from the maxilla bone that forms the anterior three quarters of the hard palate

paranasal sinuses
: cavities within the skull that are connected to the conchae that serve to warm and humidify incoming air, produce mucus, and lighten the weight of the skull; consist of frontal, maxillary, sphenoidal, and ethmoidal sinuses

parietal bone
: paired bones that form the upper, lateral sides of the skull

perpendicular plate of the ethmoid bone
: downward, midline extension of the ethmoid bone that forms the superior portion of the nasal septum

petrous ridge
: petrous portion of the temporal bone that forms a large, triangular ridge in the floor of the cranial cavity, separating the middle and posterior cranial fossae; houses the middle and inner ear structures

posterior cranial fossa
: deepest and most posterior cranial fossa; extends from the petrous ridge to the occipital bone

pterion
: H-shaped suture junction region that unites the frontal, parietal, temporal, and sphenoid bones on the lateral side of the skull

ramus of the mandible
: vertical portion of the mandible

sagittal suture
: joint that unites the right and left parietal bones at the midline along the top of the skull

sella turcica
: elevated area of sphenoid bone located at midline of the middle cranial fossa

septal cartilage
: flat cartilage structure that forms the anterior portion of the nasal septum

sphenoid bone
: unpaired bone that forms the central base of skull

sphenoid sinus
air-filled space located within the sphenoid bone; most posterior of the paranasal sinuses

squamous portion of the temporal bone
flat, superior area of the temporal bone

squamous suture
joint that unites the parietal bone to the squamous portion of the temporal bone on the lateral side of the skull

styloid process
downward projecting, elongated bony process located on the inferior aspect of the skull

stylomastoid foramen
opening located on inferior skull, between the styloid process and mastoid process

superior nasal concha
smallest and most superiorly located of the nasal conchae; formed by the ethmoid bone

superior nuchal line
paired bony lines on the posterior skull that extend laterally from the external occipital protuberance

superior orbital fissure
irregularly shaped opening between the middle cranial fossa and the posterior orbit

supraorbital foramen
opening located on anterior skull, at the superior margin of the orbit

supraorbital margin
superior margin of the orbit

suture
junction line at which adjacent bones of the skull are united by fibrous connective tissue

temporal bone
paired bones that form the lateral, inferior portions of the skull, with squamous, mastoid, and petrous portions

temporal fossa
shallow space on the lateral side of the skull, above the level of the zygomatic arch

temporal process of the zygomatic bone
short extension from the zygomatic bone that forms the anterior portion of the zygomatic arch

vomer bone
unpaired bone that forms the inferior and posterior portions of the nasal septum

zygomatic arch
elongated, free-standing arch on the lateral skull, formed anteriorly by the temporal process of the zygomatic bone and posteriorly by the zygomatic process of the temporal bone

zygomatic bone
cheekbone; paired bones that contribute to the lateral orbit and anterior zygomatic arch

zygomatic process of the maxilla
extension from the maxillary bone that articulates with the zygomatic bone

zygomatic process of the temporal bone
extension from the temporal bone that forms the posterior portion of the zygomatic arch

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6.4: The Vertebral Column

By the end of this section, you will be able to:

- Describe each region of the vertebral column and the number of bones in each region
- Discuss the curves of the vertebral column and how these change after birth
- Describe a typical vertebra and determine the distinguishing characteristics for vertebrae in each vertebral region and features of the sacrum and the coccyx
- Define the structure of an intervertebral disc
- Determine the location of the ligaments that provide support for the vertebral column

The vertebral column is also known as the spinal column or spine (Figure 6.4.1). It consists of a sequence of vertebrae (singular = vertebra), each of which is separated and united by an **intervertebral disc,** composed of a pad of fibrocartilage. Together, the vertebrae and intervertebral discs form the vertebral column. It is a flexible column that supports the head, neck, and body and allows for their movements. It also protects the spinal cord, which passes down the back through openings in the vertebrae.

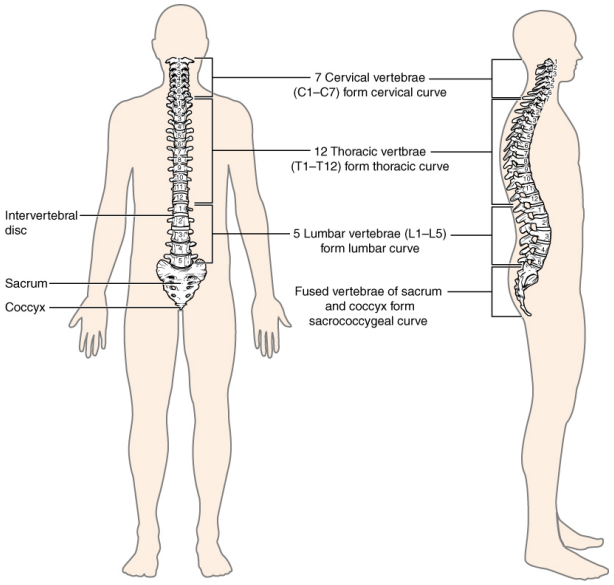

Figure 6.4.1: Vertebral Column. The adult vertebral column consists of 24 vertebrae, plus the sacrum and coccyx. The vertebrae are divided into three regions: cervical C1–C7 vertebrae, thoracic T1–T12 vertebrae, and lumbar L1–L5 vertebrae. The vertebral column is curved, with two primary curvatures (thoracic and sacrococcygeal curves) and two secondary curvatures (cervical and lumbar curves). (Image credit: "Vertebral Column" by OpenStax is licensed under CC BY 3.0)

Regions of the Vertebral Column

The vertebral column originally develops as a series of 33 vertebrae, but this number is eventually reduced to 24 vertebrae, plus the sacrum and coccyx. The vertebral column is subdivided into five regions, with the vertebrae in each area named for that region and numbered in descending order. In the neck, there are seven cervical vertebrae, each designated with the letter “C” followed by its number. Superiorly, the C1 vertebra articulates (forms a joint) with the occipital condyles of the occipital bone of the skull. Inferiorly, C1 articulates with the superior portion of the C2 vertebra. The inferior portion of C2 then articulates with the superior portion of the C3 vertebra, and so on. Below the cervical vertebrae are the 12 thoracic vertebrae, designated T1–T12. The lower back contains the L1–L5 lumbar vertebrae. The single sacrum, which is also part of the pelvis, is formed by the fusion of five sacral vertebrae. Similarly, the coccyx, or tailbone, results from the fusion of four small coccygeal vertebrae. However, the sacral and coccygeal fusions do not start until age 20 and are usually completed around age 30.

An interesting anatomical fact is that almost all mammals have seven cervical vertebrae, regardless of body size. This means that there are large variations in the size of cervical vertebrae, ranging from the very small cervical vertebrae of a shrew to the greatly

elongated vertebrae in the neck of a giraffe. In a full-grown giraffe, each cervical vertebra is 11 inches tall.

Curvatures of the Vertebral Column

The adult vertebral column does not form a straight line, but instead has four curvatures along its length (see Figure 6.4.1). These curves increase the vertebral column's strength, flexibility, and ability to absorb shock. When the load on the spine is increased, by carrying a heavy backpack for example, the curvatures increase in depth (become more curved) to accommodate the extra weight. They then spring back when the weight is removed. The four adult curvatures are classified as either primary or secondary curvatures. Primary curves are retained from the original fetal curvature, while secondary curvatures develop after birth.

During fetal development, the body is flexed anteriorly into the fetal position, giving the entire vertebral column a single curvature that is concave anteriorly. In the adult, this fetal curvature is retained in two regions of the vertebral column as the **thoracic curve**, which involves the thoracic vertebrae, and the **sacrococcygeal curve**, formed by the sacrum and coccyx. Each of these is thus called a **primary curve** because they are retained from the original fetal curvature of the vertebral column.

A **secondary curve** develops gradually after birth as the child learns to sit upright, stand, and walk. Secondary curves are concave posteriorly, opposite in direction to the original fetal curvature. The **cervical curve** of the neck region develops as the infant begins to hold their head upright when sitting. Later, as the child begins to stand and then to walk, the **lumbar curve** of the lower back develops. In adults, the lumbar curve is generally deeper in females, which helps to reduce back pressure during pregnancy.

DISORDERS OF THE...

Vertebral Column

Developmental anomalies, pathological changes, or obesity can enhance the normal vertebral column curves, resulting in the development of abnormal or excessive curvatures (Figure 6.4.2). **Kyphosis**, also referred to as humpback or hunchback, is an excessive posterior curvature of the thoracic region. This can develop when osteoporosis causes weakening and erosion of the anterior portions of the upper thoracic vertebrae, resulting in their gradual collapse (Figure 6.4.3). **Lordosis**, or swayback, is an excessive anterior curvature of the lumbar region and is most commonly associated with obesity or late pregnancy. The accumulation of body weight in the abdominal region results an anterior shift in the line of gravity that carries the weight of the body. This causes in an anterior tilt of the pelvis and a pronounced enhancement of the lumbar curve.

Scoliosis is an abnormal, lateral curvature, accompanied by twisting of the vertebral column. Compensatory curves may also develop in other areas of the vertebral column to help maintain the head positioned over the feet. Scoliosis is the most common vertebral abnormality among girls. The cause is usually unknown, but it may result from weakness of the back muscles, defects such as differential growth rates in the right and left sides of the vertebral column, or differences in the length of the lower limbs. When present, scoliosis tends to get worse during adolescent growth spurts. Although most individuals do not require treatment, a back brace may be recommended for growing children. In extreme cases, surgery may be required.

Excessive vertebral curves can be identified while an individual stands in the anatomical position. Observe the vertebral profile from the side and then from behind to check for kyphosis or lordosis. Then have the person bend forward. If scoliosis is present, an individual will have difficulty in bending directly forward, and the right and left sides of the back will not be level with each other in the bent position.

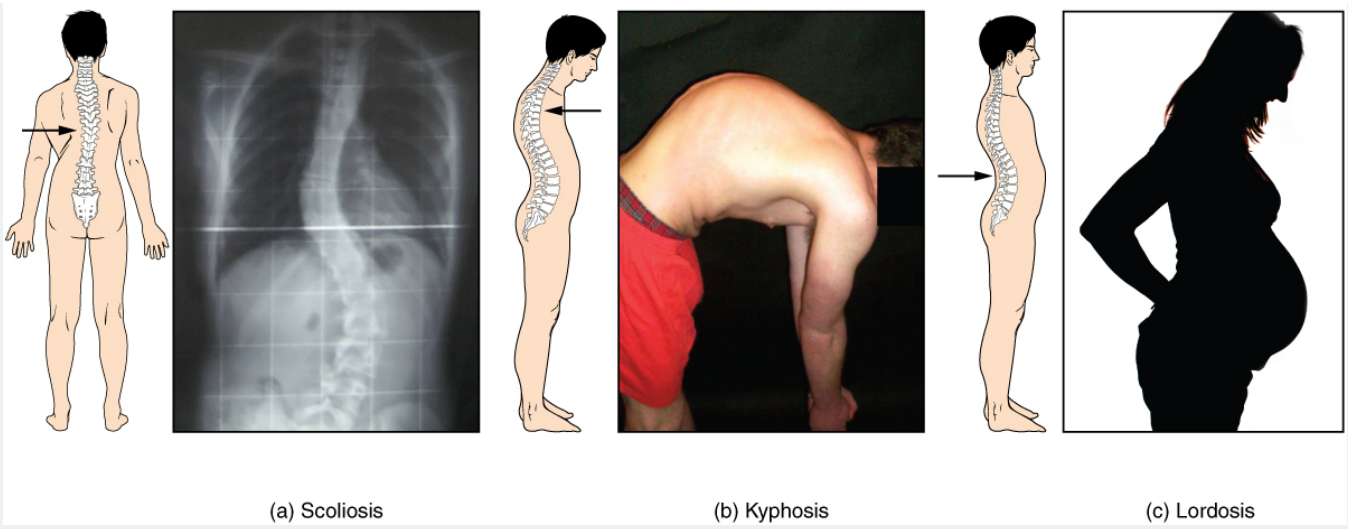

Figure 6.4.2: Abnormal Curvatures of the Vertebral Column. (a) Scoliosis is an abnormal lateral bending of the vertebral column. (b) An excessive curvature of the upper thoracic vertebral column is called kyphosis. (c) Lordosis is an excessive curvature in the lumbar region of the vertebral column. (Image credit: "Abnormal Curves of Vertebral Column" by OpenStax is licensed under CC BY 3.0)

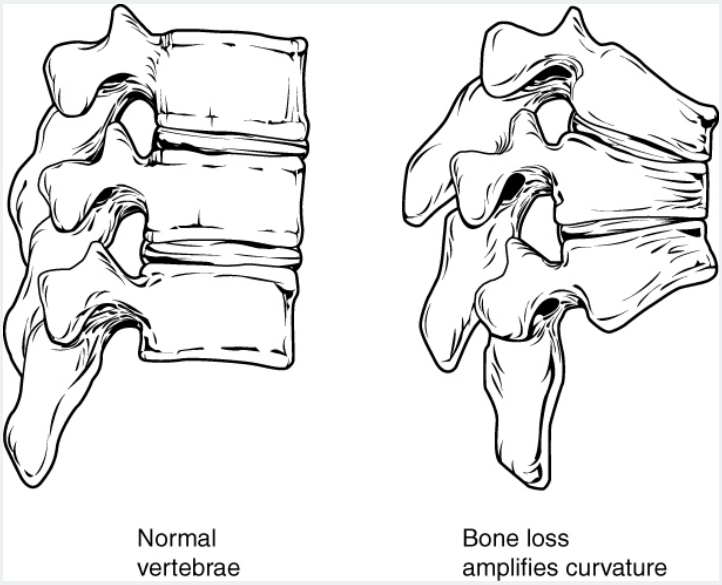

Figure 6.4.3: Kyphosis. Osteoporosis is an age-related disorder that causes the gradual loss of bone density and strength. When the thoracic vertebrae are affected, there can be a gradual collapse of the vertebrae. This results in kyphosis, an excessive curvature of the thoracic region. (Image credit: "Feature Osteoprosis of Spine" by OpenStax is licensed under CC BY 3.0)

General Structure of a Vertebra

Within the different regions of the vertebral column, vertebrae vary in size and shape, but they all follow a similar structural pattern. A typical vertebra will consist of a body, a vertebral arch, and seven processes (Figure 6.4.4). The **body** is the anterior portion of each vertebra and is the part that supports the body weight. Because of this, the vertebral bodies progressively increase in size and thickness going down the vertebral column. The bodies of adjacent vertebrae are separated and strongly united by an intervertebral disc.

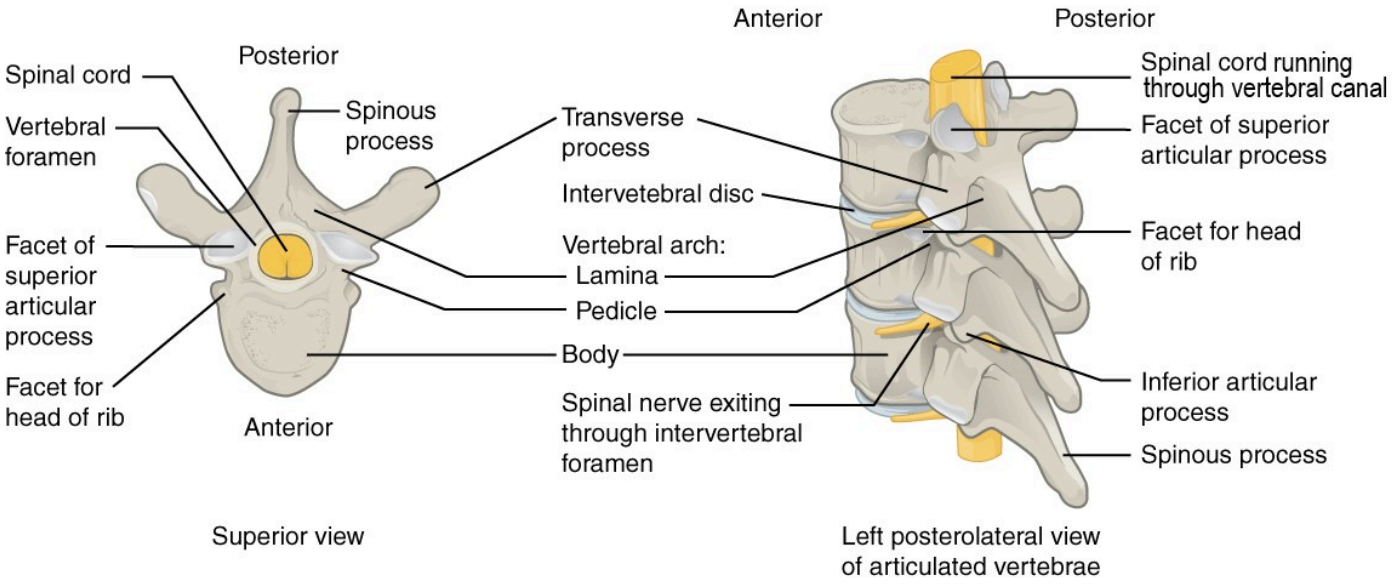

Figure 6.4.4: Parts of a Typical Vertebra. A typical vertebra consists of a body and a vertebral arch. The arch is formed by the paired pedicles and paired laminae. Arising from the vertebral arch are the transverse, spinous, superior articular, and inferior articular processes. The vertebral foramen provides for passage of the spinal cord. Each spinal nerve exits through an intervertebral foramen, located between adjacent vertebrae. Intervertebral discs unite the bodies of adjacent vertebrae. (Image credit: "Vertebra" by Whitney Menefee is licensed under CC BY 4.0 / A derivative from the original work)

The **vertebral arch** forms the posterior portion of each vertebra. It consists of four parts, the right and left pedicles and the right and left laminae. Each **pedicle** forms one of the lateral sides of the vertebral arch. The pedicles are anchored to the posterior side of the vertebral body. Each **lamina** forms part of the posterior roof of the vertebral arch. The large opening between the vertebral arch and body is the **vertebral foramen**, which contains the spinal cord. In the intact vertebral column, the vertebral foramina of all of the vertebrae align to form the **vertebral (spinal) canal**, which serves as the bony protection and passageway for the spinal cord down the back. When the vertebrae are aligned together in the vertebral column, notches in the margins of the pedicles of adjacent vertebrae together form an **intervertebral foramen**, the opening through which a spinal nerve exits from the vertebral column (see also Figure 6.4.10).

Seven processes arise from the vertebral arch. Each paired **transverse process** projects laterally and arises from the junction point between the pedicle and lamina. The single **spinous process** (vertebral spine) projects posteriorly at the midline of the back. The vertebral spines can easily be felt as a series of bumps just under the skin down the middle of the back. The transverse and spinous processes serve as important muscle attachment sites. A **superior articular process** extends or faces upward, and an **inferior articular process** faces or projects downward on each side of a vertebrae. The paired superior articular processes of one vertebra join with the corresponding paired inferior articular processes from the next higher vertebra. Each process has a **facet**, or flat surface, to accommodate this joining of the vertebrae. These junctions form slightly moveable joints between the adjacent vertebrae. The shape and orientation of the articular processes vary in different regions of the vertebral column and play a major role in determining the type and range of motion available in each region.

Regional Modifications of Vertebrae

In addition to the general characteristics of a typical vertebra described above, vertebrae also display characteristic size and structural features that vary between the different vertebral column regions. For example, cervical vertebrae are smaller than lumbar vertebrae due to differences in the proportion of body weight that each supports. Only thoracic vertebrae have sites for rib attachment, and the vertebrae that give rise to the sacrum and coccyx have fused together into single bones.

Cervical Vertebrae

Typical **cervical vertebrae**, such as C3 through C7, have several characteristic features that differentiate them from thoracic or lumbar vertebrae (Figure 6.4.5). Cervical vertebrae have a small body, reflecting the fact that they carry the least amount of body weight. Cervical vertebrae usually have a bifid (Y-shaped) spinous process. The spinous processes of the C3–C6 vertebrae are short, but the spine of C7 is much longer. You can find these vertebrae by running your finger down the midline of the posterior

neck until you encounter the prominent C7 spine located at the base of the neck. Because of this feature, the C7 vertebra is also known as the **vertebra prominens**. The transverse processes of the cervical vertebrae are sharply curved (U-shaped) to allow for passage of the cervical spinal nerves. Each transverse process also has an opening called the **transverse foramen**. An important artery that supplies the brain ascends up the neck by passing through these openings. The superior and inferior articular processes of the cervical vertebrae are flattened and largely face upward or downward, respectively.

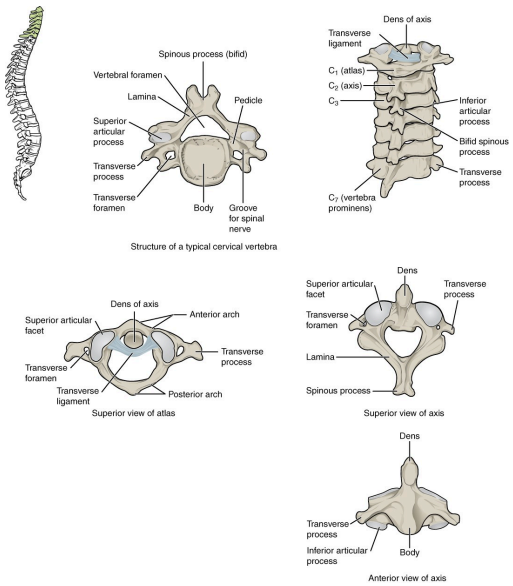

Figure 6.4.5: Cervical Vertebrae. A typical cervical vertebra has a small body, a bifid spinous process, transverse processes that have a transverse foramen and are curved for spinal nerve passage. The atlas (C1 vertebra) does not have a body or spinous process. It consists of an anterior and a posterior arch and elongated transverse processes. The axis (C2 vertebra) has the upward projecting dens, which articulates with the anterior arch of the atlas. (Image credit: "Cervical Vertebrae" by Whitney Menefee is licensed under CC BY 3.0 / A derivative from the original work)

The first and second cervical vertebrae are further modified, giving each a distinctive appearance. The first cervical (C1) vertebra is also called the **atlas**, because this is the vertebra that supports the skull on top of the vertebral column (in Greek mythology, Atlas was the god who supported the heavens on his shoulders). The C1 vertebra does not have a body or spinous process. Instead, it is ring-shaped, consisting of an **anterior arch** and a **posterior arch**. The transverse processes of the atlas are longer and extend more laterally than do the transverse processes of any other cervical vertebrae. The superior articular processes face upward and are deeply curved for articulation with the occipital condyles on the base of the skull. The inferior articular processes are flat and face downward to join with the superior articular processes of the C2 vertebra.

The second cervical (C2) vertebra is called the **axis**, because it serves as the axis for rotation when turning the head toward the right or left. The axis resembles typical cervical vertebrae in most respects, but is easily distinguished by the **dens** (odontoid process), a bony projection that extends upward from the vertebral body. The dens joins with the inner aspect of the anterior arch of the atlas, where it is held in place by transverse ligament.

Thoracic Vertebrae

The bodies of the **thoracic vertebrae** are larger than those of cervical vertebrae (Figure 6.4.6). The characteristic feature for a typical midthoracic vertebra is the spinous process, which is long and has a pronounced downward angle that causes it to overlap the next inferior vertebra. The superior articular processes of thoracic vertebrae face anteriorly and the inferior processes face posteriorly. These orientations are important determinants for the type and range of movements available to the thoracic region of the vertebral column.

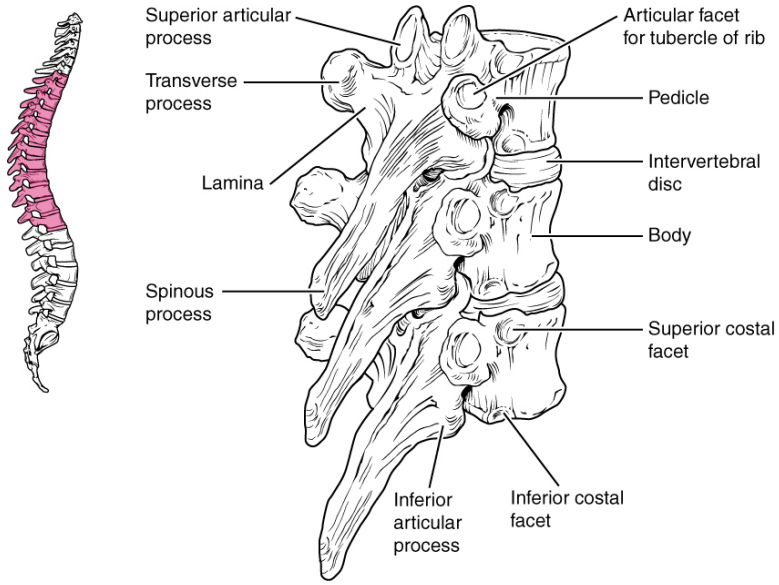

Figure 6.4.6: Thoracic Vertebrae. A typical thoracic vertebra is distinguished by the spinous process, which is long and projects downward to overlap the next inferior vertebra. It also has articulation sites (facets) on the vertebral body and a transverse process for rib attachment. (Image credit: "Thoracic Vertebra" by OpenStax is licensed under CC BY 3.0)

Thoracic vertebrae have several additional articulation sites, each of which is called a **facet**, where a rib is attached (Figure 6.4.7). Most thoracic vertebrae have a superior and inferior facet located on the lateral sides of the body, each of which is called a **costal facet** (costal = "rib"). These are for articulation with the head (end) of a rib. An additional facet is located on the transverse process for articulation with the tubercle of a rib.

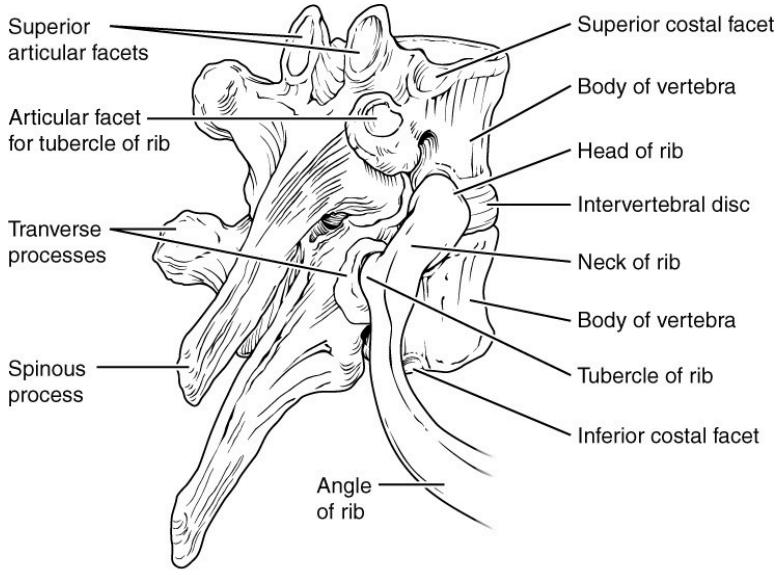

Figure 6.4.7: Rib Articulation in Thoracic Vertebrae. Thoracic vertebrae have superior and inferior articular facets on the vertebral body for articulation with the head of a rib, and a transverse process facet for articulation with the rib tubercle. (Image credit: "Thoracic Vertebra and Rib" by Whitney Menefee is licensed under CC BY 3.0 / A derivative from the original work)

Lumbar Vertebrae

Lumbar vertebrae carry the greatest amount of body weight and are thus characterized by the large size and thickness of the vertebral body (Figure 6.4.8). They have short transverse processes and a short, blunt spinous process that projects posteriorly. The articular processes are large, with the superior process facing backward and the inferior facing forward.

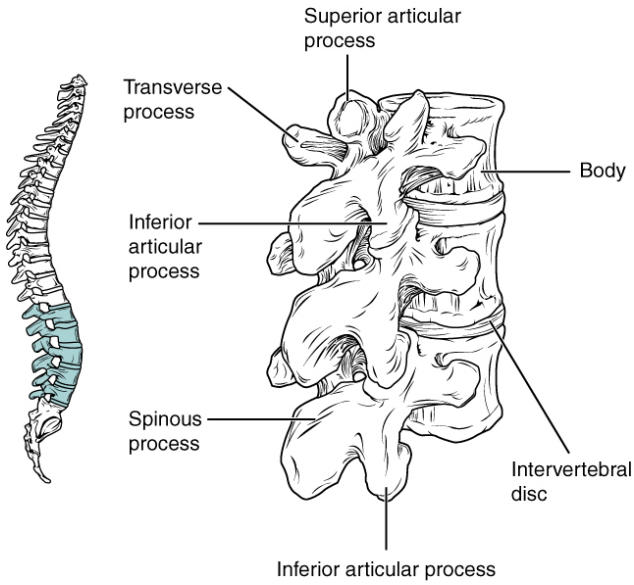

Figure 6.4.8: Lumbar Vertebrae. Lumbar vertebrae are characterized by having a large, thick body and a short, rounded spinous process. (Image credit: "Lumbar Vertebra" by OpenStax is licensed under CC BY 3.0)

Sacrum and Coccyx

The **sacrum** is a triangular-shaped bone that is thick and wide across its superior base where it is weight bearing and then tapers down to an inferior, non-weight bearing apex (Figure 6.4.9). It is formed by the fusion of five sacral vertebrae, a process that does not begin until after the age of 20 and continues until around age 30. On the anterior surface of the older adult sacrum, the lines of vertebral fusion can be seen as four **transverse ridges**. On the posterior surface, running down the midline, is the **median sacral crest**, a bumpy ridge that is the remnant of the fused spinous processes (median = “midline”; while medial = “toward, but not necessarily at, the midline”). Similarly, the fused transverse processes of the sacral vertebrae form the **lateral sacral crest**.

The **sacral promontory** is the anterior lip of the superior base of the sacrum. Lateral to this is the roughened auricular surface, which joins with the ilium portion of the hipbone to form the immobile sacroiliac joints of the pelvis. Passing inferiorly through the sacrum is a bony tunnel called the **sacral canal**, which terminates at the **sacral hiatus** near the inferior tip of the sacrum. The anterior and posterior surfaces of the sacrum have a series of paired openings called **sacral foramina** (singular = foramen) that connect to the sacral canal. Each of these openings is called a **posterior (dorsal) sacral foramen** or **anterior (ventral) sacral foramen**. These openings allow for the anterior and posterior branches of the sacral spinal nerves to exit the sacrum. The **superior articular process of the sacrum**, one of which is found on either side of the superior opening of the sacral canal, articulates with the inferior articular processes from the L5 vertebra.

The **coccyx**, or tailbone, is derived from the fusion of four very small coccygeal vertebrae (see Figure 6.4.9). It articulates with the inferior tip of the sacrum. It is not weight bearing in the standing position, but may receive some body weight when sitting.

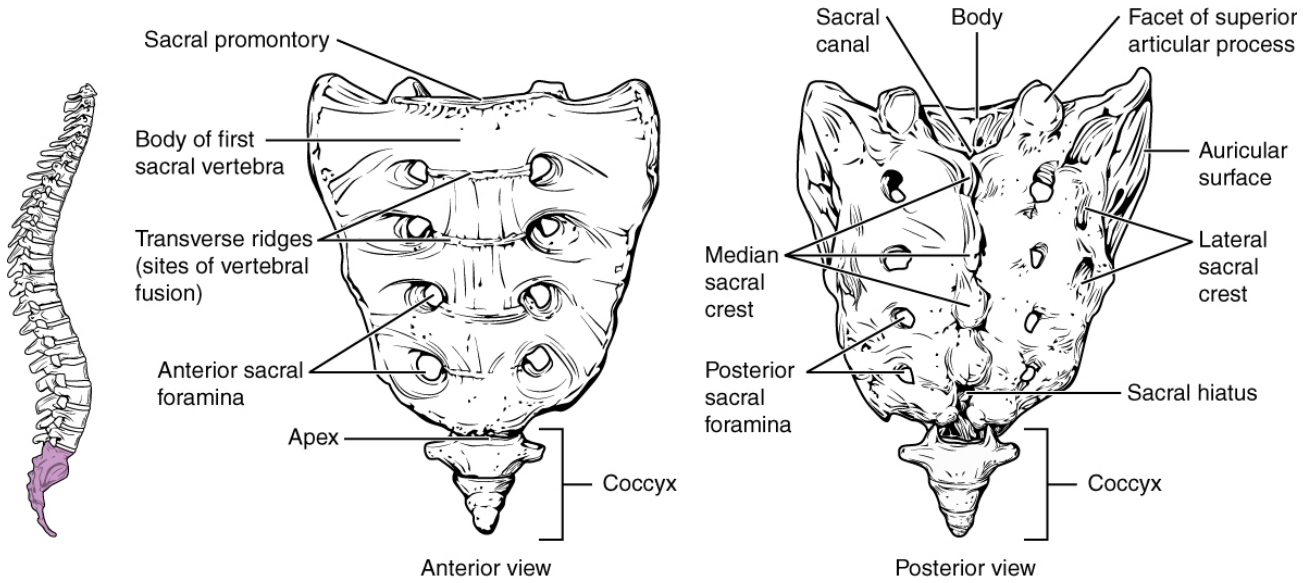

Figure 6.4.9: Sacrum and Coccyx. The sacrum is formed from the fusion of five sacral vertebrae, whose lines of fusion are indicated by the transverse ridges. The fused spinous processes form the median sacral crest, while the lateral sacral crest arises from the fused transverse processes. The coccyx is formed by the fusion of four small coccygeal vertebrae. (Image credit: "Sacrum and Coccyx" by OpenStax is licensed under CC BY 3.0)

Intervertebral Discs and Ligaments of the Vertebral Column

The bodies of adjacent vertebrae are strongly anchored to each other by an intervertebral disc. This structure provides padding between the bones when they bear wieght, and because it can change shape, also allows for movement between the vertebrae. Although the total amount of movement available between any two adjacent vertebrae is small, when these movements are summed together along the entire length of the vertebral column, large body movements can be produced. Ligaments that extend along the length of the vertebral column also contribute to its overall support and stability.

Intervertebral Disc

An **intervertebral disc** is a fibrocartilaginous pad that fills the gap between adjacent vertebral bodies (Figure 6.4.10). Each disc is anchored to the bodies of its adjacent vertebrae, thus strongly uniting the set. The discs also provide padding between vertebrae during weight bearing. Because of this, intervertebral discs are thin in the cervical region and thickest in the lumbar region, which carries the most body weight. In total, the intervertebral discs account for approximately 25 percent of your body height between the top of the pelvis and the base of the skull. Intervertebral discs are also flexible and can change shape to allow for movements of the vertebral column.

Each intervertebral disc consists of two parts. The **anulus fibrosus** is the tough, fibrous outer layer of the disc. It forms a circle (anulus = “ring” or “circle”) and is firmly anchored to the outer margins of the adjacent vertebral bodies. Inside is the **nucleus pulposus**, consisting of a softer, more gel-like material. It has a high water content that serves to resist compression and thus is important for weight bearing. With increasing age, the water content of the nucleus pulposus gradually declines. This causes the disc to become thinner, decreasing total body height somewhat, and reduces the flexibility and range of motion of the disc, making bending more difficult.

The gel-like nature of the nucleus pulposus also allows the intervertebral disc to change shape as one vertebra rocks side to side or forward and back in relation to its neighbors during movements of the vertebral column. Thus, bending forward causes compression of the anterior portion of the disc but expansion of the posterior disc. If the posterior anulus fibrosus is weakened due to injury or increasing age, the pressure exerted on the disc when bending forward and lifting a heavy object can cause the nucleus pulposus to protrude posteriorly through the anulus fibrosus, resulting in a herniated disc (“ruptured” or “slipped” disc) (Figure 6.4.11). The posterior bulging of the nucleus pulposus can cause compression of a spinal nerve at the point where it exits through the intervertebral foramen, with resulting pain and/or muscle weakness in those body regions supplied by that nerve. The most common sites for disc herniation are the L4/L5 or L5/S1 intervertebral discs, which can cause sciatica, a widespread pain that radiates from the lower back down the thigh and into the leg. Similar injuries of the C5/C6 or C6/C7 intervertebral discs,

following forcible hyperflexion of the neck from a collision accident or football injury, can produce pain in the neck, shoulder, and upper limb.

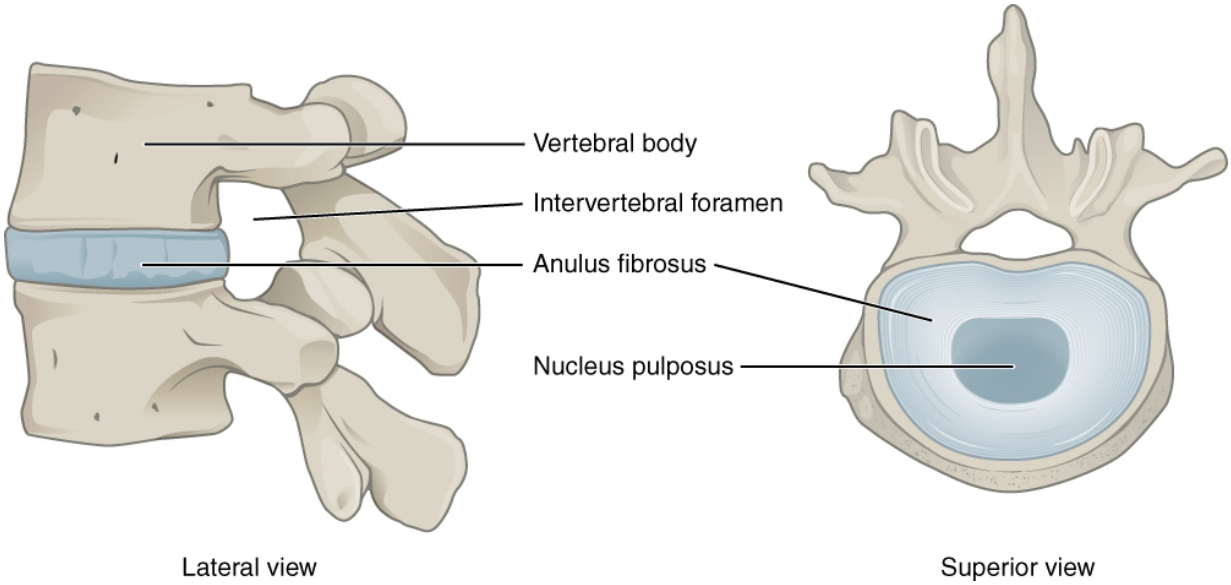

Figure 6.4.10: Intervertebral Disc. The bodies of adjacent vertebrae are separated and united by an intervertebral disc, which provides padding and allows for movements between adjacent vertebrae. The disc consists of a fibrous outer layer called the anulus fibrosus and a gel-like center called the nucleus pulposus. The intervertebral foramen is the opening formed between adjacent vertebrae for the exit of a spinal nerve. (Image credit: "Intervertebral Disk" by OpenStax is licensed under CC BY 3.0)

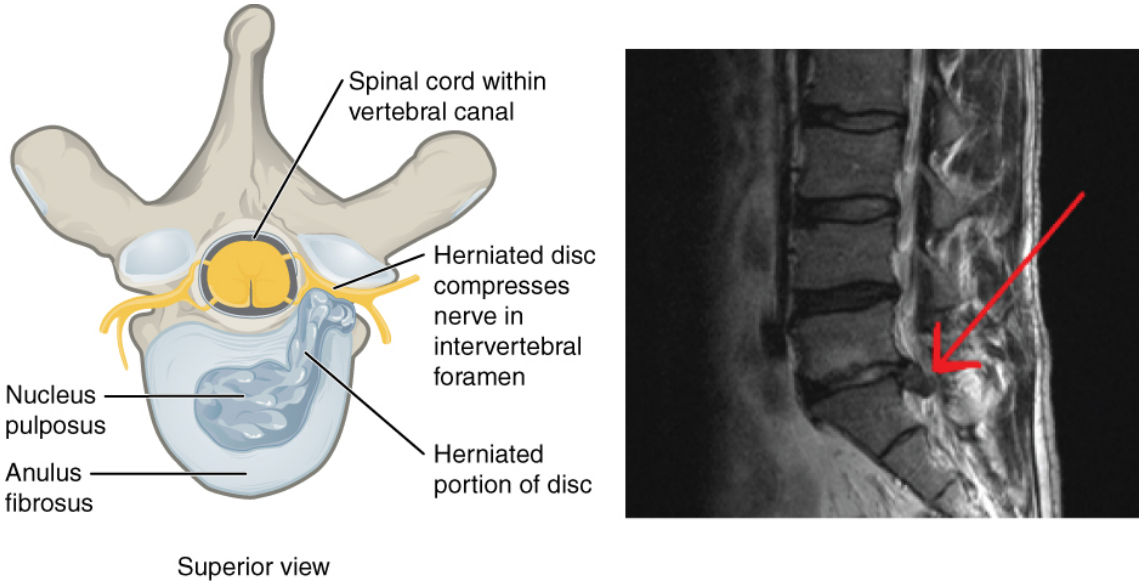

Figure 6.4.11: Herniated Intervertebral Disc. Weakening of the anulus fibrosus can result in herniation (protrusion) of the nucleus pulposus and compression of a spinal nerve, resulting in pain and/or muscle weakness in the body regions supplied by that nerve. (Image credit: "Herniated Disk" by OpenStax is licensed under CC BY 3.0)

Ligaments of the Vertebral Column

Adjacent vertebrae are united by ligaments that run the length of the vertebral column along both its posterior and anterior aspects (Figure 6.4.12). These serve to resist excess forward or backward bending movements of the vertebral column, respectively.

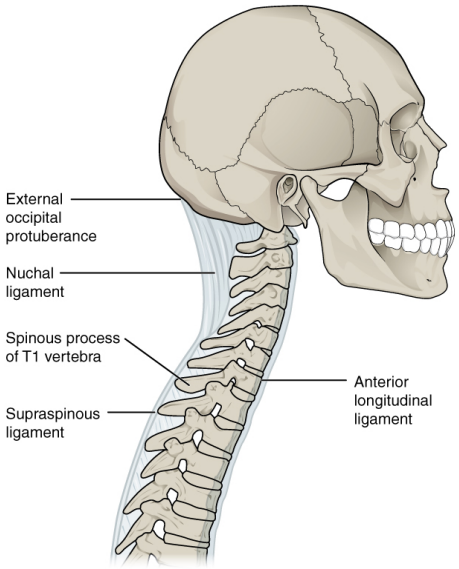

Figure 6.4.12: Ligaments of Vertebral Column. The anterior longitudinal ligament runs the length of the vertebral column, uniting the anterior sides of the vertebral bodies. The supraspinous ligament connects the spinous processes of the thoracic and lumbar vertebrae. In the posterior neck, the supraspinous ligament enlarges to form the nuchal ligament, which attaches to the cervical spinous processes and to the base of the skull. (Image credit: "Ligaments of Vertebral Column" by OpenStax is licensed under CC BY 3.0)

The **anterior longitudinal ligament** runs down the anterior side of the entire vertebral column, uniting the vertebral bodies. It serves to resist excess backward bending of the vertebral column. Protection against this movement is particularly important in the neck, where extreme posterior bending of the head and neck can stretch or tear this ligament, resulting in a painful whiplash injury. Prior to the mandatory installation of seat headrests, whiplash injuries were common for passengers involved in a rear-end automobile collision.

The **supraspinous ligament** is located on the posterior side of the vertebral column, where it interconnects the spinous processes of the thoracic and lumbar vertebrae. This strong ligament supports the vertebral column during forward bending motions. In the posterior neck, where the cervical spinous processes are short, the supraspinous ligament expands to become the **nuchal ligament** (nuchae = “nape” or “back of the neck”). The nuchal ligament is attached to the cervical spinous processes and extends upward and posteriorly to attach to the midline base of the skull, out to the external occipital protuberance. It supports the skull and prevents it from falling forward. This ligament is much larger and stronger in four-legged animals such as cows, where the large skull hangs off the front end of the vertebral column. You can easily feel this ligament by first extending your head backward and pressing down on the posterior midline of your neck. Then tilt your head forward and you will fill the nuchal ligament popping out as it tightens to limit anterior bending of the head and neck.

Additional ligaments are located inside the vertebral canal, next to the spinal cord, along the length of the vertebral column. The **posterior longitudinal ligament** is found anterior to the spinal cord, where it is attached to the posterior sides of the vertebral bodies. Posterior to the spinal cord is the **ligamentum flavum** (“yellow ligament”). This consists of a series of short, paired ligaments, each of which interconnects the lamina regions of adjacent vertebrae. The ligamentum flavum has large numbers of elastic fibers, which have a yellowish color, allowing it to stretch and then pull back. Both of these ligaments provide important support for the vertebral column when bending forward.

Interactive Link

Structures of the Vertebral Column

Use this Anatomy Explorer - The Spine to identify the bones, intervertebral discs, and ligaments of the vertebral column. The thickest portions of the anterior longitudinal ligament and the supraspinous ligament are found in which regions of the vertebral column?

Answer available at the end of this section.

CAREER CONNECTIONS

Chiropractor

Chiropractors are health professionals who use nonsurgical techniques to help patients with musculoskeletal system problems that involve the bones, muscles, ligaments, tendons, or nervous system. They treat problems such as neck pain, back pain, joint pain, or headaches. Chiropractors focus on the patient's overall health and can also provide counseling related to lifestyle issues, such as diet, exercise, or sleep problems. If needed, they will refer the patient to other medical specialists.

Chiropractors use a drug-free, hands-on approach for patient diagnosis and treatment. They will perform a physical exam, assess the patient's posture and spine, and may perform additional diagnostic tests, including taking X-ray images. They primarily use manual techniques, such as spinal manipulation, to adjust the patient's spine or other joints. They can recommend therapeutic or rehabilitative exercises, and some also include acupuncture, massage therapy, or ultrasound as part of the treatment program. In addition to those in general practice, some chiropractors specialize in sport injuries, neurology, orthopaedics, pediatrics, nutrition, internal disorders, or diagnostic imaging.

To become a chiropractor, students must have 3–4 years of undergraduate education, attend an accredited, four-year Doctor of Chiropractic (D.C.) degree program, and pass a licensure examination to be licensed for practice in their state. With the aging of the baby-boom generation, employment for chiropractors is expected to increase.

Concept Review

The vertebral column forms the neck and back. The vertebral column originally develops as 33 vertebrae, but is eventually reduced to 24 vertebrae, plus the sacrum and coccyx. The vertebrae are divided into the cervical region (C1–C7 vertebrae), the thoracic region (T1–T12 vertebrae), and the lumbar region (L1–L5 vertebrae). The sacrum arises from the fusion of five sacral vertebrae and the coccyx from the fusion of four small coccygeal vertebrae. The vertebral column has four curvatures, the cervical, thoracic, lumbar, and sacrococcygeal curves. The thoracic and sacrococcygeal curves are primary curves retained from the original fetal curvature. The cervical and lumbar curves develop after birth and thus are secondary curves. The cervical curve develops as the infant begins to hold up the head, and the lumbar curve appears with standing and walking.

A typical vertebra consists of an enlarged anterior portion called the body, which provides weight-bearing support. Attached posteriorly to the body is a vertebral arch, which surrounds and defines the vertebral foramen for passage of the spinal cord. The vertebral arch consists of the pedicles, which attach to the vertebral body, and the laminae, which come together to form the roof of the arch. Arising from the vertebral arch are the laterally projecting transverse processes and the posteriorly oriented spinous process. The superior articular processes project upward, where they articulate with the downward projecting inferior articular

processes of the next higher vertebrae.

A typical cervical vertebra has a small body, a bifid (Y-shaped) spinous process, and U-shaped transverse processes with a transverse foramen. In addition to these characteristics, the axis (C2 vertebra) also has the dens projecting upward from the vertebral body. The atlas (C1 vertebra) differs from the other cervical vertebrae in that it does not have a body, but instead consists of bony ring formed by the anterior and posterior arches. The atlas articulates with the dens from the axis. A typical thoracic vertebra is distinguished by its long, downward projecting spinous process. Thoracic vertebrae also have articulation facets on the body and transverse processes for attachment of the ribs. Lumbar vertebrae support the greatest amount of body weight and thus have a large, thick body. They also have a short, blunt spinous process. The sacrum is triangular in shape. The median sacral crest is formed by the fused vertebral spinous processes and the lateral sacral crest is derived from the fused transverse processes. Anterior (ventral) and posterior (dorsal) sacral foramina allow branches of the sacral spinal nerves to exit the sacrum. The auricular surfaces are articulation sites on the lateral sacrum that anchor the sacrum to the hipbones to form the pelvis. The coccyx is small and derived from the fusion of four small vertebrae.

The intervertebral discs fill in the gaps between the bodies of adjacent vertebrae. They provide strong attachments and padding between the vertebrae. The outer, fibrous layer of a disc is called the anulus fibrosus. The gel-like interior is called the nucleus pulposus. The disc can change shape to allow for movement between vertebrae. If the anulus fibrosus is weakened or damaged, the nucleus pulposus can protrude outward, resulting in a herniated disc.

The anterior longitudinal ligament runs along the full length of the anterior vertebral column, uniting the vertebral bodies. The supraspinous ligament is located posteriorly and interconnects the spinous processes of the thoracic and lumbar vertebrae. In the neck, this ligament expands to become the nuchal ligament. The nuchal ligament is attached to the cervical spinous processes and superiorly to the base of the skull, out to the external occipital protuberance. The posterior longitudinal ligament runs within the vertebral canal and unites the posterior sides of the vertebral bodies. The ligamentum flavum unites the lamina of adjacent vertebrae.

Review Questions

Q. The cervical region of the vertebral column consists of _____.

A. seven vertebrae

B. twelve vertebrae

C. five vertebrae

D. a single bone derived from the fusion of five vertebrae

Answer

Answer: A

Q. The primary curvatures of the vertebral column _____.

A. include the lumbar curve

B. are remnants of the original fetal curvature

C. include the cervical curve

D. develop after the time of birth

Answer

Answer: B

Q. A typical vertebra has _____.

A. a vertebral foramen that passes through the body

B. a superior articular process that projects downward to articulate with the superior portion of the next lower vertebra

C. lamina that spans between the transverse process and spinous process

D. a pair of laterally projecting spinous processes

Answer

Answer: C

Q. A typical lumbar vertebra has _____.

A. a short, rounded spinous process

B. a bifid spinous process

C. articulation sites for ribs

D. a transverse foramen

Answer

Answer: A

Q. Which is found only in the cervical region of the vertebral column?

A. nuchal ligament

B. ligamentum flavum

C. supraspinous ligament

D. anterior longitudinal ligament

Answer

Answer: A

Critical Thinking Questions

Q. Describe the vertebral column and define each region.

Answer

Answer: The adult vertebral column consists of 24 vertebrae, plus the sacrum and coccyx. The vertebrae are subdivided into cervical, thoracic, and lumbar regions. There are seven cervical vertebrae (C1–C7), 12 thoracic vertebrae (T1–T12), and five lumbar vertebrae (L1–L5). The sacrum is derived from the fusion of five sacral vertebrae and the coccyx is formed by the fusion of four small coccygeal vertebrae.

Q. Describe a typical vertebra.

Answer

Answer: A typical vertebra consists of an anterior body and a posterior vertebral arch. The body serves for weight bearing. The vertebral arch surrounds and protects the spinal cord. The vertebral arch is formed by the pedicles, which are attached to the posterior side of the vertebral body, and the lamina, which come together to form the top of the arch. A pair of transverse processes extends laterally from the vertebral arch, at the junction between each pedicle and lamina. The spinous process extends posteriorly from the top of the arch. A pair of superior articular processes project upward and a pair of inferior articular processes project downward. Together, the notches found in the margins of the pedicles of adjacent vertebrae form an intervertebral foramen.

Q. Describe the sacrum.

Answer

Answer: The sacrum is a single, triangular-shaped bone formed by the fusion of five sacral vertebrae. On the posterior sacrum, the median sacral crest is derived from the fused spinous processes, and the lateral sacral crest results from the fused transverse processes. The sacral canal contains the sacral spinal nerves, which exit via the anterior (ventral) and posterior (dorsal) sacral foramina. The sacral promontory is the anterior lip. The sacrum also forms the posterior portion of the pelvis.

Q. Describe the structure and function of an intervertebral disc.

Answer

Answer: An intervertebral disc fills in the space between adjacent vertebrae, where it provides padding and weight-bearing ability, and allows for movements between the vertebrae. It consists of an outer anulus fibrosus and an inner nucleus pulposus. The anulus fibrosus strongly anchors the adjacent vertebrae to each other, and the high water content of the nucleus pulposus resists compression for weight bearing and can change shape to allow for vertebral column movements.

Q. Define the ligaments of the vertebral column.

Answer

Answer: The anterior longitudinal ligament is attached to the vertebral bodies on the anterior side of the vertebral column. The supraspinous ligament is located on the posterior side, where it interconnects the thoracic and lumbar spinous processes. In the posterior neck, this ligament expands to become the nuchal ligament, which attaches to the cervical spinous processes and the base of the skull. The posterior longitudinal ligament and ligamentum flavum are located inside the vertebral canal. The posterior longitudinal ligament unites the posterior sides of the vertebral bodies. The ligamentum flavum unites the lamina of adjacent vertebrae.

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https://www.nytimes.com/2007/12/13/s...3pregnant.html

Glossary

anterior arch
anterior portion of the ring-like C1 (atlas) vertebra

anterior longitudinal ligament
ligament that runs the length of the vertebral column, uniting the anterior aspects of the vertebral bodies

anterior (ventral) sacral foramen
one of the series of paired openings located on the anterior (ventral) side of the sacrum

anulus fibrosus
tough, fibrous outer portion of an intervertebral disc, which is strongly anchored to the bodies of the adjacent vertebrae

atlas
first cervical (C1) vertebra

axis
second cervical (C2) vertebra

body of vertebra
the anterior portion of each vertebra and is the part that supports the body weight

cervical curve
posteriorly concave curvature of the cervical vertebral column region; a secondary curve of the vertebral column

cervical vertebrae
seven vertebrae numbered as C1–C7 that are located in the neck region of the vertebral column

coccyx
bone of the vertebral column consisting of four fused coccygeal vertebrae

costal facet
site on the lateral sides of a thoracic vertebra for articulation with the head of a rib

dens
bony projection (odontoid process) that extends upward from the body of the C2 (axis) vertebra

facet
small, flattened area on a bone for an articulation (joint) with another bone, or for muscle attachment

inferior articular process
bony process that extends downward from the vertebral arch of a vertebra that articulates with the superior articular process of the next lower vertebra

intervertebral disc
structure located between the bodies of adjacent vertebrae that strongly joins the vertebrae; provides padding, weight bearing ability, and enables vertebral column movements

intervertebral foramen
opening located between adjacent vertebrae for exit of a spinal nerve

kyphosis
(also, humpback or hunchback) excessive posterior curvature of the thoracic vertebral column region

lamina
portion of the vertebral arch on each vertebra that extends between the transverse and spinous process

lateral sacral crest
paired irregular ridges running down the lateral sides of the posterior sacrum that was formed by the fusion of the transverse processes from the five sacral vertebrae

ligamentum flavum
series of short ligaments that unite the lamina of adjacent vertebrae

lordosis
(also, swayback) excessive anterior curvature of the lumbar vertebral column region

lumbar curve
posteriorly concave curvature of the lumbar vertebral column region; a secondary curve of the vertebral column

lumbar vertebrae
five vertebrae numbered as L1–L5 that are located in lumbar region (lower back) of the vertebral column

median sacral crest
irregular ridge running down the midline of the posterior sacrum that was formed from the fusion of the spinous processes of the five sacral vertebrae

nuchal ligament
expanded portion of the supraspinous ligament within the posterior neck; interconnects the spinous processes of the cervical vertebrae and attaches to the base of the skull

nucleus pulposus
gel-like central region of an intervertebral disc; provides for padding, weight-bearing, and movement between adjacent vertebrae

pedicle
portion of the vertebral arch that extends from the vertebral body to the transverse process

posterior arch
posterior portion of the ring-like C1 (atlas) vertebra

posterior longitudinal ligament
ligament that runs the length of the vertebral column, uniting the posterior sides of the vertebral bodies

posterior (dorsal) sacral foramen
one of the series of paired openings located on the posterior (dorsal) side of the sacrum

primary curve
anteriorly concave curvatures of the thoracic and sacrococcygeal regions that are retained from the original fetal curvature of the vertebral column

sacral canal
bony tunnel that runs through the sacrum

sacral foramina
series of paired openings for nerve exit located on both the anterior (ventral) and posterior (dorsal) aspects of the sacrum

sacral hiatus
inferior opening and termination of the sacral canal

sacral promontory
anterior lip of the base (superior end) of the sacrum

sacrococcygeal curve
anteriorly concave curvature formed by the sacrum and coccyx; a primary curve of the vertebral column

sacrum
bone of the vertebral column consisting of five fused sacral vertebrae

scoliosis
abnormal lateral curvature of the vertebral column

secondary curve
posteriorly concave curvatures of the cervical and lumbar regions of the vertebral column that develop after the time of birth

spinous process
unpaired bony process that extends posteriorly from the vertebral arch of a vertebra

superior articular process
bony process that extends upward from the vertebral arch of a vertebra that articulates with the inferior articular process of the next higher vertebra

superior articular process of the sacrum
paired processes that extend upward from the sacrum to articulate (join) with the inferior articular processes from the L5 vertebra

supraspinous ligament
ligament that interconnects the spinous processes of the thoracic and lumbar vertebrae

thoracic curve
anteriorly concave curvature of the thoracic vertebral column region; a primary curve of the vertebral column

thoracic vertebrae
twelve vertebrae numbered as T1–T12 that are located in the thoracic region (upper back) of the vertebral column

transverse foramen
opening found only in the transverse processes of cervical vertebrae

transverse ligament
ligament attached to the atlas that wraps anteriorly around the dens of the axis

transverse process
paired bony processes that extends laterally from the vertebral arch of a vertebra

transverse ridges
lines on the anterior surface of the sacrum that represent the fusion point of the sacral vertebrae

vertebra prominens
seventh cervical (C7) vertebra

vertebral arch
bony arch formed by the posterior portion of each vertebra that surrounds and protects the spinal cord

vertebral (spinal) canal
bony passageway within the vertebral column for the spinal cord that is formed by the series of individual vertebral foramina

vertebral foramen
opening associated with each vertebra defined by the vertebral arch that provides passage for the spinal cord

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Answers

Interactive Link

Answer: The anterior longitudinal ligament is thickest in the thoracic region of the vertebral column, while the supraspinous ligament is thickest in the lumbar region.

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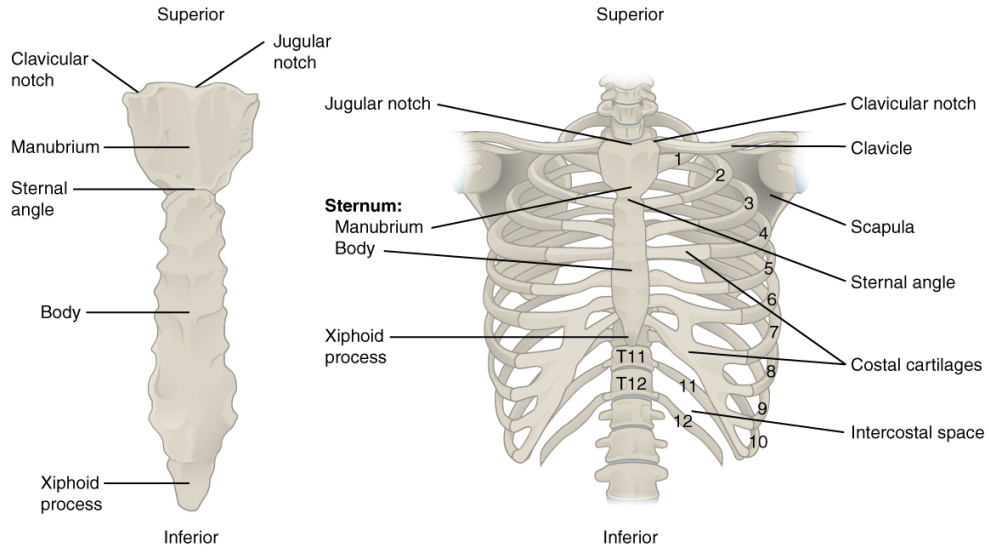
6.5: The Thoracic Cage

By the end of this section, you will be able to:

- Discuss the components that make up the thoracic cage
- Identify the parts of the sternum and define the sternal angle
- Discuss the parts of a rib and rib classifications

The thoracic cage (rib cage) forms the thorax (chest) portion of the body. It consists of the 12 pairs of ribs with their costal cartilages and the sternum (Figure 6.5.1). The ribs are anchored posteriorly to the 12 thoracic vertebrae (T1–T12). The thoracic cage protects the heart and lungs.



(a) Anterior view of sternum (b) Anterior view of skeleton of thorax

Figure 6.5.1: Thoracic Cage. The thoracic cage is formed by the (a) sternum and (b) 12 pairs of ribs with their costal cartilages. The ribs are anchored posteriorly to the 12 thoracic vertebrae. The sternum consists of the manubrium, body, and xiphoid process. The ribs are classified as true ribs (1–7) and false ribs (8–12). The last two pairs of false ribs are also known as floating ribs (11–12). (Image credit: "Rib Cage" by OpenStax is licensed under CC BY 3.0)

Sternum

The **sternum** is the elongated bony structure that anchors the anterior thoracic cage. It consists of three parts: the manubrium, body, and xiphoid process. The **manubrium** is the wider, superior portion of the sternum. The top of the manubrium has a shallow, U-shaped border called the **jugular (suprasternal) notch**. This can be easily felt at the anterior base of the neck, between the medial ends of the clavicles. The **clavicular notch** is the shallow depression located on either side at the superior-lateral margins of the manubrium. This is the site of the sternoclavicular joint, between the sternum and clavicle. The first ribs also attach to the manubrium.

The elongated, central portion of the sternum is the body. The manubrium and body join together at the **sternal angle**, so called because the junction between these two components is not flat, but forms a slight bend. The second rib attaches to the sternum at the sternal angle. Since the first rib is hidden behind the clavicle, the second rib is the highest rib that can be identified by palpation, or felt with the fingers through the skin. Thus, the sternal angle and second rib are important landmarks for the identification and counting of the lower ribs. Ribs 3–7 attach to the sternal body.

The inferior tip of the sternum is the **xiphoid process**. This small structure is cartilaginous early in life, but gradually becomes ossified starting during middle age.

Ribs

Each **rib** is a curved, flattened bone that contributes to the wall of the thorax. The ribs articulate posteriorly with the T1–T12 thoracic vertebrae, and most attach anteriorly via their costal cartilages to the sternum. There are 12 pairs of ribs. The ribs are numbered 1–12 in accordance with the thoracic vertebrae.

Parts of a Typical Rib

Figure 6.5.2 diagrams the bone markings of a typical rib. The posterior end of a typical rib is called the **head of the rib**. This region articulates primarily with the costal facet located on the body of the same numbered thoracic vertebra and to a lesser degree, with the costal facet located on the body of the next higher vertebra (see Figure 6.4.8: Rib Articulation in Thoracic Vertebrae). Lateral to the head is the narrowed **neck of the rib**. A small bump on the posterior rib surface is the **tubercle of the rib**, which articulates with the facet located on the transverse process of the same numbered vertebra. The remainder of the rib is the **body of the rib** (shaft). Just lateral to the tubercle is the **angle of the rib**, the point at which the rib has its greatest degree of curvature. The angles of the ribs form the most posterior extent of the thoracic cage. In the anatomical position, the angles align with the medial border of the scapula. A shallow **costal groove** for the passage of blood vessels and a nerve is found along the inferior margin of each rib.

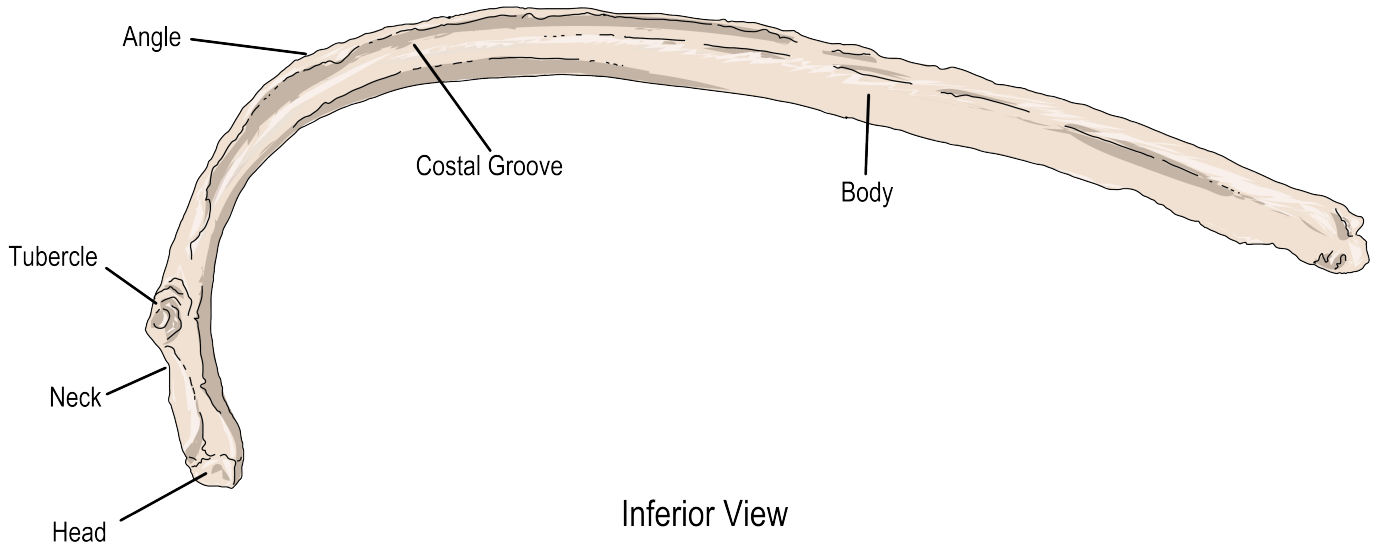


Figure 6.5.2: A typical rib. Inferior view shows bone markings of a typical rib. (Image credit:"A Typical Rib" by Whitney Menefee is a derivative from the original work of Daniel Donnelly and is licensed under CC BY 4.0)

Rib Classifications

The bony ribs do not extend anteriorly completely around to the sternum. Instead, each rib ends in a **costal cartilage**. These cartilages are made of hyaline cartilage and can extend for several inches. Most ribs are then attached, either directly or indirectly, to the sternum via their costal cartilage (see Figure 6.5.1). The ribs are classified into three groups based on their relationship to the sternum.

Ribs 1–7 are classified as **true ribs** (vertebrosternal ribs). The costal cartilage from each of these ribs attaches directly to the sternum. Ribs 8–12 are called **false ribs** (vertebrochondral ribs). The costal cartilages from these ribs do not attach directly to the sternum. For ribs 8–10, the costal cartilages are attached to the cartilage of the next higher rib. Thus, the cartilage of rib 10 attaches to the cartilage of rib 9, rib 9 then attaches to rib 8, and rib 8 is attached to rib 7. The last two false ribs (11–12) are also called **floating ribs** (vertebral ribs). These are short ribs that do not attach to the sternum at all. Instead, their small costal cartilages terminate within the musculature of the lateral abdominal wall.

Concept Review

The thoracic cage protects the heart and lungs. It is composed of 12 pairs of ribs with their costal cartilages and the sternum. The ribs are anchored posteriorly to the 12 thoracic vertebrae. The sternum consists of the manubrium, body, and xiphoid process. The manubrium and body are joined at the sternal angle, which is also the site for attachment of the second ribs.

Ribs are flattened, curved bones and are numbered 1–12. Posteriorly, the head of the rib articulates with the costal facets located on the bodies of thoracic vertebrae and the rib tubercle articulates with the facet located on the vertebral transverse process. The angle of the ribs forms the most posterior portion of the thoracic cage. The costal groove in the inferior margin of each rib carries blood vessels and a nerve. Anteriorly, each rib ends in a costal cartilage. True ribs (1–7) attach directly to the sternum via their costal cartilage. The false ribs (8–12) either attach to the sternum indirectly or not at all. Ribs 8–10 have their costal cartilages attached to the cartilage of the next higher rib. The floating ribs (11–12) are short and do not attach to the sternum or to another rib.

Review Questions

Q. The sternum _____.

A. consists of only two parts, the manubrium and xiphoid process

B. has the sternal angle located between the manubrium and body

C. receives direct attachments from the costal cartilages of all 12 pairs of ribs

D. articulates directly with the thoracic vertebrae

Answer

Answer: B

Q. The tubercle of a rib _____.

A. is for articulation with the transverse process of a thoracic vertebra

B. is for articulation with the body of a thoracic vertebra

C. provides for passage of blood vessels and a nerve

D. is the area of greatest rib curvature

Answer

Answer: A

Q. True ribs are _____.

A. ribs 8–12

B. attached via their costal cartilage to the next higher rib

C. made entirely of bone, and thus do not have a costal cartilage

D. attached via their costal cartilage directly to the sternum

Answer

Answer: D

Critical Thinking Questions

Q. Define the parts and functions of the thoracic cage.

Answer

A. The thoracic cage is formed by the 12 pairs of ribs with their costal cartilages and the sternum. The ribs are attached posteriorly to the 12 thoracic vertebrae and most are anchored anteriorly either directly or indirectly to the sternum. The thoracic cage functions to protect the heart and lungs.

Q. Describe the parts of the sternum.

Answer

A. The sternum consists of the manubrium, body, and xiphoid process. The manubrium forms the expanded, superior end of the sternum. It has a jugular (suprasternal) notch, a pair of clavicular notches for articulation with the clavicles, and receives the costal cartilage of the first rib. The manubrium is joined to the body of the sternum at the sternal angle, which is also the site for attachment of the second rib costal cartilages. The body receives the costal cartilage attachments for ribs 3–7. The small xiphoid process forms the inferior tip of the sternum.

Q. Discuss the parts of a typical rib.

Answer

A. A typical rib is a flattened, curved bone. The head of a rib is attached posteriorly to the costal facets of the thoracic vertebrae. The rib tubercle articulates with the transverse process of a thoracic vertebra. The angle is the area of greatest rib curvature and forms the largest portion of the thoracic cage. The body (shaft) of a rib extends anteriorly and terminates at the attachment to its costal cartilage. The shallow costal groove runs along the inferior margin of a rib and carries blood vessels and a nerve.

Q. Define the classes of ribs.

Answer

A. Ribs are classified based on if and how their costal cartilages attach to the sternum. True (vertebrosternal) ribs are ribs 1–7. The costal cartilage for each of these attaches directly to the sternum. False (vertebrochondral) ribs, 8–12, are attached either indirectly or not at all to the sternum. Ribs 8–10 are attached indirectly to the sternum. For these ribs, the costal cartilage of each attaches to the cartilage of the next higher rib. The last false ribs (11–12) are also called floating (vertebral) ribs, because these ribs do not attach to the sternum at all. Instead, the ribs and their small costal cartilages terminate within the muscles of the lateral abdominal wall.

Glossary

angle of the rib
portion of rib with greatest curvature; together, the rib angles form the most posterior extent of the thoracic cage

body of the rib
shaft portion of a rib

clavicular notch
paired notches located on the superior-lateral sides of the sternal manubrium, for articulation with the clavicle

costal cartilage
hyaline cartilage structure attached to the anterior end of each rib that provides for either direct or indirect attachment of most ribs to the sternum

costal groove
shallow groove along the inferior margin of a rib that provides passage for blood vessels and a nerve

false ribs
vertebrochondral ribs 8–12 whose costal cartilage either attaches indirectly to the sternum via the costal cartilage of the next higher rib or does not attach to the sternum at all

floating ribs
vertebral ribs 11–12 that do not attach to the sternum or to the costal cartilage of another rib

head of the rib
posterior end of a rib that articulates with the bodies of thoracic vertebrae

jugular (suprasternal) notch
shallow notch located on superior surface of sternal manubrium

manubrium
expanded, superior portion of the sternum

neck of the rib
narrowed region of a rib, next to the rib head

rib
curved, flattened bone of the thoracic cage

sternal angle
junction line between manubrium and body of the sternum and the site for attachment of the second rib to the sternum

sternum
elongated, flat bone of the thoracic cage

true ribs
vertebrosternal ribs 1–7 that attach via their costal cartilage directly to the sternum

tubercle of the rib
small bump on the posterior side of a rib for articulation with the transverse process of a thoracic vertebra

xiphoid process
small process that forms the inferior tip of the sternum

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6.6: Embryonic Development of the Axial Skeleton

By the end of this section,

- Discuss the two types of embryonic bone development within the skull
- Describe the development of the vertebral column and thoracic cage

The axial skeleton begins to form during early embryonic development. However, growth, remodeling, and ossification (bone formation) continue for several decades after birth before the adult skeleton is fully formed. Knowledge of the developmental processes that give rise to the skeleton is important for understanding the abnormalities that may arise in skeletal structures.

Development of the Skull

During the third week of embryonic development, a rod-like structure called the **notochord** develops dorsally along the length of the embryo. The tissue overlying the notochord enlarges and forms the neural tube, which will give rise to the brain and spinal cord. By the fourth week, mesoderm tissue located on either side of the notochord thickens and separates into a repeating series of block-like tissue structures, each of which is called a **somite**. As the somites enlarge, each one will split into several parts. The most medial of these parts is called a **sclerotome**. The sclerotomes consist of an embryonic tissue called mesenchyme, which will give rise to the fibrous connective tissues, cartilages, and bones of the body.

The bones of the skull arise from mesenchyme during embryonic development in two different ways. The first mechanism produces the bones that form the top and sides of the brain case. This involves the local accumulation of mesenchymal cells at the site of the future bone. These cells then differentiate directly into bone producing cells, which form the skull bones through the process of intramembranous ossification. As the brain case bones grow in the fetal skull, they remain separated from each other by large areas of dense connective tissue, each of which is called a **fontanelle** (Figure 6.6.1). The fontanelles are the soft spots on an infant's head. They are important during birth because these areas allow the skull to change shape as it squeezes through the birth canal. After birth, the fontanelles allow for continued growth and expansion of the skull as the brain enlarges. The largest fontanelle is located on the anterior head, at the junction of the frontal and parietal bones. The fontanelles decrease in size and disappear by age 2. However, the skull bones remain separated from each other at the sutures, which contain dense fibrous connective tissue that unites the adjacent bones. The connective tissue of the sutures allows for continued growth of the skull bones as the brain enlarges during childhood growth.

The second mechanism for bone development in the skull produces the facial bones and floor of the brain case. This also begins with the localized accumulation of mesenchymal cells. However, these cells differentiate into cartilage cells, which produce a hyaline cartilage model of the future bone. As this cartilage model grows, it is gradually converted into bone through the process of endochondral ossification. This is a slow process and the cartilage is not completely converted to bone until the skull achieves its full adult size.

At birth, the brain case and orbits of the skull are disproportionally large compared to the bones of the jaws and lower face. This reflects the relative underdevelopment of the maxilla and mandible, which lack teeth, and the small sizes of the paranasal sinuses and nasal cavity. During early childhood, the mastoid process enlarges, the two halves of the mandible and frontal bone fuse together to form single bones, and the paranasal sinuses enlarge. The jaws also expand as the teeth begin to appear. These changes all contribute to the rapid growth and enlargement of the face during childhood.

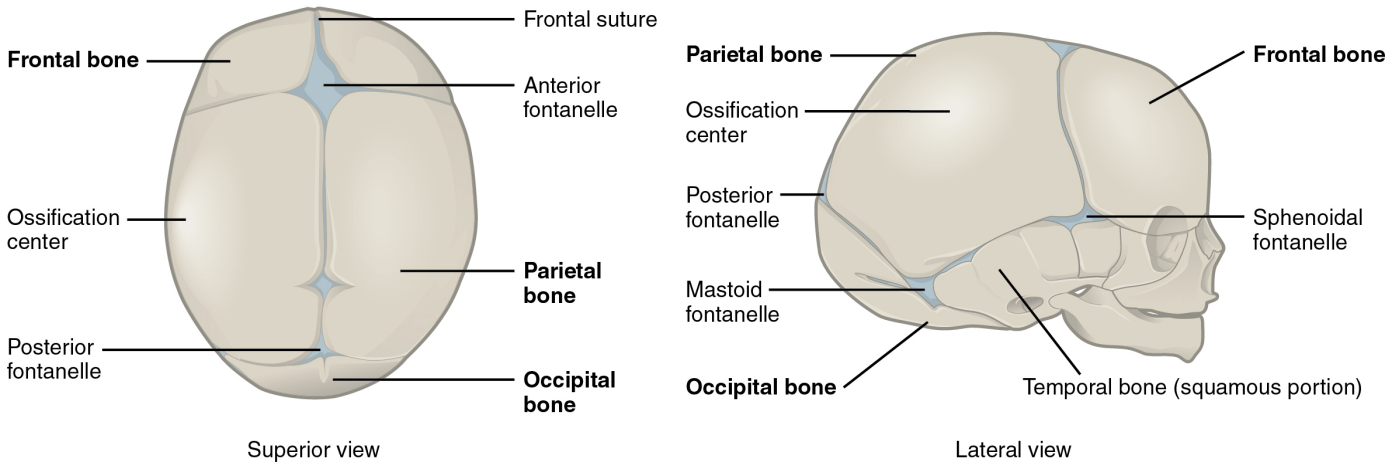

Figure 6.6.1: Newborn Skull. The bones of the newborn skull are not fully ossified and are separated by large areas called fontanelles, which are filled with fibrous connective tissue. The fontanelles allow for continued growth of the skull after birth. At the time of birth, the facial bones are small and underdeveloped, and the mastoid process has not yet formed. (Image credit: "New Born Skull" by OpenStax is licensed under CC BY 3.0)

Development of the Vertebral Column and Thoracic Cage

Development of the vertebrae begins with the accumulation of mesenchyme cells from each sclerotome around the notochord. These cells differentiate into a hyaline cartilage model for each vertebra, which then grow and eventually ossify into bone through the process of endochondral ossification. As the developing vertebrae grow, the notochord largely disappears. However, small areas of notochord tissue persist between the adjacent vertebrae and this contributes to the formation of each intervertebral disc.

The ribs and sternum also develop from mesenchyme. The ribs initially develop as part of the cartilage model for each vertebra, but in the thorax region, the rib portion separates from the vertebra by the eighth week. The cartilage model of the rib then ossifies, except for the anterior portion, which remains as the costal cartilage. The sternum initially forms as paired hyaline cartilage models on either side of the anterior midline, beginning during the fifth week of development. The cartilage models of the ribs become attached to the lateral sides of the developing sternum. Eventually, the two halves of the cartilaginous sternum fuse together along the midline and then ossify into bone. The manubrium and body of the sternum are converted into bone first, with the xiphoid process remaining as cartilage until late in life.

HOMEOSTATIC IMBALANCES

Craniosynostosis

The premature closure (fusion) of a suture line is a condition called craniosynostosis. This error in the normal developmental process results in abnormal growth of the skull and deformity of the head. It is produced either by defects in the ossification process of the skull bones or failure of the brain to properly enlarge. Genetic factors are involved, but the underlying cause is unknown. It is a relatively common condition, occurring in approximately 1:2000 births, with males being more commonly affected. Primary craniosynostosis involves the early fusion of one cranial suture, whereas complex craniosynostosis results from the premature fusion of several sutures.

The early fusion of a suture in primary craniosynostosis prevents any additional enlargement of the cranial bones and skull along this line. Continued growth of the brain and skull is therefore diverted to other areas of the head, causing an abnormal enlargement of these regions. For example, the early disappearance of the anterior fontanelle and premature closure of the sagittal suture prevents growth across the top of the head. This is compensated by upward growth by the bones of the lateral skull, resulting in a long, narrow, wedge-shaped head. This condition, known as scaphocephaly, accounts for approximately 50 percent of craniosynostosis abnormalities. Although the skull is misshapen, the brain still has adequate room to grow and thus there is no accompanying abnormal neurological development.

In cases of complex craniosynostosis, several sutures close prematurely. The amount and degree of skull deformity is determined by the location and extent of the sutures involved. This results in more severe constraints on skull growth, which can alter or impede proper brain growth and development.

Cases of craniosynostosis are usually treated with surgery. A team of physicians will open the skull along the fused suture, which will then allow the skull bones to resume their growth in this area. In some cases, parts of the skull will be removed and replaced with an artificial plate. The earlier after birth that surgery is performed, the better the outcome. After treatment, most children continue to grow and develop normally and do not exhibit any neurological problems.

Concept Review

Formation of the axial skeleton begins during early embryonic development with the appearance of the rod-like notochord along the dorsal length of the early embryo. Repeating, paired blocks of tissue called somites then appear along either side of notochord. As the somites grow, they split into parts, one of which is called a sclerotome. This consists of mesenchyme, the embryonic tissue that will become the bones, cartilages, and connective tissues of the body.

Mesenchyme in the head region will produce the bones of the skull via two different mechanisms. The bones of the brain case arise via intramembranous ossification in which embryonic mesenchyme tissue converts directly into bone. At the time of birth, these bones are separated by fontanelles, wide areas of fibrous connective tissue. As the bones grow, the fontanelles are reduced to sutures, which allow for continued growth of the skull throughout childhood. In contrast, the cranial base and facial bones are produced by the process of endochondral ossification, in which mesenchyme tissue initially produces a hyaline cartilage model of the future bone. The cartilage model allows for growth of the bone and is gradually converted into bone over a period of many years.

The vertebrae, ribs, and sternum also develop via endochondral ossification. Mesenchyme accumulates around the notochord and produces hyaline cartilage models of the vertebrae. The notochord largely disappears, but remnants of the notochord contribute to formation of the intervertebral discs. In the thorax region, a portion of the vertebral cartilage model splits off to form the ribs. These then become attached anteriorly to the developing cartilage model of the sternum. Growth of the cartilage models for the vertebrae, ribs, and sternum allow for enlargement of the thoracic cage during childhood and adolescence. The cartilage models gradually undergo ossification and are converted into bone.

Review Questions

Q. Embryonic development of the axial skeleton involves _____.

A. intramembranous ossification, which forms the facial bones.

B. endochondral ossification, which forms the ribs and sternum

C. the notochord, which produces the cartilage models for the vertebrae

D. the formation of hyaline cartilage models, which give rise to the flat bones of the skull

Answer

Answer: B

Q. A fontanelle _____.

A. is the cartilage model for a vertebra that later is converted into bone

B. gives rise to the facial bones and vertebrae

C. is the rod-like structure that runs the length of the early embryo

D. is the area of fibrous connective tissue found at birth between the brain case bones

Answer

Answer: D

Critical Thinking Questions

Q. Discuss the processes by which the brain-case bones of the skull are formed and grow during skull enlargement.

Answer

A. The brain-case bones that form the top and sides of the skull are produced by intramembranous ossification. In this, mesenchyme from the sclerotome portion of the somites accumulates at the site of the future bone and differentiates into bone-producing cells. These generate areas of bone that are initially separated by wide regions of fibrous connective tissue called fontanelles. After birth, as the bones enlarge, the fontanelles disappear. However, the bones remain separated by the sutures, where bone and skull growth can continue until the adult size is obtained.

Q. Discuss the process that gives rise to the base and facial bones of the skull.

Answer

A. The facial bones and base of the skull arise via the process of endochondral ossification. This process begins with the localized accumulation of mesenchyme tissue at the sites of the future bones. The mesenchyme differentiates into hyaline cartilage, which forms a cartilage model of the future bone. The cartilage allows for growth and enlargement of the model. It is gradually converted into bone over time.

Q. Discuss the development of the vertebrae, ribs, and sternum.

Answer

A. The vertebrae, ribs, and sternum all develop via the process of endochondral ossification. Mesenchyme tissue from the sclerotome portion of the somites accumulates on either side of the notochord and produces hyaline cartilage models for each vertebra. In the thorax region, a portion of this cartilage model splits off to form the ribs. Similarly, mesenchyme forms cartilage models for the right and left halves of the sternum. The ribs then become attached anteriorly to the developing sternum, and the two halves of sternum fuse together. Ossification of the cartilage model into bone occurs within these structures over time. This process continues until each is converted into bone, except for the sternal ends of the ribs, which remain as the costal cartilages.

Glossary

fontanelle
: expanded area of fibrous connective tissue that separates the brain case bones of the skull prior to birth and during the first year after birth

notochord
: rod-like structure along dorsal side of the early embryo; largely disappears during later development but does contribute to formation of the intervertebral discs

sclerotome
: medial portion of a somite consisting of mesenchyme tissue that will give rise to bone, cartilage, and fibrous connective tissues

somite
: one of the paired, repeating blocks of tissue located on either side of the notochord in the early embryo

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7: APPENDICULAR SKELETON

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7.1: Introduction to the Appendicular Skeleton

Chapter Learning Objectives

After studying this chapter, you will be able to:

- Discuss the bones of the pectoral and pelvic girdles, and describe how these unite the limbs with the axial skeleton
- Describe the bones of the upper limb, including the bones of the arm, forearm, wrist, and hand
- Identify the features of the pelvis and explain how these differ between the adult male and female pelvis
- Describe the bones of the lower limb, including the bones of the thigh, leg, ankle, and foot
- Describe the embryonic formation and growth of the limb bones

Figure 7.1.1: Dancer. The appendicular skeleton consists of the upper and lower limb bones, the bones of the hands and feet, and the bones that anchor the limbs to the axial skeleton. (Image credit: "Dancer" by OpenStax is licensed under CC BY 4.0)

Your skeleton provides the internal supporting structure of the body. The adult axial skeleton consists of 80 bones that form the head and body trunk. Attached to this are the limbs, whose 126 bones constitute the appendicular skeleton. These bones are divided into two groups: the bones that are located within the limbs themselves, and the girdle bones that attach the limbs to the axial skeleton. The bones of the shoulder region form the pectoral girdle, which anchors the upper limb to the thoracic cage of the axial skeleton. The lower limb is attached to the vertebral column by the pelvic girdle.

Because of our upright stance, different functional demands are placed upon the upper and lower limbs. Thus, the bones of the lower limbs are adapted for weight-bearing support and stability, as well as for body locomotion via walking or running. In contrast, our upper limbs are not required for these functions. Instead, our upper limbs are highly mobile and can be utilized for a wide variety of activities. The large range of upper limb movements, coupled with the ability to easily manipulate objects with our hands and opposable thumbs, has allowed humans to construct the modern world in which we live.

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7.2: The Pectoral Girdle

By the end of this section, you will be able to:

- Describe the bones that form the pectoral girdle
- List the functions of the pectoral girdle

The appendicular skeleton includes all of the limb bones, plus the bones that unite each limb with the axial skeleton (Figure 7.2.1). The bones that attach each upper limb to the axial skeleton form the pectoral girdle (shoulder girdle). This consists of two bones, the scapula and clavicle (Figure 7.2.2). The clavicle (collarbone) is an S-shaped bone located on the anterior side of the shoulder. It is attached on its medial end to the sternum of the thoracic cage, which is part of the axial skeleton. The lateral end of the clavicle articulates (joins) with the scapula just above the shoulder joint. You can easily palpate, or feel with your fingers, the entire length of your clavicle.

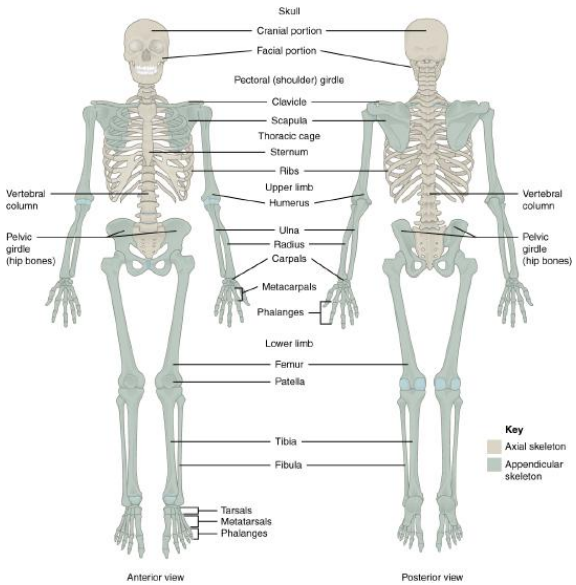

Figure 7.2.1: Axial and Appendicular Skeletons. The axial skeleton forms the central axis of the body and consists of the skull, vertebral column, and thoracic cage. The appendicular skeleton consists of the pectoral and pelvic girdles, the limb bones, and the bones of the hands and feet. (Image credit: "Axial Skeleton" by OpenStax is licensed under CC BY 3.0)

The **scapula** (shoulder blade) lies on the posterior aspect of the shoulder. It is supported by the **clavicle**, which also articulates with the humerus (arm bone) to form the shoulder joint. The scapula is a flat, triangular-shaped bone with a prominent ridge running across its posterior surface. This ridge extends out laterally, where it forms the bony tip of the shoulder and joins with the lateral end of the clavicle. By following along the clavicle, you can palpate out to the bony tip of the shoulder, and from there, you can move back across your posterior shoulder to follow the ridge of the scapula. Move your shoulder around and feel how the clavicle and scapula move together as a unit. Both of these bones serve as important attachment sites for muscles that aid with movements of the shoulder and arm.

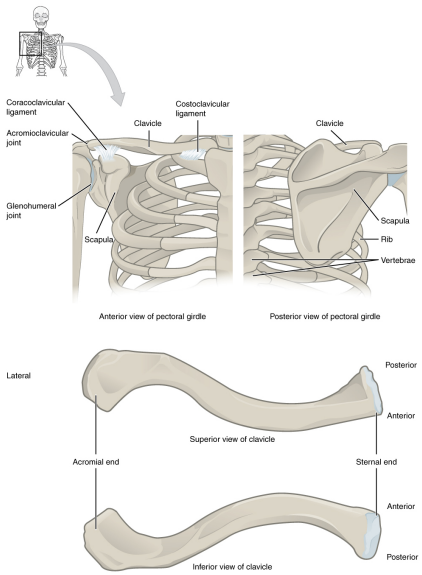

Figure 7.2.2: Pectoral Girdle. The pectoral girdle consists of the clavicle and the scapula, which serve to attach the upper limb to the sternum of the axial skeleton. (Image credit: "Pectoral Girdle" by OpenStax is licensed under CC BY 3.0)

The right and left pectoral girdles are not joined to each other, allowing each to operate independently. In addition, the clavicle of each **pectoral girdle** is anchored to the axial skeleton by a single, highly mobile joint. This allows for the extensive mobility of the entire pectoral girdle, which in turn enhances movements of the shoulder and upper limb.

Clavicle

The **clavicle** is the only long bone that lies in a horizontal position in the body (Figure 7.2.2). The clavicle has several important functions. First, anchored by muscles from above, it serves as a strut that extends laterally to support the scapula. This in turn holds the shoulder joint superiorly and laterally from the body trunk, allowing for maximal freedom of motion for the upper limb. The clavicle also transmits forces acting on the upper limb to the sternum and axial skeleton. Finally, it serves to protect the underlying nerves and blood vessels as they pass between the trunk of the body and the upper limb.

The clavicle has three regions: the medial end, the lateral end, and the shaft. The medial end, known as the **sternal end of the clavicle**, has a triangular shape and articulates with the manubrium portion of the sternum. This forms the **sternoclavicular joint**, which is the only bony articulation between the pectoral girdle of the upper limb and the axial skeleton. This joint allows considerable mobility, enabling the clavicle and scapula to move in upward/downward and anterior/posterior directions during shoulder movements. The sternoclavicular joint is indirectly supported by the **costoclavicular ligament** (costo- = “rib”), which spans the sternal end of the clavicle and the underlying first rib. The lateral or **acromial end of the clavicle** articulates with the acromion of the scapula, the portion of the scapula that forms the bony tip of the shoulder. There are some sex differences in the morphology of the clavicle. In women, the clavicle tends to be shorter, thinner, and less curved. In men, the clavicle is heavier and longer, and has a greater curvature and rougher surfaces where muscles attach, features that are more pronounced in manual workers.

The clavicle is the most commonly fractured bone in the body. Such breaks often occur because of the force exerted on the clavicle when a person falls onto his or her outstretched arms, or when the lateral shoulder receives a strong blow. Because the sternoclavicular joint is strong and rarely dislocated, excessive force results in the breaking of the clavicle, usually between the middle and lateral portions of the bone. If the fracture is complete, the shoulder and lateral clavicle fragment will drop due to the weight of the upper limb, causing the person to support the sagging limb with their other hand. Muscles acting across the shoulder will also pull the shoulder and lateral clavicle anteriorly and medially, causing the clavicle fragments to override. The clavicle overlies many important blood vessels and nerves for the upper limb, but fortunately, due to the anterior displacement of a broken clavicle, these structures are rarely affected when the clavicle is fractured.

Scapula

The **scapula** is also part of the pectoral girdle and thus plays an important role in anchoring the upper limb to the body. The

scapula is located on the posterior side of the shoulder. It is surrounded by muscles on both its anterior (deep) and posterior (superficial) sides, and thus does not articulate with the ribs of the thoracic cage.

The scapula has several important landmarks (Figure 7.2.3). The three margins or borders of the scapula, named for their positions within the body, are the **superior border of the scapula**, the **medial border of the scapula**, and the **lateral border of the scapula**. The **suprascapular notch** is located lateral to the midpoint of the superior border. The corners of the triangular scapula, at either end of the medial border, are the **superior angle of the scapula**, located between the medial and superior borders, and the **inferior angle of the scapula**, located between the medial and lateral borders. The inferior angle is the most inferior portion of the scapula, and is particularly important because it serves as the attachment point for several powerful muscles involved in shoulder and upper limb movements. The remaining corner of the scapula, between the superior and lateral borders, is the location of the **glenoid cavity** (glenoid fossa). This shallow depression articulates with the humerus bone of the arm to form the **glenohumeral joint** (shoulder joint) (Figure 7.2.2). The small bony bumps located immediately above and below the glenoid cavity are the **supraglenoid tubercle** and the **infraglenoid tubercle**, respectively. These provide attachments for muscles of the arm.

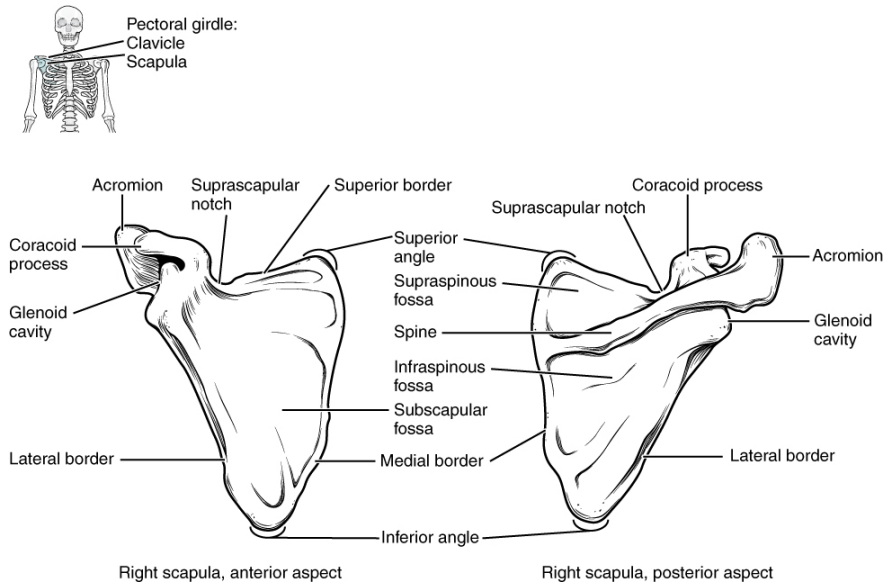

Figure 7.2.3: Scapula. The isolated scapula is shown here from its anterior (deep) side and its posterior (superficial) side. (Image credit: "The Scapula" by OpenStax is licensed under CC BY 3.0)

The scapula also has two prominent projections. Toward the lateral end of the superior border, between the suprascapular notch and glenoid cavity, is the hook-like **coracoid process** (coracoid = “shaped like a crow’s beak”). This process projects anteriorly and curves laterally. At the shoulder, the coracoid process is located inferior to the lateral end of the clavicle. It is anchored to the clavicle by a strong ligament, and serves as the attachment site for muscles of the anterior chest and arm. On the posterior aspect, the **spine of the scapula** is a long and prominent ridge that runs across its upper portion. Extending laterally from the spine is a flattened and expanded region called the **acromion**, or acromial process. The acromion forms the bony tip of the superior shoulder region and articulates with the lateral end of the clavicle, forming the **acromioclavicular joint** (see Figure 7.2.2). Together, the clavicle, acromion, and spine of the scapula form a V-shaped bony line that provides for the attachment of neck and back muscles that act on the shoulder, as well as muscles that pass across the shoulder joint to act on the arm.

The scapula has three depressions, each of which is called a **fossa** (plural = fossae). Two of these are found on the posterior scapula, above and below the scapular spine. Superior to the spine is the narrow **supraspinous fossa**, and inferior to the spine is the broad **infraspinous fossa**. The anterior (deep) surface of the scapula forms the broad **subscapular fossa**. All of these fossae provide large surface areas for the attachment of muscles that cross the shoulder joint to act on the humerus.

The acromioclavicular joint transmits forces from the upper limb to the clavicle. The ligaments around this joint are relatively weak. A hard fall onto the elbow or outstretched hand can stretch or tear the acromioclavicular ligaments, resulting in a moderate injury to the joint. However, the primary support for the acromioclavicular joint comes from a very strong ligament called the **coracoclavicular ligament** (see Figure 7.2.2). This connective tissue band anchors the coracoid process of the scapula to the inferior surface of the acromial end of the clavicle and thus provides important indirect support for the acromioclavicular joint. Following a strong blow to the lateral shoulder, such as when a hockey player is driven into the boards, a complete dislocation of the acromioclavicular joint can result. In this case, the acromion is thrust under the acromial end of the clavicle, resulting in ruptures of both the acromioclavicular and coracoclavicular ligaments. The scapula then separates from the clavicle, with the

weight of the upper limb pulling the shoulder downward. This dislocation injury of the acromioclavicular joint is known as a “shoulder separation” and is common in contact sports such as hockey, football, or martial arts.

Concept Review

The pectoral girdle, consisting of the clavicle and the scapula, attaches each upper limb to the axial skeleton. The clavicle is an anterior bone whose sternal end articulates with the manubrium of the sternum at the sternoclavicular joint. The sternal end is also anchored to the first rib by the costoclavicular ligament. The acromial end of the clavicle articulates with the acromion of the scapula at the acromioclavicular joint. This end is also anchored to the coracoid process of the scapula by the coracoclavicular ligament, which provides indirect support for the acromioclavicular joint. The clavicle supports the scapula, transmits the weight and forces from the upper limb to the body trunk, and protects the underlying nerves and blood vessels.

The scapula lies on the posterior aspect of the pectoral girdle. It mediates the attachment of the upper limb to the clavicle, and contributes to the formation of the glenohumeral (shoulder) joint. This triangular bone has three sides called the medial, lateral, and superior borders. The suprascapular notch is located on the superior border. The scapula also has three corners, two of which are the superior and inferior angles. The third corner is occupied by the glenoid cavity. Posteriorly, the spine separates the supraspinous and infraspinous fossae, and then extends laterally as the acromion. The subscapular fossa is located on the anterior surface of the scapula. The coracoid process projects anteriorly, passing inferior to the lateral end of the clavicle.

Review Questions

Q. Which part of the clavicle articulates with the manubrium?

A. shaft

B. sternal end

C. acromial end

D. coracoid process

Answer

Answer: B

Q. A shoulder separation results from injury to the _____.

A. glenohumeral joint

B. costoclavicular joint

C. acromioclavicular joint

D. sternoclavicular joint

Answer

Answer: C

Q. Which feature lies between the spine and superior border of the scapula?

A. suprascapular notch

B. glenoid cavity

C. superior angle

D. supraspinous fossa

Answer

Answer: D

Q. What structure is an extension of the spine of the scapula?

A. acromion

B. coracoid process

C. supraglenoid tubercle

D. glenoid cavity

Answer

Answer: A

Q. Name the short, hook-like bony process of the scapula that projects anteriorly.

A. acromial process

B. clavicle

C. coracoid process

D. glenoid fossa

Answer

Answer: C

Critical Thinking Questions

Q. Describe the shape and palpable line formed by the clavicle and scapula.

Answer

A. The clavicle extends laterally across the anterior shoulder and can be palpated along its entire length. At its lateral end, the clavicle articulates with the acromion of the scapula, which forms the bony tip of the shoulder. The acromion is continuous with the spine of the scapula, which can be palpated medially and posteriorly along its length. Together, the clavicle, acromion, and spine of the scapula form a V-shaped line that serves as an important area for muscle attachment.

Q. Discuss two possible injuries of the pectoral girdle that may occur following a strong blow to the shoulder or a hard fall onto an outstretched hand.

Answer

A. A blow to the shoulder or falling onto an outstretched hand passes strong forces through the scapula to the clavicle and sternum. A hard fall may thus cause a fracture of the clavicle (broken collarbone) or may injure the ligaments of the acromioclavicular joint. In a severe case, the coracoclavicular ligament may also rupture, resulting in complete dislocation of the acromioclavicular joint (a “shoulder separation”).

Glossary

acromial end of the clavicle
lateral end of the clavicle that articulates with the acromion of the scapula

acromioclavicular joint
articulation between the acromion of the scapula and the acromial end of the clavicle

acromion
also acromial process; flattened bony process that extends laterally from the scapular spine to form the bony tip of the shoulder

clavicle
collarbone; elongated bone that articulates with the manubrium of the sternum medially and the acromion of the scapula laterally

coracoclavicular ligament
strong band of connective tissue that anchors the coracoid process of the scapula to the lateral clavicle; provides important indirect support for the acromioclavicular joint

coracoid process
short, hook-like process that projects anteriorly and laterally from the superior margin of the scapula

costoclavicular ligament
band of connective tissue that unites the medial clavicle with the first rib

fossa
(plural = fossae) shallow depression on the surface of a bone

glenohumeral joint
shoulder joint; formed by the articulation between the glenoid cavity of the scapula and the head of the humerus

glenoid cavity
(also, glenoid fossa) shallow depression located on the lateral scapula, between the superior and lateral borders

inferior angle of the scapula
inferior corner of the scapula located where the medial and lateral borders meet

infraglenoid tubercle
small bump or roughened area located on the lateral border of the scapula, near the inferior margin of the glenoid cavity

infraspinous fossa
broad depression located on the posterior scapula, inferior to the spine

lateral border of the scapula
diagonally oriented lateral margin of the scapula

medial border of the scapula
elongated, medial margin of the scapula

pectoral girdle
shoulder girdle; the set of bones, consisting of the scapula and clavicle, which attaches each upper limb to the axial skeleton

scapula
shoulder blade bone located on the posterior side of the shoulder

spine of the scapula
prominent ridge passing mediolaterally across the upper portion of the posterior scapular surface

sternal end of the clavicle
medial end of the clavicle that articulates with the manubrium of the sternum

sternoclavicular joint
articulation between the manubrium of the sternum and the sternal end of the clavicle; forms the only bony attachment between the pectoral girdle of the upper limb and the axial skeleton

subscapular fossa
broad depression located on the anterior (deep) surface of the scapula

superior angle of the scapula
corner of the scapula between the superior and medial borders of the scapula

superior border of the scapula
superior margin of the scapula

supraglenoid tubercle
small bump located at the superior margin of the glenoid cavity

suprascapular notch
small notch located along the superior border of the scapula, medial to the coracoid process

supraspinous fossa
narrow depression located on the posterior scapula, superior to the spine

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7.3: Bones of the Upper Limb

By the end of this section, you will be able to:

- Identify the divisions of the upper limb and describe the bones in each region
- List the bones and bony landmarks that articulate at each joint of the upper limb

The upper limb is divided into three regions. These consist of the upper **arm**, located between the shoulder and elbow joints; the **forearm**, which is between the elbow and wrist joints; and the **hand**, which is located distal to the wrist. There are 30 bones in each upper limb (see [link]). The humerus is the single bone of the upper arm, and the **ulna** (medially) and the **radius** (laterally) are the paired bones of the forearm. The base of the hand contains eight bones, each called a **carpal bone**, and the palm of the hand is formed by five bones, each called a **metacarpal bone**. The fingers and thumb contain a total of 14 bones, each of which is a **phalanx** (plural = phalanges) bone of the hand.

Humerus

The **humerus** is the single bone of the upper arm region (Figure 7.3.1). At its proximal end is the **head of the humerus**. This is the large, round, smooth region that faces medially. The head articulates with the glenoid cavity of the scapula to form the glenohumeral (shoulder) joint (see Figure 7.2.2). The margin of the smooth area of the head is the **anatomical neck** of the humerus. Located on the lateral side of the proximal humerus is an expanded bony area called the **greater tubercle**. The smaller **lesser tubercle** of the humerus is found on the anterior aspect of the humerus. Both the greater and lesser tubercles serve as attachment sites for muscles that act across the shoulder joint. Passing between the greater and lesser tubercles is the narrow **intertubercular groove (sulcus)**, which is also known as the bicipital groove because it provides passage for a tendon of the biceps brachii muscle. The **surgical neck** is located at the base of the expanded, proximal end of the humerus, where it joins the narrow body, or **shaft of the humerus**. The surgical neck is a common site of arm fractures. The **deltoid tuberosity** is a roughened, V-shaped region located on the lateral side in the middle of the humerus shaft. As its name indicates, it is the site of attachment for the deltoid muscle.

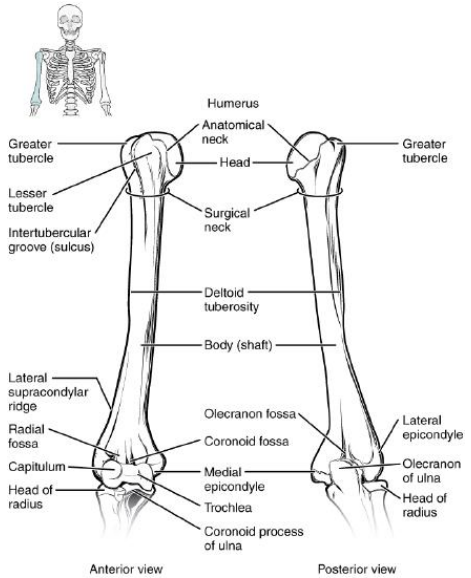

Figure 7.3.1: Humerus and Elbow Joint. The humerus is the single bone of the upper arm region. It articulates with the radius and ulna bones of the forearm to form the elbow joint. (Image credit: "Humerus and Elbow" by OpenStax is licensed under CC BY 3.0)

Distally, the humerus becomes flattened. The prominent bony projection on the medial side is the **medial epicondyle of the humerus**. The much smaller **lateral epicondyle of the humerus** is found on the lateral side of the distal humerus. The roughened ridge of bone above the lateral epicondyle is the **lateral supracondylar ridge**. All of these areas are attachment points for muscles that act on the forearm, wrist, and hand. The powerful grasping muscles of the anterior forearm arise from the medial

epicondyle, which is thus larger and more robust than the lateral epicondyle that gives rise to the weaker posterior forearm muscles.

The distal end of the humerus has two articulation areas, which join the ulna and radius bones of the forearm to form the **elbow joint**. The more medial of these areas is the **trochlea**, a spindle- or pulley-shaped region (trochlea = “pulley”), which articulates with the ulna bone. Immediately lateral to the trochlea is the **capitulum** (“small head”), a knob-like structure located on the anterior surface of the distal humerus. The capitulum articulates with the radius bone of the forearm. Just above these bony areas are two small depressions. These spaces accommodate the forearm bones when the elbow is fully bent (flexed). Superior to the trochlea is the **coronoid fossa**, which receives the coronoid process of the ulna, and above the capitulum is the **radial fossa**, which receives the head of the radius when the elbow is flexed. Similarly, the posterior humerus has the **olecranon fossa**, a larger depression that receives the olecranon process of the ulna when the forearm is fully extended.

Ulna

The **ulna** is the medial bone of the forearm. It runs parallel to the radius, which is the lateral bone of the forearm (Figure 7.3.2). The proximal end of the ulna resembles a crescent wrench with its large, C-shaped **trochlear notch**. This region articulates with the trochlea of the humerus as part of the elbow joint. The inferior margin of the trochlear notch is formed by a prominent lip of bone called the **coronoid process of the ulna**. Just below this on the anterior ulna is a roughened area called the **ulnar tuberosity**. To the lateral side and slightly inferior to the trochlear notch is a small, smooth area called the **radial notch of the ulna**. This area is the site of articulation between the proximal radius and the ulna, forming the **proximal radioulnar joint**. The posterior portion of the proximal ulna makes up the **olecranon process**, which forms the bony tip of the elbow.

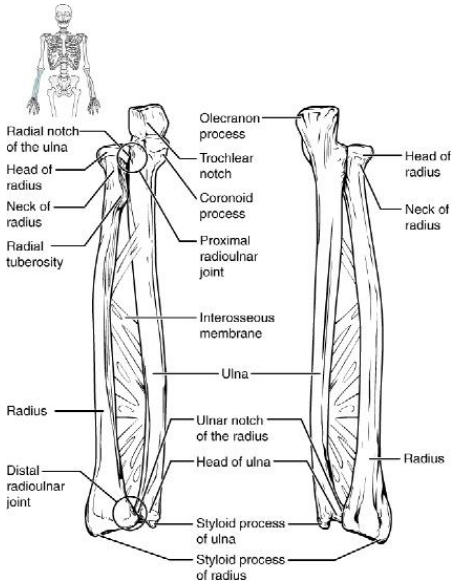

Figure 7.3.2: Ulna and Radius. The ulna is located on the medial side of the forearm, and the radius is on the lateral side. These bones are attached to each other by an interosseous membrane. (Image credit: "Ulna and Radius" by OpenStax is licensed under CC BY 3.0)

More distal is the **shaft of the ulna**. The lateral side of the shaft forms a ridge called the **interosseous border of the ulna**. This is the line of attachment for the **interosseous membrane of the forearm**, also known as the antebrachial interosseous membrane, a sheet of dense connective tissue that unites the ulna and radius bones. The small, rounded area that forms the distal end is the **head of the ulna**. Projecting from the posterior side of the ulnar head is the **styloid process of the ulna**, a short bony projection. This serves as an attachment point for a connective tissue structure that unites the distal ends of the ulna and radius.

In the anatomical position, with the elbow fully extended and the palms facing forward, the arm and forearm do not form a straight line. Instead, the forearm deviates laterally by 5–15 degrees from the line of the arm. This deviation is called the carrying angle. It allows the forearm and hand to swing freely or to carry an object without hitting the hip. The carrying angle is larger in females to accommodate their wider pelvis.

Radius

The **radius** runs parallel to the ulna, on the lateral (thumb) side of the forearm (see Figure 7.3.2). The **head of the radius** is a disc-shaped structure that forms the proximal end. The small depression on the surface of the head articulates with the capitulum of the humerus as part of the elbow joint, whereas the smooth, outer margin of the head articulates with the radial notch of the ulna at the proximal radioulnar joint. The **neck of the radius** is the narrowed region immediately below the expanded head. Inferior to this point on the medial side is the **radial tuberosity**, an oval-shaped, bony protuberance that serves as a muscle attachment point. The **shaft of the radius** is slightly curved and has a small ridge along its medial side. This ridge forms the **interosseous border of the radius**, which, like the similar border of the ulna, is the line of attachment for the interosseous membrane that unites the two forearm bones. The distal end of the radius has a smooth surface for articulation with two carpal bones to form the **radiocarpal joint** or wrist joint (Figure 7.3.4). On the medial side of the distal radius is the **ulnar notch of the radius**. This shallow depression articulates with the head of the ulna, which together form the **distal radioulnar joint**. The lateral end of the radius has a pointed projection called the **styloid process of the radius**. This provides attachment for ligaments that support the lateral side of the wrist joint. Compared to the styloid process of the ulna, the styloid process of the radius projects more distally, thereby limiting the range of movement for lateral deviations of the hand at the wrist joint.

Carpal Bones

The wrist and base of the hand are formed by a series of eight small **carpal bones** (see Figure 7.3.3). The carpal bones are arranged in two rows, forming a proximal row of four carpal bones and a distal row of four carpal bones. The bones in the proximal row, running from the lateral (thumb) side to the medial side, are the **scaphoid** (“boat-shaped”), **lunate** (“moon-shaped”), **triquetrum** (“three-cornered”), and **pisiform** (“pea-shaped”) bones. The small, rounded pisiform bone articulates with the anterior surface of the triquetrum bone. The pisiform thus projects anteriorly, where it forms the bony bump that can be felt at the medial base of your hand. The distal bones (lateral to medial) are the **trapezium** (“table”), **trapezoid** (“resembles a table”), **capitate** (“head-shaped”), and **hamate** (“hooked bone”) bones. The hamate bone is characterized by a prominent bony extension on its anterior side called the **hook of the hamate bone**.

A helpful mnemonic for remembering the arrangement of the carpal bones is “So Long To Pinky, Here Comes The Thumb.” This mnemonic starts on the lateral side and names the proximal bones from lateral to medial (scaphoid, lunate, triquetrum, pisiform), then makes a U-turn to name the distal bones from medial to lateral (hamate, capitate, trapezoid, trapezium). Thus, it starts and finishes on the lateral side.

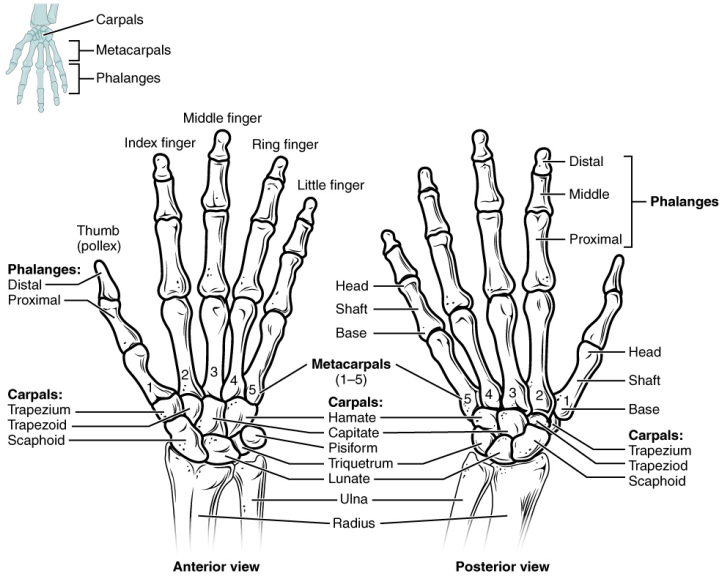

Figure 7.3.3: Bones of the Wrist and Hand. The eight carpal bones form the base of the hand. These are arranged into proximal and distal rows of four bones each. The metacarpal bones form the palm of the hand. The thumb and fingers consist of the phalanx bones. (Image credit: "Hand and Wrist" by OpenStax is licensed under CC BY 3.0)

The carpal bones form the base of the hand. This can be seen in the radiograph (X-ray image) of the hand that shows the relationships of the hand bones to the skin creases of the hand (see Figure 7.3.4). Within the carpal bones, the four proximal bones

are united to each other by ligaments to form a unit. Only three of these bones, the scaphoid, lunate, and triquetrum, contribute to the radiocarpal joint. The scaphoid and lunate bones articulate directly with the distal end of the radius, whereas the triquetrum bone articulates with a fibrocartilaginous pad that spans the radius and styloid process of the ulna. The distal end of the ulna thus does not directly articulate with any of the carpal bones.

The four distal carpal bones are also held together as a group by ligaments. The proximal and distal rows of carpal bones articulate with each other to form the **midcarpal joint** (see Figure 7.3.4). Together, the radiocarpal and midcarpal joints are responsible for all movements of the hand at the wrist. The distal carpal bones also articulate with the metacarpal bones of the hand.

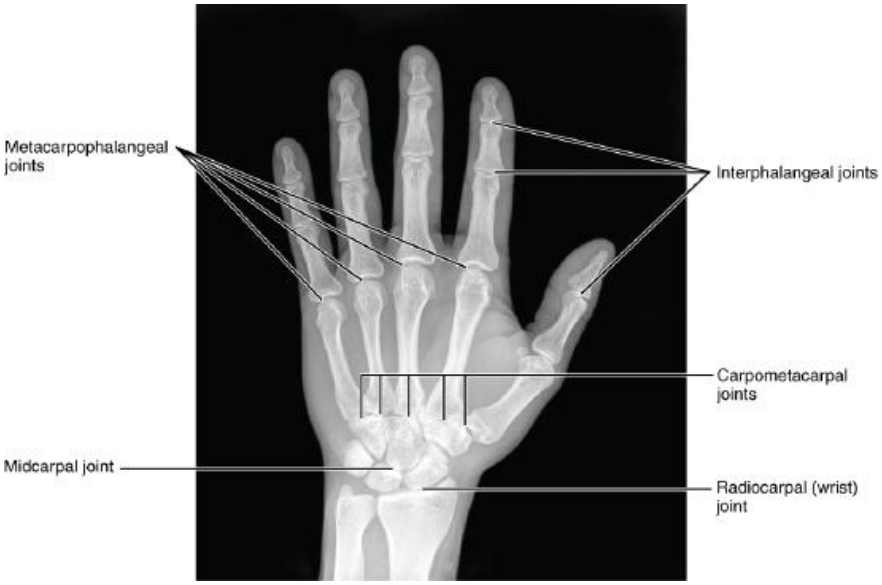

Figure 7.3.4: Bones of the Hand. This radiograph shows the position of the bones within the hand. Note the carpal bones that form the base of the hand. (Image credit: "Radiograph of Hand" by OpenStax is licensed under CC BY 3.0)

In the articulated hand, the carpal bones form a U-shaped grouping. A strong ligament called the **flexor retinaculum** spans the top of this U-shaped area to maintain this grouping of the carpal bones (Figure 7.3.5). The flexor retinaculum is attached laterally to the trapezium and scaphoid bones, and medially to the hamate and pisiform bones. Together, the carpal bones and the flexor retinaculum form a passageway called the **carpal tunnel**, with the carpal bones forming the walls and floor, and the flexor retinaculum forming the roof of this space. The tendons of nine muscles of the anterior forearm and an important nerve pass through this narrow tunnel to enter the hand. Overuse of the muscle tendons or wrist injury can produce inflammation and swelling within this space. This produces compression of the nerve, resulting in carpal tunnel syndrome, which is characterized by pain or numbness, and muscle weakness in those areas of the hand supplied by this nerve.

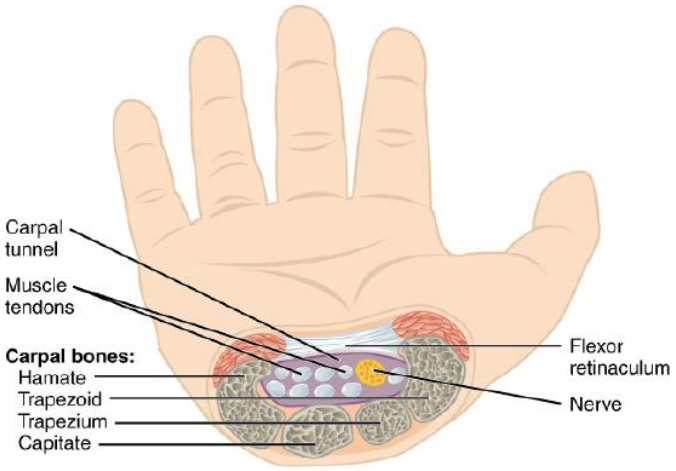

Figure 7.3.5: Carpal Tunnel. The carpal tunnel is the passageway by which nine muscle tendons and a major nerve enter the hand from the anterior forearm. The walls and floor of the carpal tunnel are formed by the U-shaped grouping of the carpal bones, and the roof is formed by the flexor retinaculum, a strong ligament that anteriorly unites the bones. (Image credit: "The Carpal Tunnel" by OpenStax is licensed under CC BY 3.0)

Metacarpal Bones

The palm of the hand contains five elongated metacarpal bones. These bones lie between the carpal bones of the wrist and the bones of the fingers and thumb (see Figure 7.3.3). The proximal end, also known as the base, of each metacarpal bone articulates with one of the distal carpal bones. Each of these articulations is a **carpometacarpal joint** (see Figure 7.3.4). The elongated portion of the metacarpal bone is the body, or shaft. The expanded distal end, also known as the head, of each metacarpal bone articulates at the **metacarpophalangeal joint** with the proximal phalanx bone of the thumb or one of the fingers. The distal end also forms the knuckles of the hand, at the base of the fingers. The metacarpal bones are numbered 1–5, beginning at the thumb (or moving lateral to medial).

The first metacarpal bone, at the base of the thumb, is separated from the other metacarpal bones. This allows it a freedom of motion that is independent of the other metacarpal bones, which is very important for thumb mobility. The remaining metacarpal bones are united together to form the palm of the hand. The second and third metacarpal bones are firmly anchored in place and are immobile. However, the fourth and fifth metacarpal bones have limited anterior-posterior mobility, a motion that is greater for the fifth bone. This mobility is important during power gripping with the hand (Figure 7.3.6). The anterior movement of these bones, particularly the fifth metacarpal bone, increases the strength of contact for the medial hand during gripping actions.

Figure 7.3.6: Hand During Gripping. During tight gripping—compare (b) to (a)—the fourth and, particularly, the fifth metatarsal bones are pulled anteriorly. This increases the contact between the object and the medial side of the hand, thus improving the firmness of the grip. (Image credit: "Hand Gripping" by OpenStax is licensed under CC BY 3.0)

Phalanx Bones

The fingers and thumb are composed of 14 bones, each of which is called a **phalanx** bone (plural = phalanges), named after the ancient Greek phalanx (a rectangular block of soldiers). The thumb (**pollex**) is digit number 1 and has two phalanges, a proximal phalanx, and a distal phalanx bone (see Figure 7.3.3). Digits 2 (index finger), 3 (middle finger), 4 (ring finger), and 5 (little finger) have three phalanges each, called the proximal, middle, and distal phalanx bones. An **interphalangeal joint** is one of the articulations between adjacent phalanges of the digits (see Figure 7.3.4). Each phalanx bone has a base (proximal end), body (shaft), and a head (distal end).

DISORDERS OF THE...

Appendicular System: Fractures of Upper Limb Bones

Due to our constant use of the hands and the rest of our upper limbs, an injury to any of these areas will cause a significant loss of functional ability. Many fractures result from a hard fall onto an outstretched hand. The resulting transmission of force up the limb may result in a fracture of the humerus, radius, or scaphoid bones. These injuries are especially common in elderly people whose bones are weakened due to osteoporosis.

Falls onto the hand or elbow, or direct blows to the arm, can result in fractures of the humerus (Figure 7.3.7). Following a fall, fractures at the surgical neck, the region at which the expanded proximal end of the humerus joins with the shaft, can result in an impacted fracture, in which the distal portion of the humerus is driven into the proximal portion. Falls or blows to the arm can also produce transverse or spiral fractures of the humeral shaft.

In children, a fall onto the tip of the elbow frequently results in a distal humerus fracture. In these, the olecranon of the ulna is driven upward, resulting in a fracture across the distal humerus, above both epicondyles (supracondylar fracture), or a fracture between the epicondyles, thus separating one or both of the epicondyles from the body of the humerus (intercondylar fracture). With these injuries, the immediate concern is possible compression of the artery to the forearm due to swelling of the surrounding tissues. If compression occurs, the resulting ischemia (lack of oxygen) due to reduced blood flow can quickly produce irreparable damage to the forearm muscles. In addition, four major nerves for shoulder and upper limb muscles are closely associated with different regions of the humerus, and thus, humeral fractures may also damage these nerves.

Another frequent injury following a fall onto an outstretched hand is a Colles fracture (“col-lees”) of the distal radius (see Figure 7.3.7). This involves a complete transverse fracture across the distal radius that drives the separated distal fragment of the radius posteriorly and superiorly. This injury results in a characteristic “dinner fork” bend of the forearm just above the wrist due to the posterior displacement of the hand. This is the most frequent forearm fracture and is a common injury in persons over the age of 50, particularly in older women with osteoporosis. It also commonly occurs following a high-speed fall onto the hand during activities such as snowboarding or skating.

The most commonly fractured carpal bone is the scaphoid, often resulting from a fall onto the hand. Deep pain at the lateral wrist may yield an initial diagnosis of a wrist sprain, but a radiograph taken several weeks after the injury, after tissue swelling has subsided, will reveal the fracture. Due to the poor blood supply to the scaphoid bone, healing will be slow and there is the danger of bone necrosis and subsequent degenerative joint disease of the wrist.

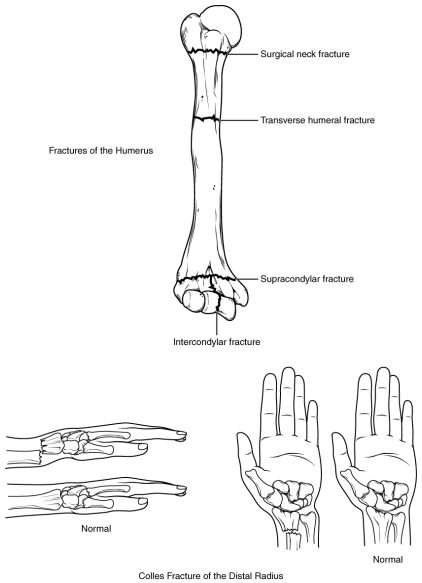

Figure 7.3.7: Fractures of the Humerus and Radius. Falls or direct blows can result in fractures of the surgical neck or shaft of the humerus. Falls onto the elbow can fracture the distal humerus. A Colles fracture of the distal radius is the most common forearm fracture. (Image credit: "Humerus Radius Fractures" by OpenStax is licensed under CC BY 3.0)

Interactive Link

Colles Fracture

QR Code representing a URL

Watch this Colles fracture video to learn more about a break of the distal radius, usually caused by falling onto an outstretched hand. When would surgery be required and how would the fracture be repaired in this case?

Answer available at the end of this section.

Concept Review

Each upper limb is divided into three regions and contains a total of 30 bones. The upper arm is the region located between the shoulder and elbow joints. This area contains the humerus. The proximal humerus consists of the head, which articulates with the scapula at the glenohumeral joint, the greater and lesser tubercles separated by the intertubercular (bicipital) groove, and the anatomical and surgical necks. The humeral shaft has the roughened area of the deltoid tuberosity on its lateral side. The distal humerus is flattened, forming a lateral supracondylar ridge that terminates at the small lateral epicondyle. The medial side of the distal humerus has the large, medial epicondyle. The articulating surfaces of the distal humerus consist of the trochlea medially and the capitulum laterally. Depressions on the humerus that accommodate the forearm bones during bending (flexing) and straightening (extending) of the elbow include the coronoid fossa, the radial fossa, and the olecranon fossa.

The forearm is the region of the upper limb located between the elbow and wrist joints. This region contains two bones, the ulna medially and the radius on the lateral (thumb) side. The elbow joint is formed by the articulation between the trochlea of the humerus and the trochlear notch of the ulna, plus the articulation between the capitulum of the humerus and the head of the radius. The proximal radioulnar joint is the articulation between the head of the radius and the radial notch of the ulna. The proximal ulna also has the olecranon process, forming an expanded posterior region, and the coronoid process and ulnar tuberosity on its anterior aspect. On the proximal radius, the narrowed region below the head is the neck; distal to this is the radial tuberosity. The shaft portions of both the ulna and radius have an interosseous border, whereas the distal ends of each bone have a pointed styloid process. The distal radioulnar joint is found between the head of the ulna and the ulnar notch of the radius. The distal end of the radius articulates with the proximal carpal bones, but the ulna does not.

The base of the hand is formed by eight carpal bones. The carpal bones are united into two rows of bones. The proximal row contains (from lateral to medial) the scaphoid, lunate, triquetrum, and pisiform bones. The scaphoid, lunate, and triquetrum bones

contribute to the formation of the radiocarpal joint. The distal row of carpal bones contains (from medial to lateral) the hamate, capitate, trapezoid, and trapezium bones (“So Long To Pinky, Here Comes The Thumb”). The anterior hamate has a prominent bony hook. The proximal and distal carpal rows articulate with each other at the midcarpal joint. The carpal bones, together with the flexor retinaculum, also form the carpal tunnel of the wrist.

The five metacarpal bones form the palm of the hand. The metacarpal bones are numbered 1–5, starting with the thumb side. The first metacarpal bone is freely mobile, but the other bones are united as a group. The digits are also numbered 1–5, with the thumb being number 1. The fingers and thumb contain a total of 14 phalanges (phalanx bones). The thumb contains a proximal and a distal phalanx, whereas the remaining digits each contain proximal, middle, and distal phalanges.

Review Questions

Q. How many bones are there in the upper limbs combined?

A. 20

B. 30

C. 40

D. 60

Answer

Answer: D

Q. Which bony landmark is located on the lateral side of the proximal humerus?

A. greater tubercle

B. trochlea

C. lateral epicondyle

D. lesser tubercle

Answer

Answer: A

Q. Which region of the humerus articulates with the radius as part of the elbow joint?

A. trochlea

B. styloid process

C. capitulum

D. olecranon process

Answer

Answer: C

Q. Which is the lateral-most carpal bone of the proximal row?

A. trapezium

B. hamate

C. pisiform

D. scaphoid

Answer

Answer: D

Q. The radius bone _____.

A. is found on the medial side of the forearm

B. has a head that articulates with the radial notch of the ulna

C. does not articulate with any of the carpal bones

D. has the radial tuberosity located near its distal end

Answer

Answer: B

Critical Thinking Questions

Q. Your friend runs out of gas and you have to help push his car. Discuss the sequence of bones and joints that convey the forces passing from your hand, through your upper limb and your pectoral girdle, and to your axial skeleton.

Answer

A. As you push against the car, forces will pass from the metacarpal bones of your hand into the carpal bones at the base of your hand. Forces will then pass through the midcarpal and radiocarpal joints into the radius and ulna bones of the forearm. These will pass the force through the elbow joint into the humerus of the arm, and then through the glenohumeral joint into the scapula. The force will travel through the acromioclavicular joint into the clavicle, and then through the sternoclavicular joint into the sternum, which is part of the axial skeleton.

Q. Name the bones in the wrist and hand, and describe or sketch out their locations and articulations.

Answer

A. The base of the hand is formed by the eight carpal bones arranged in two rows (distal and proximal) of four bones each. The proximal row contains (from lateral to medial) the scaphoid, lunate, triquetrum, and pisiform bones. The distal row contains (from medial to lateral) the hamate, capitate, trapezoid, and trapezium bones. (Use the mnemonic “So Long To Pinky, Here Comes The Thumb” to remember this sequence). The rows of the proximal and distal carpal bones articulate with each other at the midcarpal joint. The palm of the hand contains the five metacarpal bones, which are numbered 1–5 starting on the thumb side. The proximal ends of the metacarpal bones articulate with the distal row of the carpal bones. The distal ends of the metacarpal bones articulate with the proximal phalanx bones of the thumb and fingers. The thumb (digit 1) has both a proximal and distal phalanx bone. The fingers (digits 2–5) all contain proximal, middle, and distal phalanges.

Glossary

anatomical neck
line on the humerus located around the outside margin of the humeral head

arm
region of the upper limb located between the shoulder and elbow joints; contains the humerus bone

capitate
from the lateral side, the third of the four distal carpal bones; articulates with the scaphoid and lunate proximally,

the trapezoid laterally, the hamate medially, and primarily with the third metacarpal distally

capitulum
knob-like bony structure located anteriorly on the lateral, distal end of the humerus

carpal bone
one of the eight small bones that form the wrist and base of the hand; these are grouped as a proximal row consisting of (from lateral to medial) the scaphoid, lunate, triquetrum, and pisiform bones, and a distal row containing (from lateral to medial) the trapezium, trapezoid, capitate, and hamate bones

carpal tunnel
passageway between the anterior forearm and hand formed by the carpal bones and flexor retinaculum

carpometacarpal joint
articulation between one of the carpal bones in the distal row and a metacarpal bone of the hand

coronoid fossa
depression on the anterior surface of the humerus above the trochlea; this space receives the coronoid process of the ulna when the elbow is maximally flexed

coronoid process of the ulna
projecting bony lip located on the anterior, proximal ulna; forms the inferior margin of the trochlear notch

deltoid tuberosity
roughened, V-shaped region located laterally on the mid-shaft of the humerus

distal radioulnar joint
articulation between the head of the ulna and the ulnar notch of the radius

elbow joint
joint located between the upper arm and forearm regions of the upper limb; formed by the articulations between the trochlea of the humerus and the trochlear notch of the ulna, and the capitulum of the humerus and the head of the radius

flexor retinaculum
strong band of connective tissue at the anterior wrist that spans the top of the U-shaped grouping of the carpal bones to form the roof of the carpal tunnel

forearm
region of the upper limb located between the elbow and wrist joints; contains the radius and ulna bones

greater tubercle
enlarged prominence located on the lateral side of the proximal humerus

hamate
from the lateral side, the fourth of the four distal carpal bones; articulates with the lunate and triquetrum proximally, the fourth and fifth metacarpals distally, and the capitate laterally

hand
region of the upper limb distal to the wrist joint

head of the humerus
smooth, rounded region on the medial side of the proximal humerus; articulates with the glenoid fossa of the scapula to form the glenohumeral (shoulder) joint

head of the radius
disc-shaped structure that forms the proximal end of the radius; articulates with the capitulum of the humerus as part of the elbow joint, and with the radial notch of the ulna as part of the proximal radioulnar joint

head of the ulna
small, rounded distal end of the ulna; articulates with the ulnar notch of the distal radius, forming the distal

radioulnar joint

hook of the hamate bone
bony extension located on the anterior side of the hamate carpal bone

humerus
single bone of the upper arm

interosseous border of the radius
narrow ridge located on the medial side of the radial shaft; for attachment of the interosseous membrane between the ulna and radius bones

interosseous border of the ulna
narrow ridge located on the lateral side of the ulnar shaft; for attachment of the interosseous membrane between the ulna and radius

interosseous membrane of the forearm
also known as antebrachial interosseous membrane; sheet of dense connective tissue that unites the radius and ulna bones

interphalangeal joint
articulation between adjacent phalanx bones of the hand or foot digits

intertubercular groove (sulcus)
also known as bicipital groove; narrow groove located between the greater and lesser tubercles of the humerus

lateral epicondyle of the humerus
small projection located on the lateral side of the distal humerus

lateral supracondylar ridge
narrow, bony ridge located along the lateral side of the distal humerus, superior to the lateral epicondyle

lesser tubercle
small, bony prominence located on anterior side of the proximal humerus

lunate
from the lateral side, the second of the four proximal carpal bones; articulates with the radius proximally, the capitate and hamate distally, the scaphoid laterally, and the triquetrum medially

medial epicondyle of the humerus
enlarged projection located on the medial side of the distal humerus

metacarpal bone
one of the five long bones that form the palm of the hand; numbered 1–5, starting on the lateral (thumb) side of the hand

metacarpophalangeal joint
articulation between the distal end of a metacarpal bone of the hand and a proximal phalanx bone of the thumb or a finger

midcarpal joint
articulation between the proximal and distal rows of the carpal bones; contributes to movements of the hand at the wrist

neck of the radius
narrowed region immediately distal to the head of the radius

olecranon fossa
large depression located on the posterior side of the distal humerus; this space receives the olecranon process of the ulna when the elbow is fully extended

olecranon process
expanded posterior and superior portions of the proximal ulna; forms the bony tip of the elbow

phalanx bone of the hand
(plural = phalanges) one of the 14 bones that form the thumb and fingers; these include the proximal and distal phalanges of the thumb, and the proximal, middle, and distal phalanx bones of the fingers two through five

pisiform
from the lateral side, the fourth of the four proximal carpal bones; articulates with the anterior surface of the triquetrum

pollex
(also, thumb) digit 1 of the hand

proximal radioulnar joint
articulation formed by the radial notch of the ulna and the head of the radius

radial fossa
small depression located on the anterior humerus above the capitulum; this space receives the head of the radius when the elbow is maximally flexed

radial notch of the ulna
small, smooth area on the lateral side of the proximal ulna; articulates with the head of the radius as part of the proximal radioulnar joint

radial tuberosity
oval-shaped, roughened protuberance located on the medial side of the proximal radius

radiocarpal joint
wrist joint, located between the forearm and hand regions of the upper limb; articulation formed proximally by the distal end of the radius and the fibrocartilaginous pad that unites the distal radius and ulna bone, and distally by the scaphoid, lunate, and triquetrum carpal bones

radius
bone located on the lateral side of the forearm

scaphoid
from the lateral side, the first of the four proximal carpal bones; articulates with the radius proximally, the trapezoid, trapezium, and capitate distally, and the lunate medially

shaft of the humerus
narrow, elongated, central region of the humerus

shaft of the radius
narrow, elongated, central region of the radius

shaft of the ulna
narrow, elongated, central region of the ulna

styloid process of the radius
pointed projection located on the lateral end of the distal radius

styloid process of the ulna
short, bony projection located on the medial end of the distal ulna

surgical neck
region of the humerus where the expanded, proximal end joins with the narrower shaft

trapezium
from the lateral side, the first of the four distal carpal bones; articulates with the scaphoid proximally, the first and second metacarpals distally, and the trapezoid medially

trapezoid
: from the lateral side, the second of the four distal carpal bones; articulates with the scaphoid proximally, the second metacarpal distally, the trapezium laterally, and the capitate medially

triquetrum
: from the lateral side, the third of the four proximal carpal bones; articulates with the lunate laterally, the hamate distally, and has a facet for the pisiform

trochlea
: pulley-shaped region located medially at the distal end of the humerus; articulates at the elbow with the trochlear notch of the ulna

trochlear notch
: large, C-shaped depression located on the anterior side of the proximal ulna; articulates at the elbow with the trochlea of the humerus

ulna
: bone located on the medial side of the forearm

ulnar notch of the radius
: shallow, smooth area located on the medial side of the distal radius; articulates with the head of the ulna at the distal radioulnar joint

ulnar tuberosity
: roughened area located on the anterior, proximal ulna inferior to the coronoid process

Contributors and Attributions

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Answers

Interactive Link

Answer: Surgery may be required if the fracture is unstable, meaning that the broken ends of the radius won't stay in place to allow for proper healing. In this case, metal plates and screws can be used to stabilize the fractured bone.

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7.4: The Pelvic Girdle and Pelvis

By the end of this section, you will be able to:

- Define the pelvic girdle and describe the bones and ligaments of the pelvis
- Explain the three regions of the hip bone and identify their bony landmarks
- Describe the openings of the pelvis and the boundaries of the greater and lesser pelvis

The **pelvic girdle** (hip girdle) is formed by a single bone, the **hip bone** or **coxal bone** (coxal = “hip”), which serves as the attachment point for each lower limb. Each hip bone, in turn, is firmly joined to the axial skeleton via its attachment to the sacrum of the vertebral column. The right and left hip bones also converge anteriorly to attach to each other. The bony **pelvis** is the entire structure formed by the two hip bones, the sacrum, and, attached inferiorly to the sacrum, the coccyx (Figure 7.4.1).

Unlike the bones of the pectoral girdle, which are highly mobile to enhance the range of upper limb movements, the bones of the pelvis are strongly united to each other to form a largely immobile, weight-bearing structure. This is important for stability because it enables the weight of the body to be easily transferred laterally from the vertebral column, through the pelvic girdle and hip joints, and into either lower limb whenever the other limb is not bearing weight. Thus, the immobility of the pelvis provides a strong foundation for the upper body as it rests on top of the mobile lower limbs.

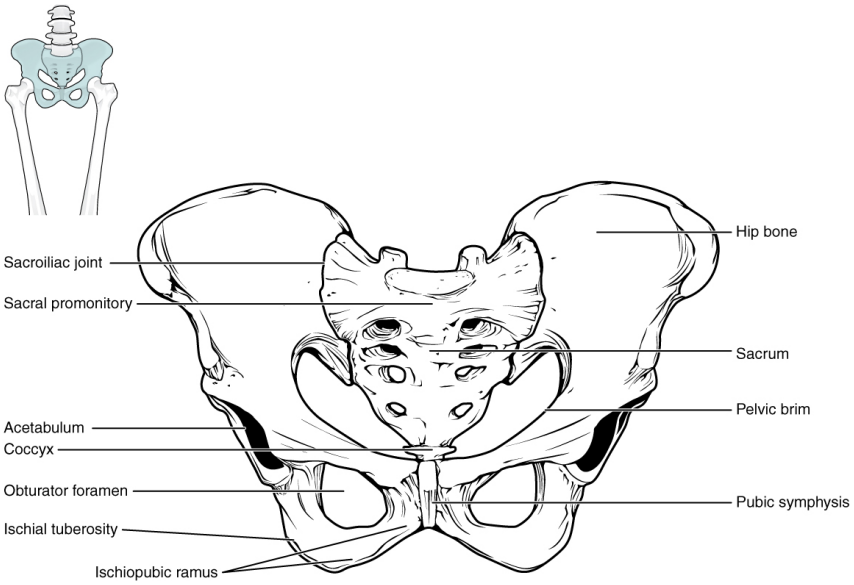

Figure 7.4.1: Pelvis. The pelvic girdle is formed by a single hip bone. The hip bone attaches the lower limb to the axial skeleton through its articulation with the sacrum. The right and left hip bones, plus the sacrum and the coccyx, together form the pelvis. (Image credit: "Pelvis" by OpenStax is licensed under CC BY 3.0)

Hip Bone

The **hip bone**, or **coxal bone**, forms the pelvic girdle portion of the pelvis. The paired hip bones are the large, curved bones that form the lateral and anterior aspects of the pelvis. Each adult hip bone is formed by three separate bones that fuse together during the late teenage years. These bony components are the ilium, ischium, and pubis (Figure 7.4.2). These names are retained and used to define the three regions of the adult hip bone.

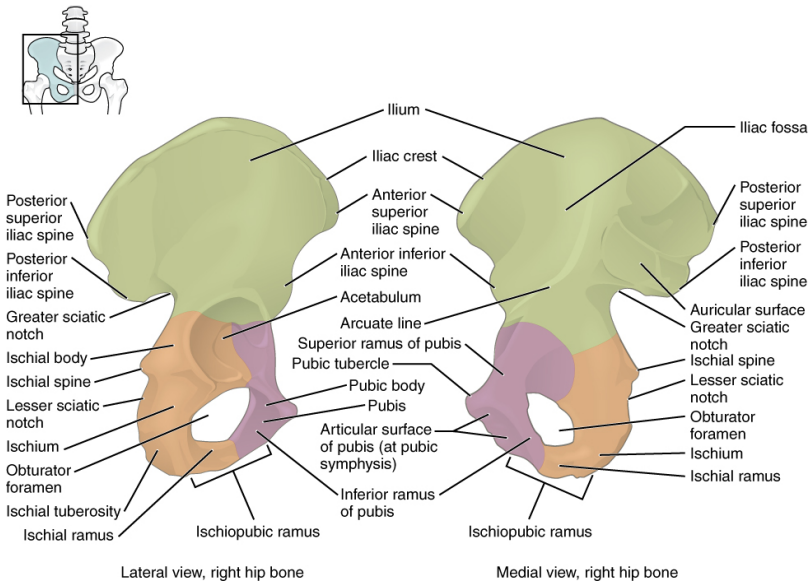

Figure 7.4.2: The Hip Bone. The adult hip bone consists of three regions. The ilium forms the large, fan-shaped superior portion, the ischium forms the posteroinferior portion, and the pubis forms the anteromedial portion. (Image credit: "Hip Bone" by OpenStax is licensed under CC BY 3.0)

The three regions of the adult hip can be seen in Figure 7.4.2. The **ilium** is the fan-like, superior region that forms the largest part of the hip bone. It is firmly united to the sacrum at the largely immobile **sacroiliac joint** (see Figure 7.4.1). The **ischium** forms the posteroinferior region of each hip bone. It supports the body when sitting. The **pubis** forms the anterior portion of the hip bone. The pubis curves medially, where it joins to the pubis of the opposite hip bone at a specialized joint called the **pubic symphysis** (see Figure 7.4.1).

Ilium

When you place your hands on your waist, you can feel the arching, superior margin of the ilium along your waistline (see Figure 7.4.2). This curved, superior margin of the ilium is the **iliac crest**. The rounded, anterior termination of the iliac crest is the **anterior superior iliac spine**. This important bony landmark can be felt at your anterolateral hip. Inferior to the anterior superior iliac spine is a rounded protuberance called the **anterior inferior iliac spine**. Both of these iliac spines serve as attachment points for muscles of the thigh. Posteriorly, the iliac crest curves downward to terminate as the **posterior superior iliac spine**. Muscles and ligaments surround but do not cover this bony landmark, thus sometimes producing a depression seen as a “dimple” located on the lower back. More inferiorly is the **posterior inferior iliac spine**. This is located at the inferior end of a large, roughened area called the **auricular surface of the ilium**. The auricular surface articulates with the auricular surface of the sacrum to form the sacroiliac joint. Both the posterior superior and posterior inferior iliac spines serve as attachment points for the muscles and very strong ligaments that support the sacroiliac joint.

The shallow depression located on the anteromedial (internal) surface of the upper ilium is called the **iliac fossa**. The inferior margin of this space is formed by the **arcuate line of the ilium**, the ridge formed by the pronounced change in curvature between the upper and lower portions of the ilium. The large, inverted U-shaped indentation located on the posterior margin of the lower ilium is called the **greater sciatic notch**.

Ischium

The ischium forms the posterolateral portion of the hip bone (see Figure 7.4.2). The large, smooth area of the superior ischium is the **ischial body**.The large, roughened area of the inferior ischium is the **ischial tuberosity**. This serves as the attachment for the posterior thigh muscles and also carries the weight of the body when sitting. You can feel the ischial tuberosity if you wiggle your pelvis against the seat of a chair. Projecting superiorly and anteriorly from the ischial tuberosity is a narrow segment of bone called the **ischial ramus**. The slightly curved posterior margin of the ischium above the ischial tuberosity is the **lesser sciatic notch**. The bony projection separating the lesser sciatic notch and greater sciatic notch is the **ischial spine**.

Pubis

The pubis forms the anterior portion of the hip bone (see Figure 7.4.2). The enlarged medial portion of the pubis is the **pubic body**. Located superiorly on the pubic body is a small bump called the **pubic tubercle**. The **superior pubic ramus** is the segment of bone that passes laterally from the pubic body to join the ilium. The narrow ridge running along the superior margin of the superior pubic ramus is the **pectineal line of the pubis**.

The pubic body is joined to the pubic body of the opposite hip bone by the pubic symphysis (Figure 7.4.1). Extending downward and laterally from the body is the **inferior pubic ramus**. The **pubic arch** is the bony structure formed by the pubic symphysis, and the bodies and inferior pubic rami of the adjacent pubic bones. The inferior pubic ramus extends downward to join the ischial ramus. Together, these form the single **ischiopubic ramus**, which extends from the pubic body to the ischial tuberosity. The inverted V-shape formed as the ischiopubic rami from both sides come together at the pubic symphysis is called the **subpubic angle** (Figure 7.4.3 & 7.4.4).

Pelvis

The pelvis consists of four bones: the right and left hip bones, the sacrum, and the coccyx (see Figure 7.4.1). The pelvis has several important functions. Its primary role is to support the weight of the upper body when sitting and to transfer this weight to the lower limbs when standing. It serves as an attachment point for trunk and lower limb muscles, and also protects the internal pelvic organs. When standing in the anatomical position, the pelvis is tilted anteriorly. In this position, the anterior superior iliac spines and the pubic tubercles lie in the same vertical plane, and the anterior (internal) surface of the sacrum faces forward and downward.

The three areas of each hip bone, the ilium, pubis, and ischium, converge centrally to form a deep, cup-shaped cavity called the **acetabulum** (Figure 7.4.2). This is located on the lateral side of the hip bone and is part of the hip joint. The large opening in the anteroinferior hip bone between the ischium and pubis is the **obturator foramen**. This space is largely filled in by a layer of connective tissue and serves for the attachment of muscles on both its internal and external surfaces.

Several ligaments unite the bones of the pelvis (Figure 7.4.3). The largely immobile sacroiliac joint is supported by a pair of strong ligaments that are attached between the sacrum and ilium portions of the hip bone. These are the **anterior sacroiliac ligament** on the anterior side of the joint and the **posterior sacroiliac ligament** on the posterior side. Also spanning the sacrum and hip bone are two additional ligaments. The **sacrospinous ligament** runs from the sacrum to the ischial spine, and the **sacrotuberous ligament** runs from the sacrum to the ischial tuberosity. These ligaments help to support and immobilize the sacrum as it carries the weight of the body.

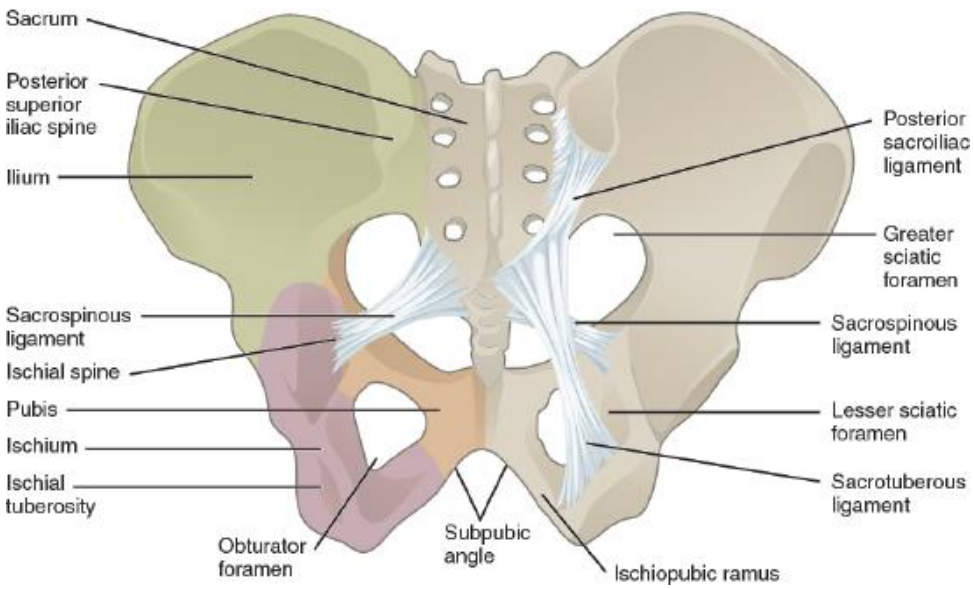

Figure 7.4.3: Ligaments of the Pelvis. The posterior sacroiliac ligament supports the sacroiliac joint. The sacrospinous ligament spans the sacrum to the ischial spine, and the sacrotuberous ligament spans the sacrum to the ischial tuberosity. The sacrospinous and sacrotuberous ligaments contribute to the formation of the greater and lesser sciatic foramens. (Image credit: "Ligaments Pelvis" by OpenStax is licensed under CC BY 3.0)

The sacrospinous and sacrotuberous ligaments also help to define two openings on the posterolateral sides of the pelvis through which muscles, nerves, and blood vessels for the lower limb exit. The superior opening is the **greater sciatic foramen**. This large opening is formed by the greater sciatic notch of the hip bone, the sacrum, and the sacrospinous ligament. The smaller, more inferior **lesser sciatic foramen** is formed by the lesser sciatic notch of the hip bone, together with the sacrospinous and sacrotuberous ligaments.

The space enclosed by the bony pelvis is divided into two regions (Figure 7.4.4). The broad, superior region, defined laterally by the large, fan-like portion of the upper hip bone, is called the **greater pelvis** (greater pelvic cavity; false pelvis). This broad area is occupied by portions of the small and large intestines, and because it is more closely associated with the abdominal cavity, it is sometimes referred to as the false pelvis. More inferiorly, the narrow, rounded space of the **lesser pelvis** (lesser pelvic cavity; true pelvis) contains the bladder and other pelvic organs, and thus is also known as the true pelvis. The **pelvic brim** (also known as the **pelvic inlet**) forms the superior margin of the lesser pelvis, separating it from the greater pelvis. The pelvic brim is defined by a line formed by the upper margin of the pubic symphysis anteriorly, and the pectineal line of the pubis, the arcuate line of the ilium, and the sacral promontory (the anterior margin of the superior sacrum) posteriorly. The inferior limit of the lesser pelvic cavity is called the **pelvic outlet**. This large opening is defined by the inferior margin of the pubic symphysis anteriorly, and the ischiopubic ramus, the ischial tuberosity, the sacrotuberous ligament, and the inferior tip of the coccyx posteriorly. Because of the anterior tilt of the pelvis, the lesser pelvis is also angled, giving it an anterosuperior (pelvic inlet) to posteroinferior (pelvic outlet) orientation.

Comparison of the Female and Male Pelvis

The differences between the adult female and male pelvis relate to function and body size. In general, the bones of the male pelvis are thicker and heavier, adapted for support of the male's heavier physical build and stronger muscles. The greater sciatic notch of the male hip bone is narrower and deeper than the broader notch of females. Because the female pelvis is adapted for childbirth, it is wider than the male pelvis, as evidenced by the distance between the anterior superior iliac spines (see Figure 7.4.4). The ischial tuberosities of females are also farther apart, which increases the size of the pelvic outlet. Because of this increased pelvic width, the subpubic angle is larger in females (greater than 80 degrees) than it is in males (less than 70 degrees). The female sacrum is wider, shorter, and less curved, and the sacral promontory projects less into the pelvic cavity, thus giving the female pelvic inlet (pelvic brim) a more rounded or oval shape compared to males. The lesser pelvic cavity of females is also wider and more shallow than the narrower, deeper, and tapering lesser pelvis of males. Because of the obvious differences between female and male hip bones, this is the one bone of the body that allows for the most accurate sex determination. Table 7.4.1 provides an overview of the general differences between the female and male pelvis.

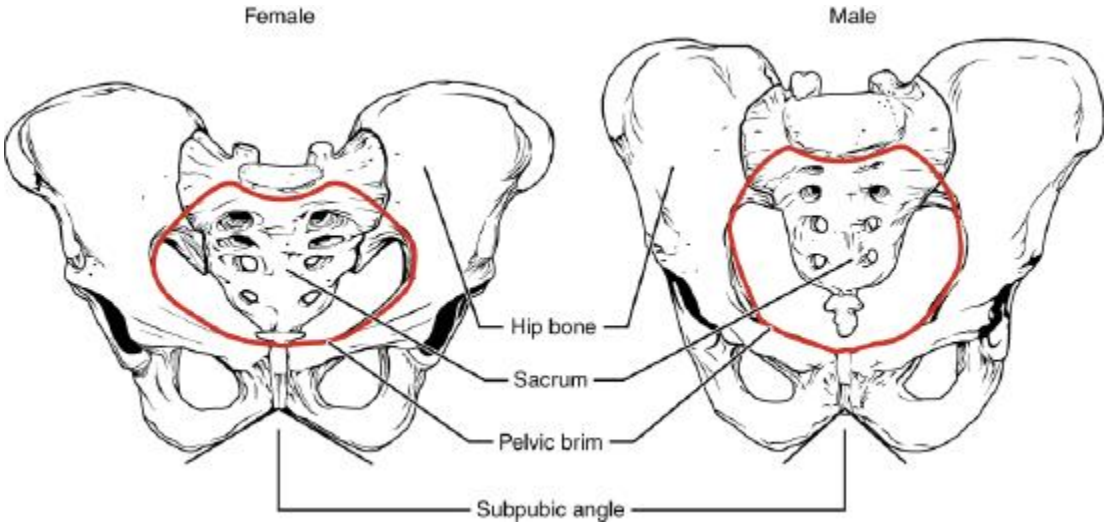

Figure 7.4.4: Male and Female Pelvis. The female pelvis is adapted for childbirth and is broader, with a larger subpubic angle, a rounder pelvic brim, and a wider and more shallow lesser pelvic cavity than the male pelvis. (Image credit: "Male Female Pelvic Girdle" by OpenStax is licensed under CC BY 3.0)

Table 7.4.1: Overview of Differences between the Female and Male Pelvis

Characteristic	Female pelvis	Male pelvis
Pelvic weight	Bones of the pelvis are lighter and thinner	Bones of the pelvis are thicker and heavier

Characteristic	Female pelvis	Male pelvis
Pelvic inlet shape	Pelvic inlet has a round or oval shape	Pelvic inlet is heart-shaped
Lesser pelvic cavity shape	Lesser pelvic cavity is shorter and wider	Lesser pelvic cavity is longer and narrower
Subpubic angle	Subpubic angle is greater than 80 degrees	Subpubic angle is less than 70 degrees
Pelvic outlet shape	Pelvic outlet is rounded and larger	Pelvic outlet is smaller

Career Connection

Forensic Pathology and Forensic Anthropology

A forensic pathologist (also known as a medical examiner) is a medically trained physician who has been specifically trained in pathology to examine the bodies of the deceased to determine the cause of death. A forensic pathologist applies his or her understanding of disease as well as toxins, blood and DNA analysis, firearms and ballistics, and other factors to assess the cause and manner of death. At times, a forensic pathologist will be called to testify under oath in situations that involve a possible crime. Forensic pathology is a field that has received much media attention on television shows or following a high-profile death.

While forensic pathologists are responsible for determining whether the cause of someone's death was natural, a suicide, accidental, or a homicide, there are times when uncovering the cause of death is more complex, and other skills are needed. Forensic anthropology brings the tools and knowledge of physical anthropology and human osteology (the study of the skeleton) to the task of investigating a death. A forensic anthropologist assists medical and legal professionals in identifying human remains. The science behind forensic anthropology involves the study of archaeological excavation; the examination of hair; an understanding of plants, insects, and footprints; the ability to determine how much time has elapsed since the person died; the analysis of past medical history and toxicology; the ability to determine whether there are any postmortem injuries or alterations of the skeleton; and the identification of the decedent (deceased person) using skeletal and dental evidence.

Due to the extensive knowledge and understanding of excavation techniques, a forensic anthropologist is an integral and invaluable team member to have on-site when investigating a crime scene, especially when the recovery of human skeletal remains is involved. When remains are bought to a forensic anthropologist for examination, he or she must first determine whether the remains are in fact human. Once the remains have been identified as belonging to a person and not to an animal, the next step is to approximate the individual's age, sex, race, and height. The forensic anthropologist does not determine the cause of death, but rather provides information to the forensic pathologist, who will use all of the data collected to make a final determination regarding the cause of death.

Concept Review

The pelvic girdle, consisting of a hip bone, serves to attach a lower limb to the axial skeleton. The hip bone articulates posteriorly at the sacroiliac joint with the sacrum, which is part of the axial skeleton. The right and left hip bones converge anteriorly and articulate with each other at the pubic symphysis. The combination of the hip bone, the sacrum, and the coccyx forms the pelvis. The pelvis has a pronounced anterior tilt. The primary function of the pelvis is to support the upper body and transfer body weight to the lower limbs. It also serves as the site of attachment for multiple muscles.

The hip bone consists of three regions: the ilium, ischium, and pubis. The ilium forms the large, fan-like region of the hip bone. The superior margin of this area is the iliac crest. Located at either end of the iliac crest are the anterior superior and posterior superior iliac spines. Inferior to these are the anterior inferior and posterior inferior iliac spines. The auricular surface of the ilium articulates with the sacrum to form the sacroiliac joint. The medial surface of the upper ilium forms the iliac fossa, with the arcuate line marking the inferior limit of this area. The posterior margin of the ilium has the large greater sciatic notch.

The posterolateral portion of the hip bone is the ischium. It has the expanded ischial tuberosity, which supports body weight when sitting. The ischial ramus projects anteriorly and superiorly. The posterior margin of the ischium has the shallow lesser sciatic notch and the ischial spine, which separates the greater and lesser sciatic notches.

The pubis forms the anterior portion of the hip bone. The body of the pubis articulates with the pubis of the opposite hip bone at

the pubic symphysis. The superior margin of the pubic body has the pubic tubercle. The pubis is joined to the ilium by the superior pubic ramus, the superior surface of which forms the pectineal line. The inferior pubic ramus projects inferiorly and laterally. The pubic arch is formed by the pubic symphysis, the bodies of the adjacent pubic bones, and the two inferior pubic rami. The inferior pubic ramus joins the ischial ramus to form the ischiopubic ramus. The subpubic angle is formed by the medial convergence of the right and left ischiopubic rami.

The lateral side of the hip bone has the cup-like acetabulum, which is part of the hip joint. The large anterior opening is the obturator foramen. The sacroiliac joint is supported by the anterior and posterior sacroiliac ligaments. The sacrum is also joined to the hip bone by the sacrospinous ligament, which attaches to the ischial spine, and the sacrotuberous ligament, which attaches to the ischial tuberosity. The sacrospinous and sacrotuberous ligaments contribute to the formation of the greater and lesser sciatic foramina.

The broad space of the upper pelvis is the greater pelvis, and the narrow, inferior space is the lesser pelvis. These areas are separated by the pelvic brim (pelvic inlet). The inferior opening of the pelvis is the pelvic outlet. Compared to the male, the female pelvis is wider to accommodate childbirth, has a larger subpubic angle, and a broader greater sciatic notch.

Review Questions

Q. How many bones fuse in adulthood to form the hip bone?

A. 2

B. 3

C. 4

D. 5

Answer

Answer: B

Q. Which component forms the superior part of the hip bone?

A. ilium

B. pubis

C. ischium

D. sacrum

Answer

Answer: A

Q. Which of the following supports body weight when sitting?

A. iliac crest

B. ischial tuberosity

C. ischiopubic ramus

D. pubic body

Answer

Answer: B

Q. The ischial spine is found between which of the following structures?

A. inferior pubic ramus and ischial ramus

B. pectineal line and arcuate line

C. lesser sciatic notch and greater sciatic notch

D. anterior superior iliac spine and posterior superior iliac spine

Answer

Answer: C

Q. The pelvis _____.

A. has a subpubic angle that is larger in females

B. consists of the two hip bones, but does not include the sacrum or coccyx

C. has an obturator foramen, an opening that is defined in part by the sacrospinous and sacrotuberous ligaments

D. has a space located inferior to the pelvic brim called the greater pelvis

Answer

Answer: A

Critical Thinking Questions

Q. Describe the articulations and ligaments that unite the four bones of the pelvis to each other.

Answer

A. The pelvis is formed by the combination of the right and left hip bones, the sacrum, and the coccyx. The auricular surfaces of each hip bone articulate with the auricular surface of the sacrum to form the sacroiliac joint. This joint is supported on either side by the strong anterior and posterior sacroiliac ligaments. The right and left hip bones converge anteriorly, where the pubic bodies articulate with each other to form the pubic symphysis joint. The sacrum is also attached to the hip bone by the sacrospinous ligament, which spans the sacrum to the ischial spine, and the sacrotuberous ligament, which runs from the sacrum to the ischial tuberosity. The coccyx is attached to the inferior end of the sacrum.

Q. Discuss the ways in which the female pelvis is adapted for childbirth.

Answer

A. Compared to the male, the female pelvis is wider to accommodate childbirth. Thus, the female pelvis has greater distances between the anterior superior iliac spines and between the ischial tuberosities. The greater width of the female pelvis results in a larger subpubic angle. This angle, formed by the anterior convergence of the right and left ischiopubic rami, is larger in females (greater than 80 degrees) than in males (less than 70 degrees). The female sacral promontory does not project anteriorly as far as it does in males, which gives the pelvic brim (pelvic inlet) of the female a rounded or oval shape. The lesser pelvic cavity is wider and more shallow in females, and the pelvic outlet is larger than in males. Thus, the greater width of the female pelvis, with its larger pelvic inlet, lesser pelvis, and pelvic outlet, are important for childbirth because the baby must pass through the pelvis during delivery.

Glossary

acetabulum
large, cup-shaped cavity located on the lateral side of the hip bone; formed by the junction of the ilium, pubis, and

ischium portions of the hip bone

anterior inferior iliac spine
small, bony projection located on the anterior margin of the ilium, below the anterior superior iliac spine

anterior sacroiliac ligament
strong ligament between the sacrum and the ilium portions of the hip bone that supports the anterior side of the sacroiliac joint

anterior superior iliac spine
rounded, anterior end of the iliac crest

arcuate line of the ilium
smooth ridge located at the inferior margin of the iliac fossa; forms the lateral portion of the pelvic brim

auricular surface of the ilium
roughened area located on the posterior, medial side of the ilium of the hip bone; articulates with the auricular surface of the sacrum to form the sacroiliac joint

coxal bone
hip bone

greater pelvis
(also, greater pelvic cavity or false pelvis) broad space above the pelvic brim defined laterally by the fan-like portion of the upper ilium

greater sciatic foramen
pelvic opening formed by the greater sciatic notch of the hip bone, the sacrum, and the sacrospinous ligament

greater sciatic notch
large, U-shaped indentation located on the posterior margin of the ilium, superior to the ischial spine

hip bone
coxal bone; single bone that forms the pelvic girdle; consists of three areas, the ilium, ischium, and pubis

iliac crest
curved, superior margin of the ilium

iliac fossa
shallow depression found on the anterior and medial surfaces of the upper ilium

ilium
superior portion of the hip bone

inferior pubic ramus
narrow segment of bone that passes inferiorly and laterally from the pubic body; joins with the ischial ramus to form the ischiopubic ramus

ischial body
large, smooth area of the superior ischium

ischial ramus
bony extension projecting anteriorly and superiorly from the ischial tuberosity; joins with the inferior pubic ramus to form the ischiopubic ramus

ischial spine
pointed, bony projection from the posterior margin of the ischium that separates the greater sciatic notch and lesser sciatic notch

ischial tuberosity
large, roughened protuberance that forms the posteroinferior portion of the hip bone; weight-bearing region of the pelvis when sitting

ischiopubic ramus
narrow extension of bone that connects the ischial tuberosity to the pubic body; formed by the junction of the ischial ramus and inferior pubic ramus

ischium
posteroinferior portion of the hip bone

lesser pelvis
(also, lesser pelvic cavity or true pelvis) narrow space located within the pelvis, defined superiorly by the pelvic brim (pelvic inlet) and inferiorly by the pelvic outlet

lesser sciatic foramen
pelvic opening formed by the lesser sciatic notch of the hip bone, the sacrospinous ligament, and the sacrotuberous ligament

lesser sciatic notch
shallow indentation along the posterior margin of the ischium, inferior to the ischial spine

obturator foramen
large opening located in the anterior hip bone, between the pubis and ischium regions

pectineal line
narrow ridge located on the superior surface of the superior pubic ramus

pelvic brim
pelvic inlet; the dividing line between the greater and lesser pelvic regions; formed by the superior margin of the pubic symphysis, the pectineal lines of each pubis, the arcuate lines of each ilium, and the sacral promontory

pelvic girdle
hip girdle; consists of a single hip bone, which attaches a lower limb to the sacrum of the axial skeleton

pelvic inlet
pelvic brim

pelvic outlet
inferior opening of the lesser pelvis; formed by the inferior margin of the pubic symphysis, right and left ischiopubic rami and sacrotuberous ligaments, and the tip of the coccyx

pelvis
ring of bone consisting of the right and left hip bones, the sacrum, and the coccyx

posterior inferior iliac spine
small, bony projection located at the inferior margin of the auricular surface on the posterior ilium

posterior sacroiliac ligament
strong ligament spanning the sacrum and ilium of the hip bone that supports the posterior side of the sacroiliac joint

posterior superior iliac spine
rounded, posterior end of the iliac crest

pubic arch
bony structure formed by the pubic symphysis, and the bodies and inferior pubic rami of the right and left pubic bones

pubic body
enlarged, medial portion of the pubis region of the hip bone

pubic symphysis
joint formed by the articulation between the pubic bodies of the right and left hip bones

pubic tubercle
small bump located on the superior aspect of the pubic body

pubis
anterior portion of the hip bone

sacroiliac joint
joint formed by the articulation between the auricular surfaces of the sacrum and ilium

sacrospinous ligament
ligament that spans the sacrum to the ischial spine of the hip bone

sacrotuberous ligament
ligament that spans the sacrum to the ischial tuberosity of the hip bone

subpubic angle
inverted V-shape formed by the convergence of the right and left ischiopubic rami; this angle is greater than 80 degrees in females and less than 70 degrees in males

superior pubic ramus
narrow segment of bone that passes laterally from the pubic body to join the ilium

Contributors and Attributions

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7.5: Bones of the Lower Limb

By the end of this section, you will be able to:

- Identify the divisions of the lower limb and describe the bones of each region
- Describe the bones and bony landmarks that articulate at each joint of the lower limb

Like the upper limb, the lower limb is divided into three regions. The **thigh** is that portion of the lower limb located between the hip joint and knee joint. The **leg** is specifically the region between the knee joint and the ankle joint. Distal to the ankle is the **foot**. The lower limb contains 30 bones. These are the femur, patella, tibia, fibula, tarsal bones, metatarsal bones, and phalanges. The **femur** is the single bone of the thigh. The **patella** is the kneecap and articulates with the distal femur. The **tibia** is the larger, weight-bearing bone located on the medial side of the leg, and the **fibula** is the thin bone of the lateral leg. The bones of the foot are divided into three groups. The posterior portion of the foot is formed by a group of seven bones, each of which is known as a **tarsal bone**, whereas the mid-foot contains five elongated bones, each of which is a **metatarsal bone**. The toes contain 14 small bones, each of which is a **phalanx bone of the foot**.

Femur

The **femur**, or thigh bone, is the single bone of the thigh region (Figure 7.5.1) . It is the longest and strongest bone of the body, and accounts for approximately one-quarter of a person's total height. The rounded, proximal end is the **head of the femur**, which articulates with the acetabulum of the hip bone to form the **hip joint**. The **fovea capitis** is a minor indentation on the medial side of the femoral head that serves as the site of attachment for the ligament of the head of the femur. This ligament spans the femur and acetabulum, but is weak and provides little support for the hip joint. It does, however, carry an important artery that supplies the head of the femur.

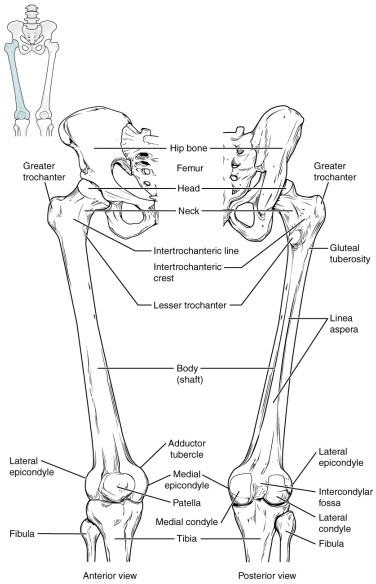

Figure 7.5.1: Femur and Patella. The femur is the single bone of the thigh region. It articulates superiorly with the hip bone at the hip joint, and inferiorly with the tibia at the knee joint. The patella only articulates with the distal end of the femur. (Image credit: "Femur and Patella" by OpenStax is licensed under CC BY 3.0)

The narrowed region below the head is the **neck of the femur**. This is a common area for fractures of the femur. The **greater trochanter** is the large, upward, bony projection located above the base of the neck. Multiple muscles that act across the hip joint attach to the greater trochanter, which, because of its projection from the femur, gives additional leverage to these muscles. The greater trochanter can be felt just under the skin on the lateral side of your upper thigh. The **lesser trochanter** is a small, bony prominence that lies on the medial aspect of the femur, just below the neck. A single, powerful muscle attaches to the lesser trochanter. Running between the greater and lesser trochanters on the anterior side of the femur is the roughened

intertrochanteric line. The trochanters are also connected on the posterior side of the femur by the larger **intertrochanteric crest**.

The elongated body, or **shaft of the femur** has a slight anterior bowing or curvature. At its proximal end, the posterior shaft has the **gluteal tuberosity**, a roughened area extending inferiorly from the greater trochanter. More inferiorly, the gluteal tuberosity becomes continuous with the **linea aspera** (“rough line”). This is the roughened ridge that passes distally along the posterior side of the mid-femur. Multiple muscles of the hip and thigh regions make long, thin attachments to the femur along the linea aspera.

The distal end of the femur has medial and lateral bony expansions. On the lateral side, the smooth portion that covers the distal and posterior aspects of the lateral expansion is the **lateral condyle of the femur**. The roughened area on the outer, lateral side of the condyle is the **lateral epicondyle of the femur**. Similarly, the smooth region of the distal and posterior medial femur is the **medial condyle of the femur**, and the irregular outer, medial side of this is the **medial epicondyle of the femur**. The lateral and medial condyles articulate with the tibia to form the knee joint. The epicondyles provide attachment for muscles and supporting ligaments of the knee. The **adductor tubercle** is a small bump located at the superior margin of the medial epicondyle. Posteriorly, the medial and lateral condyles are separated by a deep depression called the **intercondylar fossa**. Anteriorly, the smooth surfaces of the condyles join together to form a wide groove called the **patellar surface**, which provides for articulation with the patella bone. The combination of the medial and lateral condyles with the patellar surface gives the distal end of the femur a horseshoe (U) shape.

Patella

The patella (kneecap) is largest sesamoid bone of the body (Figure 7.5.1) . A sesamoid bone is a bone that is incorporated into the tendon of a muscle where that tendon crosses a joint. The sesamoid bone articulates with the underlying bones to prevent damage to the muscle tendon due to rubbing against the bones during movements of the joint. The patella is found in the tendon of the quadriceps femoris muscle, the large muscle of the anterior thigh that passes across the anterior knee to attach to the tibia. The patella articulates with the patellar surface of the femur and thus prevents rubbing of the muscle tendon against the distal femur. The patella also lifts the tendon away from the knee joint, which increases the leverage power of the quadriceps femoris muscle as it acts across the knee. The patella does not articulate with the tibia.

DISORDER OF THE .....

Skeletal System: Runner's Knee

Runner’s knee, also known as patellofemoral syndrome, is the most common overuse injury among runners. It is most frequent in adolescents and young adults, and is more common n females. It often results from excessive running, particularly downhill, but may also occur in athletes who do a lot of knee bending, such as jumpers, skiers, cyclists, weight lifters, and soccer players. It is felt as a dull, aching pain around the front of the knee and deep to the patella. The pain may be felt when walking or running, going up or down stairs, kneeling or squatting, or after sitting with the knee bent for an extended period.

Patellofemoral syndrome may be initiated by a variety of causes, including individual variations in the shape and movement of the patella, a direct blow to the patella, or flat feet or improper shoes that cause excessive turning in or out of the feet or leg. These factors may cause in an imbalance in the muscle pull that acts on the patella, resulting in an abnormal tracking of the patella that allows it to deviate too far toward the lateral side of the patellar surface on the distal femur.

Because the hips are wider than the knee region, the femur has a diagonal orientation within the thigh, in contrast to the vertically oriented tibia of the leg (Figure 7.5.2) . The Q-angle is a measure of how far the femur is angled laterally away from vertical. The Q-angle is normally 10–15 degrees, with females typically having a larger Q-angle due to their wider pelvis. During extension of the knee, the quadriceps femoris muscle pulls the patella both superiorly and laterally, with the lateral pull greater in women due to their large Q-angle. This makes women more vulnerable to developing patellofemoral syndrome than men. Normally, the large lip on the lateral side of the patellar surface of the femur compensates for the lateral pull on the patella, and thus helps to maintain its proper tracking.

However, if the pull produced by the medial and lateral sides of the quadriceps femoris muscle is not properly balanced, abnormal tracking of the patella toward the lateral side may occur. With continued use, this produces pain and could result in damage to the articulating surfaces of the patella and femur, and the possible future development of arthritis. Treatment

generally involves stopping the activity that produces knee pain for a period of time, followed by a gradual resumption of activity. Proper strengthening of the quadriceps femoris muscle to correct for imbalances is also important to help prevent reoccurrence.

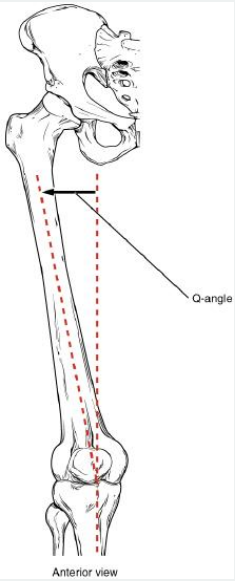

Figure 7.5.2: The Q-Angle. The Q-angle is a measure of the amount of lateral deviation of the femur from the vertical line of the tibia. Adult females have a larger Q-angle due to their wider pelvis than adult males. (Image credit: "Femur Q Angle" by OpenStax is licensed under CC BY 3.0)

Tibia

The **tibia** (shin bone) is the medial bone of the leg and is larger than the fibula, with which it is paired (Figure 7.5.3) . The tibia is the main weight-bearing bone of the lower leg and the second longest bone of the body, after the femur. The medial side of the tibia is located immediately under the skin, allowing it to be easily palpated down the entire length of the medial leg.

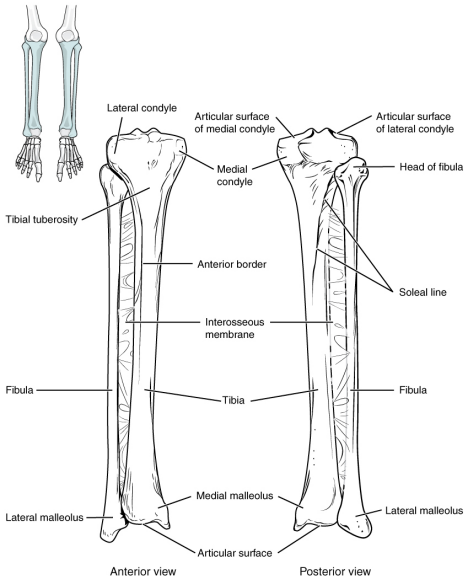

Figure 7.5.3: Tibia and Fibula. The tibia is the larger, weight-bearing bone located on the medial side of the leg. The fibula is the slender bone of the lateral side of the leg and does not bear weight. (Image credit: "Tibia and Fibula" by OpenStax is licensed under CC BY 3.0)

The proximal end of the tibia is greatly expanded. The two sides of this expansion form the **medial condyle of the tibia** and the **lateral condyle of the tibia**. The tibia does not have epicondyles. The top surface of each condyle is smooth and flattened, which forms an articular surface. These areas articulate with the medial and lateral condyles of the femur to form the **knee joint**.

Between the articulating surfaces of the tibial condyles is the **intercondylar eminence**, an irregular, elevated area that serves as the inferior attachment point for two supporting ligaments of the knee.

The **tibial tuberosity** is an elevated area on the anterior side of the tibia, near its proximal end. It is the final site of attachment for the muscle tendon associated with the patella. More inferiorly, the body, or **shaft of the tibia**, becomes triangular in shape. The anterior apex of this triangle forms the **anterior border of the tibia**, which begins at the tibial tuberosity and runs inferiorly along the length of the tibia. Both the anterior border and the medial side of the triangular shaft are located immediately under the skin and can be easily palpated along the entire length of the tibia. A small ridge running down the lateral side of the tibial shaft is the **interosseous border of the tibia**. This is for the attachment of the **interosseous membrane of the leg**, the sheet of dense connective tissue that unites the tibia and fibula bones. Located on the posterior side of the tibia is the **soleal line**, a diagonally running, roughened ridge that begins below the base of the lateral condyle, and runs down and medially across the proximal third of the posterior tibia. Muscles of the posterior leg attach to this line.

The large expansion found on the medial side of the distal tibia is the **medial malleolus** ("little hammer"). This forms the large bony bump found on the medial side of the ankle region. Both the smooth surface on the inside of the medial malleolus and the smooth area at the distal end of the tibia articulate with the talus bone of the foot as part of the ankle joint. On the lateral side of the distal tibia is a wide groove called the **fibular notch**. This area articulates with the distal end of the fibula, forming the **distal tibiofibular joint**.

Fibula

The fibula is the slender bone located on the lateral side of the leg (Figure 7.5.3) . The fibula does not bear weight. It serves primarily for muscle attachments and thus is largely surrounded by muscles. Only the proximal and distal ends of the fibula can be palpated.

The **head of the fibula** is the small, knob-like, proximal end of the fibula. It articulates with the inferior aspect of the lateral tibial condyle, forming the **proximal tibiofibular joint**. The thin **shaft of the fibula** has the **interosseous border of the fibula**, a narrow ridge running down its medial side for the attachment of the interosseous membrane that spans the fibula and tibia. The distal end of the fibula forms the **lateral malleolus**, which forms the easily palpated bony bump on the lateral side of the ankle. The deep (medial) side of the lateral malleolus articulates with the talus bone of the foot as part of the ankle joint. The distal fibula also articulates with the fibular notch of the tibia.

Tarsal Bones

The posterior half of the foot is formed by seven tarsal bones (Figure 7.5.4) . The most superior bone is the **talus**. This has a relatively square-shaped, upper surface that articulates with the tibia and fibula to form the **ankle joint**. The talus has distinct bone markings that allow for easy identification of the three articulation areas that form the ankle joint. Found on the superomedial surface of the talus is a **facet for the medial malleolus** of the tibia. Another **facet for the lateral malleolus** of the fibula can be found on the lateral side of the talus. The **trochlea of the talus** can be found on top of the bone, and is the structure that articulates with the distal end of the tibia. Inferiorly, the talus articulates with the **calcaneus** (heel bone), the largest bone of the foot, which forms the heel. Body weight is transferred from the tibia to the talus to the calcaneus, which rests on the ground. The medial calcaneus has a prominent bony extension called the **sustentaculum tali** ("support for the talus"), also known as the talar shelf, that supports the medial side of the talus bone. The posterior inferior portion of the calcaneus is formed by the **calcaneal tuberosity**, which serves as the insertion point for several muscles of the lower leg.

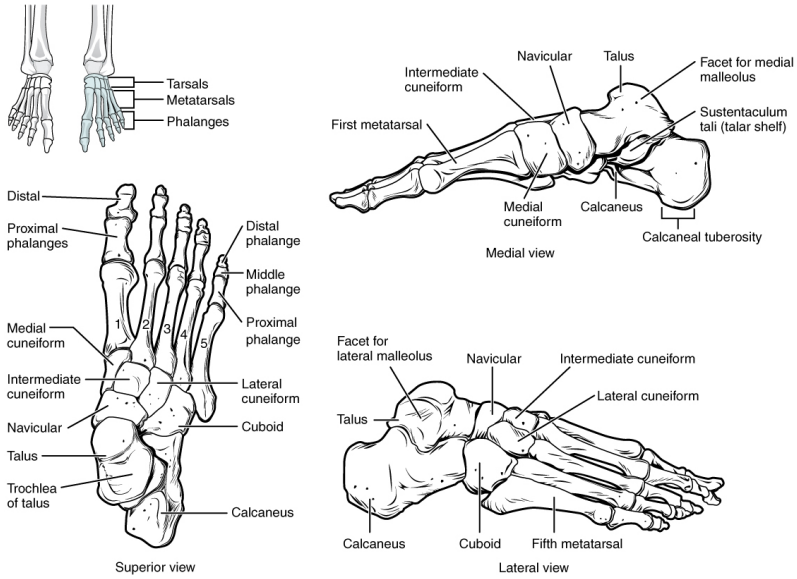

Figure 7.5.4: Bones of the Foot. The bones of the foot are divided into three groups. The posterior foot is formed by the seven tarsal bones. The mid-foot has the five metatarsal bones. The toes contain the phalanges. (Image credit: "Bone of the Foot" by OpenStax is licensed under CC BY 3.0)

The **cuboid** bone articulates with the anterior end of the calcaneus bone. The cuboid has a deep groove running across its inferior surface, which provides passage for a muscle tendon. The talus bone articulates anteriorly with the **navicular** bone, which in turn articulates anteriorly with the three cuneiform ("wedge-shaped") bones. These bones are the **medial cuneiform**, the **intermediate cuneiform**, and the **lateral cuneiform**. Each of these bones has a broad superior surface and a narrow inferior surface, which together produce the transverse (medial-lateral) curvature of the foot. The navicular and lateral cuneiform bones also articulate with the medial side of the cuboid bone.

Metatarsal Bones

The anterior half of the foot is formed by the five metatarsal bones, which are located between the tarsal bones of the posterior foot and the phalanges of the toes (Figure 7.5.4) . These elongated bones are numbered 1–5, starting with the medial side of the foot. The first metatarsal bone is shorter and thicker than the others. The second metatarsal is the longest. The **base of the metatarsal bone** is the proximal end of each metatarsal bone. These articulate with the cuboid or cuneiform bones. The base of the fifth metatarsal has a large, lateral expansion that provides for muscle attachments. This expanded base of the fifth metatarsal can be felt as a bony bump at the midpoint along the lateral border of the foot. The expanded distal end of each metatarsal is the **head of the metatarsal bone**. Each metatarsal bone articulates with the proximal phalanx of a toe to form a **metatarsophalangeal joint**. The heads of the metatarsal bones also rest on the ground and form the ball (anterior end) of the foot.

Phalanges

The toes contain a total of 14 phalanx bones (phalanges), arranged in a similar manner as the phalanges of the fingers (Figure 7.5.4) . The toes are numbered 1–5, starting with the big toe, known as the **hallux**. The hallux has two phalanx bones, the proximal and distal phalanges. The remaining toes all have proximal, middle, and distal phalanges. A joint between adjacent phalanx bones is called an interphalangeal joint.

Arches of the Foot

When the foot comes into contact with the ground during walking, running, or jumping activities, the impact of the body weight puts a tremendous amount of pressure and force on the foot. During running, the force applied to each foot as it contacts the ground can be up to 2.5 times your body weight. The bones, joints, ligaments, and muscles of the foot absorb this force, thus greatly reducing the amount of shock that is passed superiorly into the lower limb and body. The arches of the foot play an important role in this shock-absorbing ability. When weight is applied to the foot, these arches will flatten somewhat, thus

absorbing energy. When the weight is removed, the arch rebounds, giving “spring” to the step. The arches also serve to distribute body weight side to side and to either end of the foot.

The foot has a transverse arch, a medial longitudinal arch, and a lateral longitudinal arch (Figure 7.5.4) . The transverse arch forms the medial-lateral curvature of the mid-foot. It is formed by the wedge shapes of the cuneiform bones and bases (proximal ends) of the first to fourth metatarsal bones. This arch helps to distribute body weight from side to side within the foot, thus allowing the foot to accommodate uneven terrain.

The longitudinal arches run down the length of the foot. The lateral longitudinal arch is relatively flat, whereas the medial longitudinal arch is larger (taller). The longitudinal arches are formed by the tarsal bones posteriorly and the metatarsal bones anteriorly. These arches are supported at either end, where they contact the ground. Posteriorly, this support is provided by the calcaneus bone and anteriorly by the heads (distal ends) of the metatarsal bones. The talus bone, which receives the weight of the body, is located at the top of the longitudinal arches. Body weight is then conveyed from the talus to the ground by the anterior and posterior ends of these arches. Strong ligaments unite the adjacent foot bones to prevent disruption of the arches during weight bearing. On the bottom of the foot, additional ligaments tie together the anterior and posterior ends of the arches. These ligaments have elasticity, which allows them to stretch somewhat during weight bearing, thus allowing the longitudinal arches to spread. The stretching of these ligaments stores energy within the foot, rather than passing these forces into the leg. Contraction of the foot muscles also plays an important role in this energy absorption. When the weight is removed, the elastic ligaments recoil and pull the ends of the arches closer together. This recovery of the arches releases the stored energy and improves the energy efficiency of walking.

Stretching of the ligaments that support the longitudinal arches can lead to pain. This can occur in overweight individuals, with people who have jobs that involve standing for long periods of time (such as a waitress), or walking or running long distances. If stretching of the ligaments is prolonged, excessive, or repeated, it can result in a gradual lengthening of the supporting ligaments, with subsequent depression or collapse of the longitudinal arches, particularly on the medial side of the foot. This condition is called pes planus (“flat foot” or “fallen arches”).

Concept Review

The lower limb is divided into three regions. These are the thigh, located between the hip and knee joints; the leg, located between the knee and ankle joints; and distal to the ankle, the foot. There are 30 bones in each lower limb. These are the femur, patella, tibia, fibula, seven tarsal bones, five metatarsal bones, and 14 phalanges.

The femur is the single bone of the thigh. Its rounded head articulates with the acetabulum of the hip bone to form the hip joint. The head has the fovea capitis for attachment of the ligament of the head of the femur. The narrow neck joins inferiorly with the greater and lesser trochanters. Passing between these bony expansions are the intertrochanteric line on the anterior femur and the larger intertrochanteric crest on the posterior femur. On the posterior shaft of the femur is the gluteal tuberosity proximally and the linea aspera in the mid-shaft region. The expanded distal end consists of three articulating surfaces: the medial and lateral condyles, and the patellar surface. The outside margins of the condyles are the medial and lateral epicondyles. The adductor tubercle is on the superior aspect of the medial epicondyle.

The patella is a sesamoid bone located within a muscle tendon. It articulates with the patellar surface on the anterior side of the distal femur, thereby protecting the muscle tendon from rubbing against the femur.

The leg contains the large tibia on the medial side and the slender fibula on the lateral side. The tibia bears the weight of the body, whereas the fibula does not bear weight. The interosseous border of each bone is the attachment site for the interosseous membrane of the leg, the connective tissue sheet that unites the tibia and fibula.

The proximal tibia consists of the expanded medial and lateral condyles, which articulate with the medial and lateral condyles of the femur to form the knee joint. Between the tibial condyles is the intercondylar eminence. On the anterior side of the proximal tibia is the tibial tuberosity, which is continuous inferiorly with the anterior border of the tibia. On the posterior side, the proximal tibia has the curved soleal line. The bony expansion on the medial side of the distal tibia is the medial malleolus. The groove on the lateral side of the distal tibia is the fibular notch.

The head of the fibula forms the proximal end and articulates with the underside of the lateral condyle of the tibia. The distal fibula articulates with the fibular notch of the tibia. The expanded distal end of the fibula is the lateral malleolus.

The posterior foot is formed by the seven tarsal bones. The talus articulates superiorly with the distal tibia, the medial malleolus

of the tibia, and the lateral malleolus of the fibula to form the ankle joint. The talus articulates inferiorly with the calcaneus bone. The sustentaculum tali of the calcaneus helps to support the talus. Anterior to the talus is the navicular bone, and anterior to this are the medial, intermediate, and lateral cuneiform bones. The cuboid bone is anterior to the calcaneus.

The five metatarsal bones form the anterior foot. The base of these bones articulate with the cuboid or cuneiform bones. The metatarsal heads, at their distal ends, articulate with the proximal phalanges of the toes. The big toe (toe number 1) has proximal and distal phalanx bones. The remaining toes have proximal, middle, and distal phalanges.

Review Questions

Q. Which bony landmark of the femur serves as a site for muscle attachments?

A. fovea capitis

B. lesser trochanter

C. head

D. medial condyle

Answer

Answer: B

Q. What structure contributes to the knee joint?

A. lateral malleolus of the fibula

B. tibial tuberosity

C. medial condyle of the tibia

D. lateral epicondyle of the femur

Answer

Answer: C

Q. Which tarsal bone articulates with the tibia and fibula?

A. calcaneus

B. cuboid

C. navicular

D. talus

Answer

Answer: D

Q. What is the total number of bones found in the foot and toes?

A. 7

B. 14

C. 26

D. 30

Answer

Answer: C

Q. The tibia _____.

A. has an expanded distal end called the lateral malleolus

B. is not a weight-bearing bone

C. is firmly anchored to the fibula by an interosseous membrane

D. can be palpated (felt) under the skin only at its proximal and distal ends

Answer

Answer: C

Critical Thinking Questions

Q. Define the regions of the lower limb, name the bones found in each region, and describe the bony landmarks that articulate together to form the hip, knee, and ankle joints.

Answer

A. The lower limb is divided into three regions. The thigh is the region located between the hip and knee joints. It contains the femur and the patella. The hip joint is formed by the articulation between the acetabulum of the hip bone and the head of the femur. The leg is the region between the knee and ankle joints, and contains the tibia (medially) and the fibula (laterally). The knee joint is formed by the articulations between the medial and lateral condyles of the femur, and the medial and lateral condyles of the tibia. Also associated with the knee is the patella, which articulates with the patellar surface of the distal femur. The foot is found distal to the ankle and contains 26 bones. The ankle joint is formed by the articulations between the talus bone of the foot and the distal end of the tibia, the medial malleolus of the tibia, and the lateral malleolus of the fibula. The posterior foot contains the seven tarsal bones, which are the talus, calcaneus, navicular, cuboid, and the medial, intermediate, and lateral cuneiform bones. The anterior foot consists of the five metatarsal bones, which are numbered 1–5 starting on the medial side of the foot. The toes contain 14 phalanx bones, with the big toe (toe number 1) having a proximal and a distal phalanx, and the other toes having proximal, middle, and distal phalanges.

Q. The talus bone of the foot receives the weight of the body from the tibia. The talus bone then distributes this weight toward the ground in two directions: one-half of the body weight is passed in a posterior direction and one-half of the weight is passed in an anterior direction. Describe the arrangement of the tarsal and metatarsal bones that are involved in both the posterior and anterior distribution of body weight.

Answer

A. The talus bone articulates superiorly with the tibia and fibula at the ankle joint, with body weight passed from the tibia to the talus. Body weight from the talus is transmitted to the ground by both ends of the medial and lateral longitudinal foot arches. Weight is passed posteriorly through both arches to the calcaneus bone, which forms the heel of the foot and is in contact with the ground. On the medial side of the foot, body weight is passed anteriorly from the talus bone to the navicular bone, and then to the medial, intermediate, and lateral cuneiform bones. The cuneiform bones pass the weight anteriorly to the first, second, and third metatarsal bones, whose heads (distal ends) are in contact with the ground. On the lateral side, body weight is passed anteriorly from the talus through the calcaneus, cuboid, and fourth and fifth metatarsal bones. The talus bone thus transmits body weight posteriorly to the calcaneus and anteriorly through the navicular, cuneiform, and cuboid bones, and metatarsals one through five.

Glossary

adductor tubercle
small, bony bump located on the superior aspect of the medial epicondyle of the femur

ankle joint
joint that separates the leg and foot portions of the lower limb; formed by the articulations between the talus bone of the foot inferiorly, and the distal end of the tibia, medial malleolus of the tibia, and lateral malleolus of the fibula superiorly

anterior border of the tibia
narrow, anterior margin of the tibia that extends inferiorly from the tibial tuberosity

base of the metatarsal bone
expanded, proximal end of each metatarsal bone

calcaneal tuberosity
posterior, inferior portion of the calcaneus bone, which serves as the insertion point for lower leg muscles

calcaneus
heel bone; posterior, inferior tarsal bone that forms the heel of the foot

cuboid
tarsal bone that articulates posteriorly with the calcaneus bone, medially with the lateral cuneiform bone, and anteriorly with the fourth and fifth metatarsal bones

distal tibiofibular joint
articulation between the distal fibula and the fibular notch of the tibia

facet for lateral malleolus
flat surface on the lateral side of the talus where it articulates with the fibula

facet for medial malleolus
flat surface on the superomedial portion of the talus it where articulates with the tibia

femur
thigh bone; the single bone of the thigh

fibula
thin, non-weight-bearing bone found on the lateral side of the leg

fibular notch
wide groove on the lateral side of the distal tibia for articulation with the fibula at the distal tibiofibular joint

foot
portion of the lower limb located distal to the ankle joint

fovea capitis
minor indentation on the head of the femur that serves as the site of attachment for the ligament to the head of the femur

gluteal tuberosity
roughened area on the posterior side of the proximal femur, extending inferiorly from the base of the greater trochanter

greater trochanter
large, bony expansion of the femur that projects superiorly from the base of the femoral neck

hallux
big toe; digit 1 of the foot

head of the femur
rounded, proximal end of the femur that articulates with the acetabulum of the hip bone to form the hip joint

head of the fibula
small, knob-like, proximal end of the fibula; articulates with the inferior aspect of the lateral condyle of the tibia

head of the metatarsal bone
expanded, distal end of each metatarsal bone

hip joint
joint located at the proximal end of the lower limb; formed by the articulation between the acetabulum of the hip bone and the head of the femur

intercondylar eminence
irregular elevation on the superior end of the tibia, between the articulating surfaces of the medial and lateral condyles

intercondylar fossa
deep depression on the posterior side of the distal femur that separates the medial and lateral condyles

intermediate cuneiform
middle of the three cuneiform tarsal bones; articulates posteriorly with the navicular bone, medially with the medial cuneiform bone, laterally with the lateral cuneiform bone, and anteriorly with the second metatarsal bone

interosseous border of the fibula
small ridge running down the medial side of the fibular shaft; for attachment of the interosseous membrane between the fibula and tibia

interosseous border of the tibia
small ridge running down the lateral side of the tibial shaft; for attachment of the interosseous membrane between the tibia and fibula

interosseous membrane of the leg
sheet of dense connective tissue that unites the shafts of the tibia and fibula bones

intertrochanteric crest
short, prominent ridge running between the greater and lesser trochanters on the posterior side of the proximal femur

intertrochanteric line
small ridge running between the greater and lesser trochanters on the anterior side of the proximal femur

knee joint
joint that separates the thigh and leg portions of the lower limb; formed by the articulations between the medial and lateral condyles of the femur, and the medial and lateral condyles of the tibia

lateral condyle of the femur
smooth, articulating surface that forms the distal and posterior sides of the lateral expansion of the distal femur

lateral condyle of the tibia
lateral, expanded region of the proximal tibia that includes the smooth surface that articulates with the lateral condyle of the femur as part of the knee joint

lateral cuneiform
most lateral of the three cuneiform tarsal bones; articulates posteriorly with the navicular bone, medially with the intermediate cuneiform bone, laterally with the cuboid bone, and anteriorly with the third metatarsal bone

lateral epicondyle of the femur
roughened area of the femur located on the lateral side of the lateral condyle

lateral malleolus
expanded distal end of the fibula

leg
portion of the lower limb located between the knee and ankle joints

lesser trochanter
small, bony projection on the medial side of the proximal femur, at the base of the femoral neck

linea aspera
longitudinally running bony ridge located in the middle third of the posterior femur

medial condyle of the femur
smooth, articulating surface that forms the distal and posterior sides of the medial expansion of the distal femur

medial condyle of the tibia
medial, expanded region of the proximal tibia that includes the smooth surface that articulates with the medial condyle of the femur as part of the knee joint

medial cuneiform
most medial of the three cuneiform tarsal bones; articulates posteriorly with the navicular bone, laterally with the intermediate cuneiform bone, and anteriorly with the first and second metatarsal bones

medial epicondyle of the femur
roughened area of the distal femur located on the medial side of the medial condyle

medial malleolus
bony expansion located on the medial side of the distal tibia

metatarsal bone
one of the five elongated bones that forms the anterior half of the foot; numbered 1–5, starting on the medial side of the foot

metatarsophalangeal joint
articulation between a metatarsal bone of the foot and the proximal phalanx bone of a toe

navicular
tarsal bone that articulates posteriorly with the talus bone, laterally with the cuboid bone, and anteriorly with the medial, intermediate, and lateral cuneiform bones

neck of the femur
narrowed region located inferior to the head of the femur

patella
kneecap; the largest sesamoid bone of the body; articulates with the distal femur

patellar surface
smooth groove located on the anterior side of the distal femur, between the medial and lateral condyles; site of articulation for the patella

phalanx bone of the foot
(plural = phalanges) one of the 14 bones that form the toes; these include the proximal and distal phalanges of the big toe, and the proximal, middle, and distal phalanx bones of toes two through five

proximal tibiofibular joint
articulation between the head of the fibula and the inferior aspect of the lateral condyle of the tibia

shaft of the femur
cylindrically shaped region that forms the central portion of the femur

shaft of the fibula
elongated, slender portion located between the expanded ends of the fibula

shaft of the tibia
triangular-shaped, central portion of the tibia

soleal line
small, diagonally running ridge located on the posterior side of the proximal tibia

sustentaculum tali
also known as the talar shelf; bony ledge extending from the medial side of the calcaneus bone

talus
tarsal bone that articulates superiorly with the tibia and fibula at the ankle joint; also articulates inferiorly with the calcaneus bone and anteriorly with the navicular bone

tarsal bone
one of the seven bones that make up the posterior foot; includes the calcaneus, talus, navicular, cuboid, medial cuneiform, intermediate cuneiform, and lateral cuneiform bones

thigh
portion of the lower limb located between the hip and knee joints

tibia
shin bone; the large, weight-bearing bone located on the medial side of the leg

tibial tuberosity
elevated area on the anterior surface of the proximal tibia

trochlea of talus
pulley-like structure on the top portion of the talus where it articulates with the tibia

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7.6: Embryonic Development of the Appendicular Skeleton

By the end of this section, you will be able to:

- Describe the growth and development of the embryonic limb buds
- Discuss the appearance of primary and secondary ossification centers

Embryologically, the appendicular skeleton arises from mesenchyme, a type of embryonic tissue that can differentiate into many types of tissues, including bone or muscle tissue. Mesenchyme gives rise to the bones of the upper and lower limbs, as well as to the pectoral and pelvic girdles. Development of the limbs begins near the end of the fourth embryonic week, with the upper limbs appearing first. Thereafter, the development of the upper and lower limbs follows similar patterns, with the lower limbs lagging behind the upper limbs by a few days.

Limb Growth

Each upper and lower limb initially develops as a small bulge called a **limb bud**, which appears on the lateral side of the early embryo. The upper limb bud appears near the end of the fourth week of development, with the lower limb bud appearing shortly after (Figure 7.6.1) .

Figure 7.6.1: Embryo at Seven Weeks. Limb buds are visible in an embryo at the end of the seventh week of development (embryo derived from an ectopic pregnancy). (Image credit: "Human Embryo" by Ed Uthman is licensed under CC BY 2.0)

Initially, the limb buds consist of a core of mesenchyme covered by a layer of ectoderm. The ectoderm at the end of the limb bud thickens to form a narrow crest called the **apical ectodermal ridge**. This ridge stimulates the underlying mesenchyme to rapidly proliferate, producing the outgrowth of the developing limb. As the limb bud elongates, cells located farther from the apical ectodermal ridge slow their rates of cell division and begin to differentiate. In this way, the limb develops along a proximal-to-distal axis.

During the sixth week of development, the distal ends of the upper and lower limb buds expand and flatten into a paddle shape. This region will become the hand or foot. The wrist or ankle areas then appear as a constriction that develops at the base of the paddle. Shortly after this, a second constriction on the limb bud appears at the future site of the elbow or knee. Within the paddle, areas of tissue undergo cell death, producing separations between the growing fingers and toes. Also during the sixth week of development, mesenchyme within the limb buds begins to differentiate into hyaline cartilage that will form models of the future limb bones.

The early outgrowth of the upper and lower limb buds initially has the limbs positioned so that the regions that will become the palm of the hand or the bottom of the foot are facing medially toward the body, with the future thumb or big toe both oriented toward the head. During the seventh week of development, the upper limb rotates laterally by 90 degrees, so that the palm of the hand faces anteriorly and the thumb points laterally. In contrast, the lower limb undergoes a 90-degree medial rotation, thus bringing the big toe to the medial side of the foot.

Ossification of Appendicular Bones

All of the girdle and limb bones, except for the clavicle, develop by the process of endochondral ossification. This process begins as the mesenchyme within the limb bud differentiates into hyaline cartilage to form cartilage models for future bones. By the twelfth week, a primary ossification center will have appeared in the diaphysis (shaft) region of the long bones, initiating the process that converts the cartilage model into bone. A secondary ossification center will appear in each epiphysis (expanded end) of these bones at a later time, usually after birth. The primary and secondary ossification centers are separated by the epiphyseal plate, a layer of growing hyaline cartilage. This plate is located between the diaphysis and each epiphysis. It continues to grow and is responsible for the lengthening of the bone. The epiphyseal plate is retained for many years, until the bone reaches its final, adult size, at which time the epiphyseal plate disappears and the epiphysis fuses to the diaphysis. (Seek additional content on ossification in the chapter on bone tissue.)

Small bones, such as the phalanges, will develop only one secondary ossification center and will thus have only a single epiphyseal plate. Large bones, such as the femur, will develop several secondary ossification centers, with an epiphyseal plate associated with each secondary center. Thus, ossification of the femur begins at the end of the seventh week with the appearance of the primary ossification center in the diaphysis, which rapidly expands to ossify the shaft of the bone prior to birth. Secondary ossification centers develop at later times. Ossification of the distal end of the femur, to form the condyles and epicondyles, begins shortly before birth. Secondary ossification centers also appear in the femoral head late in the first year after birth, in the greater trochanter during the fourth year, and in the lesser trochanter between the ages of 9 and 10 years. Once these areas have ossified, their fusion to the diaphysis and the disappearance of each epiphyseal plate follow a reversed sequence. Thus, the lesser trochanter is the first to fuse, doing so at the onset of puberty (around 11 years of age), followed by the greater trochanter approximately 1 year later. The femoral head fuses between the ages of 14–17 years, whereas the distal condyles of the femur are the last to fuse, between the ages of 16–19 years. Knowledge of the age at which different epiphyseal plates disappear is important when interpreting radiographs taken of children. Since the cartilage of an epiphyseal plate is less dense than bone, the plate will appear dark in a radiograph image. Thus, a normal epiphyseal plate may be mistaken for a bone fracture.

The clavicle is the one appendicular skeleton bone that does not develop via endochondral ossification. Instead, the clavicle develops through the process of intramembranous ossification. During this process, mesenchymal cells differentiate directly into bone-producing cells, which produce the clavicle directly, without first making a cartilage model. Because of this early production of bone, the clavicle is the first bone of the body to begin ossification, with ossification centers appearing during the fifth week of development. However, ossification of the clavicle is not complete until age 25.

DISORDERS OF THE...

Appendicular System: Congenital Clubfoot

Clubfoot, also known as talipes, is a congenital (present at birth) disorder of unknown cause and is the most common deformity of the lower limb. It affects the foot and ankle, causing the foot to be twisted inward at a sharp angle, like the head of a golf club (Figure 7.6.2) . Clubfoot has a frequency of about 1 out of every 1,000 births, and is twice as likely to occur in a male child as in a female child. In 50 percent of cases, both feet are affected.

Figure 7.6.2: Clubfoot. Clubfoot is a common deformity of the ankle and foot that is present at birth. Most cases are corrected without surgery, and affected individuals will grow up to lead normal, active lives. (Image credit: "Clubfoot" by OpenStax is licensed under CC BY 3.0)

At birth, children with a clubfoot have the heel turned inward and the anterior foot twisted so that the lateral side of the foot is facing inferiorly, commonly due to ligaments or leg muscles attached to the foot that are shortened or abnormally tight. These pull the foot into an abnormal position, resulting in bone deformities. Other symptoms may include bending of the ankle that lifts the heel of the foot and an extremely high foot arch. Due to the limited range of motion in the affected foot, it is difficult to place the foot into the correct position. Additionally, the affected foot may be shorter than normal, and the calf muscles are usually underdeveloped on the affected side. Despite the appearance, this is not a painful condition for newborns. However, it must be treated early to avoid future pain and impaired walking ability.

Although the cause of clubfoot is idiopathic (unknown), evidence indicates that fetal position within the uterus is not a contributing factor. Genetic factors are involved, because clubfoot tends to run within families. Cigarette smoking during pregnancy has been linked to the development of clubfoot, particularly in families with a history of clubfoot.

Previously, clubfoot required extensive surgery. Today, 90 percent of cases are successfully treated without surgery using new corrective casting techniques. The best chance for a full recovery requires that clubfoot treatment begin during the first 2 weeks after birth. Corrective casting gently stretches the foot, which is followed by the application of a holding cast to keep the foot in the proper position. This stretching and casting is repeated weekly for several weeks. In severe cases, surgery may also be required, after which the foot typically remains in a cast for 6 to 8 weeks. After the cast is removed following either surgical or nonsurgical treatment, the child will be required to wear a brace part-time (at night) for up to 4 years. In addition, special exercises will be prescribed, and the child must also wear special shoes. Close monitoring by the parents and adherence to postoperative instructions are imperative in minimizing the risk of relapse.

Despite these difficulties, treatment for clubfoot is usually successful, and the child will grow up to lead a normal, active life. Numerous examples of individuals born with a clubfoot who went on to successful careers include Dudley Moore (comedian and actor), Damon Wayans (comedian and actor), Troy Aikman (three-time Super Bowl-winning quarterback), Kristi Yamaguchi (Olympic gold medalist in figure skating), Mia Hamm (two-time Olympic gold medalist in soccer), and Charles Woodson (Heisman trophy and Super Bowl winner).

Concept Review

The bones of the appendicular skeleton arise from embryonic mesenchyme. Limb buds appear at the end of the fourth week. The apical ectodermal ridge, located at the end of the limb bud, stimulates growth and elongation of the limb. During the sixth week, the distal end of the limb bud becomes paddle-shaped, and selective cell death separates the developing fingers and toes. At

the same time, mesenchyme within the limb bud begins to differentiate into hyaline cartilage, forming models for future bones. During the seventh week, the upper limbs rotate laterally and the lower limbs rotate medially, bringing the limbs into their final positions.

Endochondral ossification, the process that converts the hyaline cartilage model into bone, begins in most appendicular bones by the twelfth fetal week. This begins as a primary ossification center in the diaphysis, followed by the later appearance of one or more secondary ossifications centers in the regions of the epiphyses. Each secondary ossification center is separated from the primary ossification center by an epiphyseal plate. Continued growth of the epiphyseal plate cartilage provides for bone lengthening. Disappearance of the epiphyseal plate is followed by fusion of the bony components to form a single, adult bone.

The clavicle develops via intramembranous ossification, in which mesenchyme is converted directly into bone tissue. Ossification within the clavicle begins during the fifth week of development and continues until 25 years of age.

Review Questions

Q. Which event takes place during the seventh week of development?

A. appearance of the upper and lower limb buds

B. flattening of the distal limb bud into a paddle shape

C. the first appearance of hyaline cartilage models of future bones

D. the rotation of the limbs

Answer

Answer: D

Q. During endochondral ossification of a long bone, _____.

A. a primary ossification center will develop within the epiphysis

B. mesenchyme will differentiate directly into bone tissue

C. growth of the epiphyseal plate will produce bone lengthening

D. all epiphyseal plates will disappear before birth

Answer

Answer: C

Q. The clavicle _____.

A. develops via intramembranous ossification

B. develops via endochondral ossification

C. is the last bone of the body to begin ossification

D. is fully ossified at the time of birth

Answer

Answer: A

Critical Thinking Questions

Q. How can a radiograph of a child's femur be used to determine the approximate age of that child?

Answer

A. A radiograph (X-ray image) of a child's femur will show the epiphyseal plates associated with each secondary ossification center. These plates of hyaline cartilage will appear dark in comparison to the white imaging of the ossified bone. Since each epiphyseal plate appears and disappears at a different age, the presence or absence of these plates can be used to give an approximate age for the child. For example, the epiphyseal plate located at the base of the lesser trochanter of the femur appears at age 9–10 years and disappears at puberty (approximately 11 years of age). Thus, a child's radiograph that shows the presence of the lesser trochanter epiphyseal plate indicates an approximate age of 10 years.

Q. How does the development of the clavicle differ from the development of other appendicular skeleton bones?

Answer

A. Unlike other bones of the appendicular skeleton, the clavicle develops by the process of intramembranous ossification. In this process, embryonic mesenchyme accumulates at the site of the future bone and then differentiates directly into bone-producing tissue. Because of this direct and early production of bone, the clavicle is the first bone of the skeleton to begin to ossify. However, the growth and enlargement of the clavicle continues throughout childhood and adolescence, and thus, it is not fully ossified until 25 years of age.

Glossary

apical ectodermal ridge
enlarged ridge of ectoderm at the distal end of a limb bud that stimulates growth and elongation of the limb

limb bud
small elevation that appears on the lateral side of the embryo during the fourth or fifth week of development, which gives rise to an upper or lower limb

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8: JOINTS

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8.2: Classification of Joints
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8.1: Introduction

Chapter Learning Objectives

After studying this chapter, you will be able to:

- Discuss both functional and structural classifications for body joints
- Describe the characteristic features for fibrous, cartilaginous, and synovial joints and give examples of each
- Describe and identify the different body movements
- Discuss the structure of specific body joints and the movements allowed by each
- Explain the development of body joints

The adult human body has 206 bones, and with the exception of the hyoid bone in the neck, each bone is connected to at least one other bone. Joints, also known as articulations, are the location where bones come together. Many joints allow for movement between the bones. At these joints, the articulating surfaces of the adjacent bones can move smoothly against each other. However, the bones of other joints may be joined to each other by connective tissue or cartilage. These joints are designed for stability and provide for little or no movement. Importantly, joint stability and movement are inversely related to each other. This means that stable joints allow for little or no mobility between the adjacent bones. Conversely, joints that provide the most movement between bones are the least stable. Understanding the relationship between joint structure and function will help to explain why particular types of joints are found in certain areas of the body.

The articulating surfaces of bones at stable types of joints, with little or no mobility, are strongly united to each other. For example, most of the joints of the skull are held together by fibrous connective tissue and do not allow for movement between the adjacent bones. This lack of mobility is important, because the skull bones serve to protect the brain. Similarly, other joints united by fibrous connective tissue allow for very little movement, which provides stability and weight-bearing support for the body. For example, the tibia and fibula of the leg are tightly united to give stability to the body when standing. At other joints, the bones are held together by cartilage, which permits limited movements between the bones. Thus, the joints of the vertebral column only allow for small movements between adjacent vertebrae, but when added together, these movements provide the flexibility that allows your body to twist, or bend to the front, back, or side. In contrast, at joints that allow for wide ranges of motion, the articulating surfaces of the bones are not directly united to each other. Instead, these surfaces are enclosed within a space filled with lubricating fluid, which allows the bones to move smoothly against each other. These joints provide greater mobility, but since the bones are free to move in relation to each other, the joint is less stable. Most of the joints between the bones of the appendicular skeleton are this freely moveable type of joint. These joints allow the muscles of the body to pull on a bone and thereby produce movement of that body region. Your ability to kick a soccer ball, pick up a fork, and dance the tango depend on mobility at these types of joints.

Figure 8.1.1: Kayaking. Without joints, body movements would be impossible. (Image credit: "Kayaking on Wembury Beach" by Graham Richardson is licensed under CC BY 2.0)

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8.2: Classification of Joints

By the end of this section, you will be able to:

- Distinguish between the functional and structural classifications for joints
- Describe the three functional types of joints and give an example of each
- List the three types of diarthrodial joints

A **joint**, also called an **articulation**, is any place where adjacent bones or bone and cartilage come together (articulate with each other) to form a connection. Joints are classified both structurally and functionally. Structural classifications of joints take into account whether the adjacent bones are strongly anchored to each other by fibrous connective tissue or cartilage, or whether the adjacent bones articulate with each other within a fluid-filled space called a **joint cavity**. Functional classifications describe the degree of movement available between the bones, ranging from immobile, to slightly mobile, to freely moveable joints. The amount of movement available at a particular joint of the body is related to the functional requirements for that joint. Thus immobile or slightly moveable joints serve to protect internal organs, give stability to the body, and allow for limited body movement. In contrast, freely moveable joints allow for much more extensive movements of the body and limbs.

Structural Classification of Joints

The structural classification of joints is based on whether the articulating surfaces of the adjacent bones are directly connected by fibrous connective tissue or cartilage, or whether the articulating surfaces contact each other within a fluid-filled joint cavity. These differences serve to divide the joints of the body into three structural classifications. A **fibrous joint** is where the adjacent bones are united by fibrous connective tissue. At a **cartilaginous joint**, the bones are joined by hyaline cartilage or fibrocartilage. At a synovial joint, the articulating surfaces of the bones are not directly connected, but instead come into contact with each other within a joint cavity that is filled with a lubricating fluid. **Synovial joints** allow for free movement between the bones and are the most common joints of the body. These three structural classifications will be discussed in further detail in the following sections of this chapter.

Functional Classification of Joints

The functional classification of joints is determined by the amount of mobility found between the adjacent bones. Joints are thus functionally classified as a synarthrosis or immobile joint, an amphiarthrosis or slightly moveable joint, or as a diarthrosis, which is a freely moveable joint (arthroun = “to fasten by a joint”). Depending on their location, fibrous joints may be functionally classified as a synarthrosis or an amphiarthrosis. Cartilaginous joints are also functionally classified as either a synarthrosis or an amphiarthrosis joint. All synovial joints are functionally classified as a diarthrosis joint.

Synarthrosis

An immobile or nearly immobile joint is called a **synarthrosis**. The immobile nature of these joints provides for a strong union between the articulating bones. This is important at locations where the bones provide protection for internal organs. Examples include sutures, such as the coronal, squamous, and lamdoid sutures, which are the fibrous joints between the bones of the skull (Figure 8.2.1) , and the manubriosternal joint, the cartilaginous joint that unites the manubrium and body of the sternum for protection of the heart.

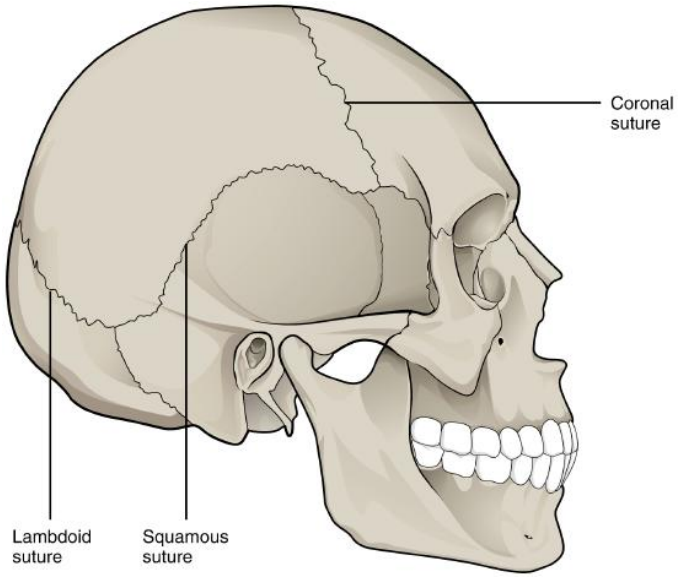

Figure 8.2.1: Suture Joints of Skull. The suture joints of the skull are an example of a synarthrosis, an immobile or essentially immobile joint. (Image credit: "Skull Sutures" by OpenStax is licensed under CC BY 3.0)

Amphiarthrosis

An **amphiarthrosis** is a joint that has limited mobility but slight movement is available in many directions. An example of this type of joint is the cartilaginous joint that unites the bodies of adjacent vertebrae. Filling the gap between the vertebrae is a thick pad of fibrocartilage called an intervertebral disc (Figure 8.2.2) . Each intervertebral disc strongly unites the vertebrae but still allows for a limited amount of movement between them. However, the small movements available between adjacent vertebrae can sum together along the length of the vertebral column to provide for large ranges of body movements.

Another example of an amphiarthrosis is the pubic symphysis of the pelvis. This is a cartilaginous joint in which the pubic regions of the right and left hip bones are strongly anchored to each other by fibrocartilage. This joint normally has very little mobility. The strength of the pubic symphysis is important in conferring weight-bearing stability to the pelvis.

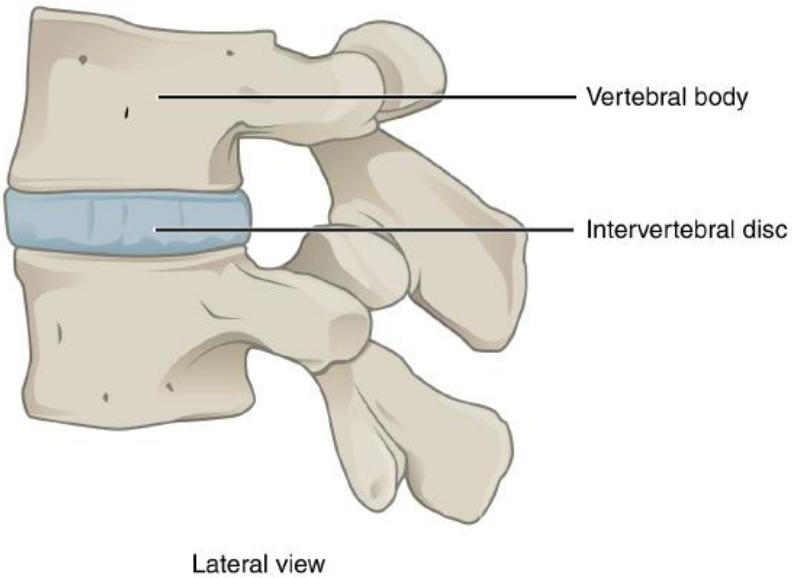

Figure 8.2.2: Intervertebral Disc. An intervertebral disc unites the bodies of adjacent vertebrae within the vertebral column. Each disc allows for limited movement between the vertebrae and thus functionally forms an amphiarthrosis type of joint. Intervertebral discs are made of fibrocartilage and thereby structurally form a symphysis type of cartilaginous joint. (Image credit: "Intervertebral Disk" by OpenStax is licensed under CC BY 3.0)

Diarthrosis

A freely mobile joint is classified as a **diarthrosis**. These types of joints include all synovial joints (structural classification) of the body, which provide the majority of body movements. Most diarthrotic joints are found in the appendicular skeleton and thus give the limbs a wide range of motion. These joints are divided into three categories, based on the number of axes of motion provided by each. An axis in anatomy is described as the movements in reference to the three anatomical planes: transverse, frontal, and sagittal. Thus, diarthroses are classified as uniaxial (for movement in one plane), biaxial (for movement in two planes), or multiaxial joints (for movement in all three anatomical planes).

A **uniaxial joint** only allows for a motion in a single plane (around a single axis). The elbow joint, which only allows for bending or straightening, is an example of a uniaxial joint. A **biaxial joint** allows for motions within two planes. An example of a biaxial joint is a metacarpophalangeal joint (knuckle joint) of the hand. The joint allows for movement along one axis to produce bending or straightening of the finger, and movement along a second axis, which allows for spreading of the fingers away from each other and bringing them together. A joint that allows for several directions of movement is called a **multiaxial joint** (polyaxial or triaxial joint). This type of diarthrotic joint allows for movement along three axes (Figure 8.2.3) . The hip joint, where the head of the femur articulates with the acetabulum of the hip bone, is a multiaxial joint. They allow the upper or lower limb to move in an anterior-posterior direction and a medial-lateral direction. In addition, the limb can also be rotated around its long axis. This third movement results in rotation of the limb so that its anterior surface is moved either toward or away from the midline of the body.

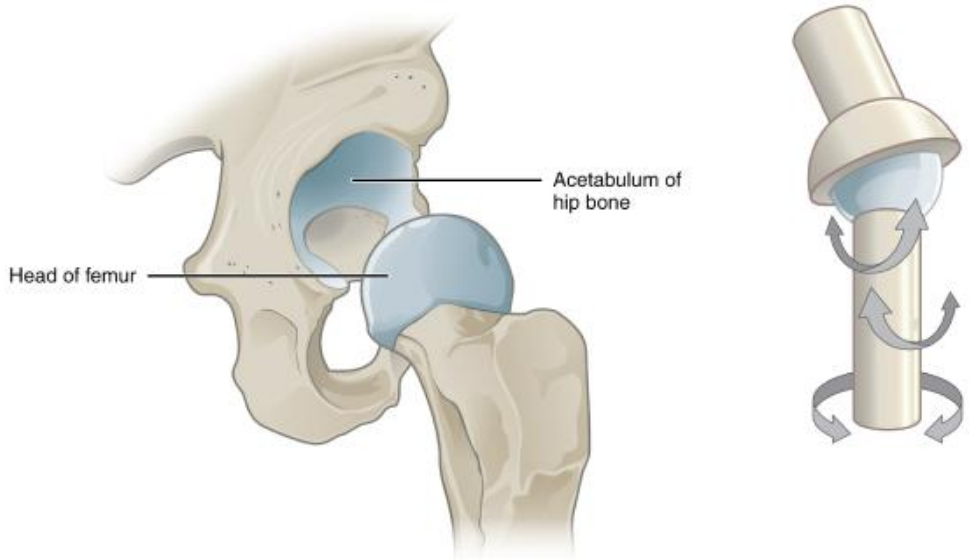

Figure 8.2.3: Multiaxial Joint. A multiaxial joint, such as the hip joint, allows for three types of movement: anterior-posterior, medial-lateral, and rotational. (Image credit: "Multiaxial Joint" by OpenStax is licensed under CC BY 3.0)

Concept Review

Structural classifications of the body joints are based on how the bones are held together and articulate with each other. At fibrous joints, the adjacent bones are directly united to each other by fibrous connective tissue. Similarly, at a cartilaginous joint, the adjacent bones are united by cartilage. In contrast, at a synovial joint, the articulating bone surfaces are not directly united to each other, but come together within a fluid-filled joint cavity.

The functional classification of body joints is based on the degree of movement found at each joint. A synarthrosis is a joint that is essentially immobile. This type of joint provides for a strong connection between the adjacent bones, which serves to protect internal structures such as the brain or heart. Examples include the fibrous joints of the skull sutures and the cartilaginous manubriosternal joint. A joint that allows for limited movement is an amphiarthrosis. An example is the pubic symphysis of the pelvis, the cartilaginous joint that strongly unites the right and left hip bones of the pelvis. The cartilaginous joints in which vertebrae are united by intervertebral discs provide for small movements between the adjacent vertebrae and are also an amphiarthrosis type of joint. Thus, based on their movement ability, both fibrous and cartilaginous joints are functionally classified as a synarthrosis or amphiarthrosis.

The most common type of joint is the diarthrosis, which is a freely moveable joint. All synovial joints are functionally classified as

diarthroses. A uniaxial diarthrosis, such as the elbow, is a joint that only allows for movement within a single anatomical plane. Joints that allow for movements in two planes are biaxial joints, such as the metacarpophalangeal joints of the fingers. A multiaxial joint, such as the shoulder or hip joint, allows for three planes of motions.

Review Questions

Q. The joint between adjacent vertebrae that includes an invertebral disc is classified as which type of joint?

A. diarthrosis

B. multiaxial

C. amphiarthrosis

D. synarthrosis

Answer

Answer: C

Q. Which of these joints is classified as a synarthrosis?

A. the pubic symphysis

B. the manubriosternal joint

C. an invertebral disc

D. the shoulder joint

Answer

Answer: B

Q. Which of these joints is classified as a biaxial diarthrosis?

A. the metacarpophalangeal joint

B. the hip joint

C. the elbow joint

D. the pubic symphysis

Answer

Answer: A

Q. Synovial joints _____.

A. may be functionally classified as a synarthrosis

B. are joints where the bones are connected to each other by hyaline cartilage

C. may be functionally classified as a amphiarthrosis

D. are joints where the bones articulate with each other within a fluid-filled joint cavity

Answer

Answer: D

Critical Thinking Questions

Q. Define how joints are classified based on function. Describe and give an example for each functional type of joint.

Answer

A. Functional classification of joints is based on the degree of mobility exhibited by the joint. A synarthrosis is an immobile or nearly immobile joint. An example is the manubriosternal joint or the joints between the skull bones surrounding the brain. An amphiarthrosis is a slightly moveable joint, such as the pubic symphysis or an intervertebral cartilaginous joint. A diarthrosis is a freely moveable joint. These are subdivided into three categories. A uniaxial diarthrosis allows movement within a single anatomical plane or axis of motion. The elbow joint is an example. A biaxial diarthrosis, such as the metacarpophalangeal joint, allows for movement along two planes or axes. The hip and shoulder joints are examples of a multiaxial diarthrosis. These allow movements along three planes or axes.

Q. Explain the reasons for why joints differ in their degree of mobility.

Answer

A. The functional needs of joints vary and thus joints differ in their degree of mobility. A synarthrosis, which is an immobile joint, serves to strongly connect bones thus protecting internal organs such as the heart or brain. A slightly moveable amphiarthrosis provides for small movements, which in the vertebral column can add together to yield a much larger overall movement. The freedom of movement provided by a diarthrosis can allow for large movements, such as is seen with most joints of the limbs.

Glossary

amphiarthrosis
slightly mobile joint

articulation
joint of the body

biaxial joint
type of diarthrosis; a joint that allows for movements within two planes (two axes)

cartilaginous joint
joint at which the bones are united by hyaline cartilage (synchondrosis) or fibrocartilage (symphysis)

diarthrosis
freely mobile joint

fibrous joint
joint where the articulating areas of the adjacent bones are connected by fibrous connective tissue

joint
site at which two or more bones or bone and cartilage come together (articulate)

joint cavity
space enclosed by the articular capsule of a synovial joint that is filled with synovial fluid and contains the articulating surfaces of the adjacent bones

multiaxial joint
type of diarthrosis; a joint that allows for movements within three planes (three axes)

synarthrosis
: immobile or nearly immobile joint

synovial joint
: joint at which the articulating surfaces of the bones are located within a joint cavity formed by an articular capsule

uniaxial joint
: type of diarthrosis; joint that allows for motion within only one plane (one axis)

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8.3: Fibrous Joints

By the end of this section, you will be able to:

- Describe the structural features of fibrous joints
- Distinguish between a suture, syndesmosis, and gomphosis
- Give an example of each type of fibrous joint

At a fibrous joint, the adjacent bones are directly connected to each other by dense regular connective tissue, and thus the bones do not have a joint cavity between them (Figure 8.3.1) . The gap between the bones may be narrow or wide. There are three types of fibrous joints. A **suture** is the narrow fibrous joint found between most bones of the skull. At a **syndesmosis** joint, the bones are more widely separated but are held together by either a narrow band of fibrous connective tissue called a **ligament** or a wide sheet of connective tissue called an **interosseous membrane**. This type of fibrous joint is found between the shaft regions of the long bones in the forearm and in the leg. Lastly, a **gomphosis** is the narrow fibrous joint between the roots of a tooth and the bony socket in the jaw into which the tooth fits.

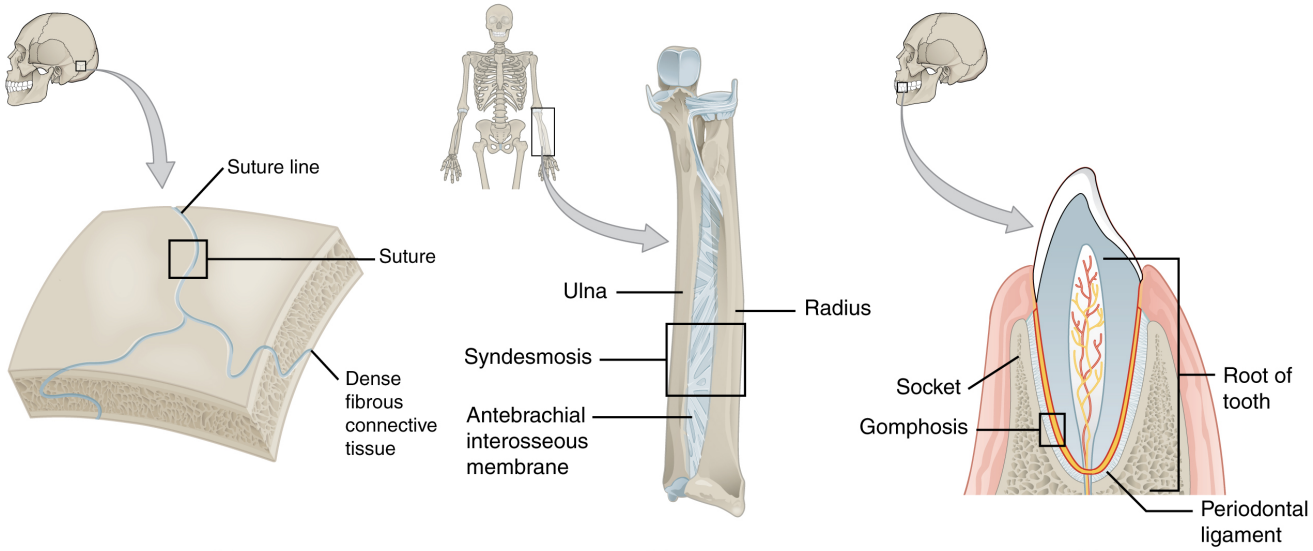


Figure 8.3.1: Fibrous Joints. Fibrous joints form strong connections between bones. (a) Sutures join most bones of the skull. (b) An interosseous membrane forms a syndesmosis between the radius and ulna bones of the forearm. (c) A gomphosis is a specialized fibrous joint that anchors a tooth to its socket in the jaw. (Image credit: "Fibrous Joints" by OpenStax is licensed under CC BY 3.0)

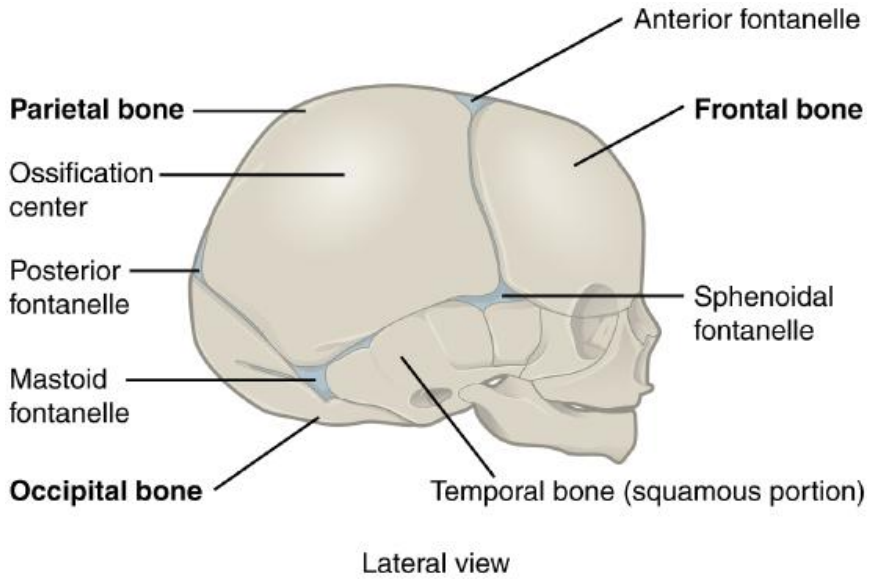
Suture

All the bones of the skull, except for the mandible, are joined to each other by a fibrous joint called a **suture**. The dense fibrous connective tissue found at a suture (“to bind or sew”) strongly unites the adjacent skull bones and thus helps to protect the brain and form the face. In adults, the skull bones are closely opposed and dense fibrous connective tissue fills the narrow gap between the bones. The suture is frequently convoluted, forming a tight union that prevents most movement between the bones. (Figure 8.3.1.a) Thus, skull sutures are functionally classified as a synarthrosis, although some sutures may allow for slight movements between the cranial bones.

In newborns and infants, the areas of connective tissue between the bones are much wider, especially in those areas on the top and sides of the skull that will become the sagittal, coronal, squamous, and lambdoid sutures. These broad areas of connective tissue are called **fontanelles** (Figure 8.3.2). The most prominent fontanelle is the **anterior fontanelle,** which can be found on top of the skull between the frontal bone and the parietal bones. For some newborns, the anterior fontanelle is visible on the top of the head, and is often called the infant's "soft spot". The **posterior fontanelle** can be found on the back side of the skull between the parietal bones and occipital bone. On the sides of the skull are two fontanelles, the **sphenoidal fontanelle** and the **mastoid**

fontanelle. The sphenoidal fontanelle is located toward the anterior of the skull just superior to the sphenoid bone and connects the sphenoid bone, frontal bone, parietal bone, and temporal bone. The mastoid fontanelle, found toward the posterior of the skull, connects that occipital bone, parietal bone, and temporal bone.

Recall that skull bones are formed via intramembranous ossification. Fontanelles are regions of mesenchymal connective tissue membranes that continue to ossify following birth. In regions that become suture joints, the mesenchymal tissue is converted to dense regular connective tissue proper by fibroblasts. During birth, the fontanelles provide flexibility to the skull, allowing the bones to push closer together or to overlap slightly, thus aiding movement of the infant's head through the birth canal. After birth, these expanded regions of connective tissue allow for rapid growth of the skull and enlargement of the brain. The fontanelles greatly decrease in width during the first year after birth as the skull bones enlarge. When the connective tissue between the adjacent bones is reduced to a narrow layer, these fibrous joints are now called sutures. At some sutures, the connective tissue will ossify and be converted into bone, causing the adjacent bones to fuse to each other. This fusion between bones is called a **synostosis** ("joined by bone"). Examples of synostosis fusions between cranial bones are found both early and late in life. At the time of birth, the frontal and maxillary bones consist of right and left halves joined together by sutures, which disappear by the eighth year of life as the halves fuse together to form a single bone. Late in life, the sagittal, coronal, and lambdoid sutures of the skull will begin to ossify and fuse, causing the suture line to gradually disappear.



(Figure 8.3.2) : The Newborn Skull. The fontanelles of a newborn's skull are broad areas of fibrous connective tissue that form fibrous joints between the bones of the skull. (Image credit: "The Newborn Skull" by OpenStax is licensed under CC BY 3.0)

Syndesmosis

A **syndesmosis** ("fastened with a band") is a type of fibrous joint in which two parallel bones are united to each other by fibrous connective tissue. The gap between the bones may be narrow, with the bones joined by ligaments, or the gap may be wide and filled in by a broad sheet of connective tissue called an **interosseous membrane**.

In the forearm, the wide gap between the shaft portions of the radius and ulna bones are strongly united by the antebrachial interosseous membrane (Figure 8.3.1.*b*) . Similarly, in the leg, the shafts of the tibia and fibula are also united by the interosseous membrane. In addition, at the distal tibiofibular joint, the articulating surfaces of the bones lack cartilage and the narrow gap between the bones is anchored by fibrous connective tissue and ligaments on both the anterior and posterior aspects of the joint. Together, the interosseous membrane and these ligaments form the tibiofibular syndesmosis.

The syndesmoses found in the forearm and leg serve to unite parallel bones and prevent their separation. However, a syndesmosis does not prevent all movement between the bones, and thus this type of fibrous joint is functionally classified as an amphiarthrosis. In the leg, the syndesmosis between the tibia and fibula strongly unites the bones, allows for little movement, and firmly locks the talus bone in place between the tibia and fibula at the ankle joint. This provides strength and stability to the leg and ankle, which are important during weight bearing. In the forearm, the interosseous membrane is flexible enough to allow for rotation of the radius bone during forearm movements. Thus in contrast to the stability provided by the tibiofibular syndesmosis, the flexibility of the antebrachial interosseous membrane allows for the much greater mobility of the forearm.

The interosseous membranes of the leg and forearm also provide areas for muscle attachment. Damage to a syndesmotic joint, which usually results from a fracture of the bone with an accompanying tear of the interosseous membrane, will produce pain, loss of stability of the bones, and may damage the muscles attached to the interosseous membrane. If the fracture site is not properly immobilized with a cast or splint, contractile activity by these muscles can cause improper alignment of the broken bones during healing.

Gomphosis

A **gomphosis** (“fastened with bolts”) is the specialized fibrous joint that anchors the root of a tooth into its bony socket within the maxilla (upper jaw) or mandible (lower jaw) bones of the skull. A gomphosis is also known as a peg-and-socket joint. Spanning between the bony walls of the socket and the root of the tooth are numerous short bands of dense fibrous connective tissue, called the a **periodontal ligament** (Figure $8.3.1.c$). Due to the immobility of a gomphosis, this type of joint is functionally classified as a synarthrosis.

Concept Review

Fibrous joints are where adjacent bones are strongly united by fibrous connective tissue. The gap filled by connective tissue may be narrow or wide. The three types of fibrous joints are sutures, gomphoses, and syndesmoses. A suture is the narrow fibrous joint that unites most bones of the skull. At a gomphosis, the root of a tooth is anchored across a narrow gap by periodontal ligament to the walls of its socket in the bony jaw. A syndesmosis is the type of fibrous joint found between parallel bones. The gap between the bones may be wide and filled with a fibrous interosseous membrane, or it may narrow with ligaments spanning between the bones. Syndesmoses are found between the bones of the forearm (radius and ulna) and the leg (tibia and fibula). Fibrous joints strongly unite adjacent bones and thus serve to provide protection for internal organs, strength to body regions, or weight-bearing stability.

Review Questions

Q. Which type of fibrous joint connects the tibia and fibula?

A. syndesmosis

B. symphysis

C. suture

D. gomphosis

Answer

Answer: A

Q. An example of a wide fibrous joint is _____.

A. the interosseous membrane of the forearm

B. a gomphosis

C. a suture joint

D. a synostosis

Answer

Answer: A

Q. A gomphosis _____.

A. is formed by an interosseous membrane

B. connects the tibia and fibula bones of the leg

C . contains a joint cavity

D. anchors a tooth to the jaw

Answer

Answer: D

Q. A syndesmosis is _____.

A. a narrow fibrous joint

B. the type of joint that unites bones of the skull

C. a fibrous joint that unites parallel bones

D. the type of joint that anchors the teeth in the jaws

Answer

Answer: C

Critical Thinking Questions

Q. Distinguish between a narrow and wide fibrous joint and give an example of each.

Answer

A. Narrow fibrous joints are found at a suture, gomphosis, or syndesmosis. A suture is the fibrous joint that joins the bones of the skull to each other (except the mandible). A gomphosis is the fibrous joint that anchors each tooth to its bony socket within the upper or lower jaw. The tooth is connected to the bony jaw by periodontal ligaments. A narrow syndesmosis is found at the distal tibiofibular joint where the bones are united by fibrous connective tissue and ligaments. A syndesmosis can also form a wide fibrous joint where the shafts of two parallel bones are connected by a broad interosseous membrane. The radius and ulna bones of the forearm and the tibia and fibula bones of the leg are united by interosseous membranes.

Q. The periodontal ligaments are made of collagen fibers and are responsible for connecting the roots of the teeth to the jaws. Describe how scurvy, a disease that inhibits collagen production, can affect the teeth.

Answer

A. The teeth are anchored into their sockets within the bony jaws by the periodontal ligaments. This is a gomphosis type of fibrous joint. In scurvy, collagen production is inhibited and the periodontal ligaments become weak. This will cause the teeth to become loose or even to fall out.

Glossary

fontanelles
expanded areas of fibrous connective tissue that separate the braincase bones of the skull prior to birth and during the first year after birth

gomphosis
type of fibrous joint in which the root of a tooth is anchored into its bony jaw socket by strong periodontal ligaments

interosseous membrane
: wide sheet of fibrous connective tissue that fills the gap between two parallel bones, forming a syndesmosis; found between the radius and ulna of the forearm and between the tibia and fibula of the leg

ligament
: strong band of dense connective tissue spanning between bones

periodontal ligament
: band of dense connective tissue that anchors the root of a tooth into the bony jaw socket

suture
: fibrous joint that connects the bones of the skull (except the mandible); an immobile joint (synarthrosis)

syndesmosis
: type of fibrous joint in which two separated, parallel bones are connected by an interosseous membrane

synostosis
: site at which adjacent bones or bony components have fused together

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8.4: Cartilaginous Joints

By the end of this section, you will be able to:

- Describe the structural features of cartilaginous joints
- Distinguish between a synchondrosis and symphysis
- Give an example of each type of cartilaginous joint

As the name indicates, at a cartilaginous joint, the adjacent bones are united by cartilage, a tough but flexible type of connective tissue. These types of joints lack a joint cavity and involve bones that are joined together by either hyaline cartilage or fibrocartilage (Figure 8.4.1) . There are two types of cartilaginous joints. A **synchondrosis** is a cartilaginous joint where the bones are joined by hyaline cartilage. Also classified as a synchondrosis are places where bone is united to a cartilage structure, such as between the anterior end of a rib and the costal cartilage of the thoracic cage. The second type of cartilaginous joint is a **symphysis**, where the bones are joined by fibrocartilage.

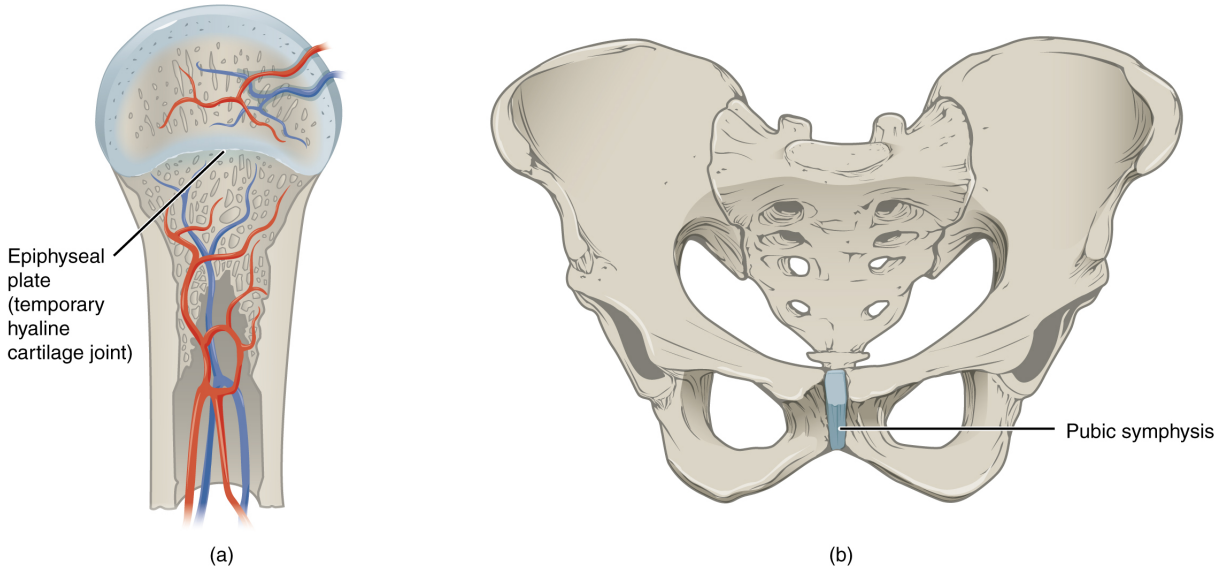

Figure 8.4.1: Cartiliginous Joints. At cartilaginous joints, bones are united by hyaline cartilage to form a synchondrosis or by fibrocartilage to form a symphysis. (a) The hyaline cartilage of the epiphyseal plate (growth plate) forms a synchondrosis that unites the shaft (diaphysis) and end (epiphysis) of a long bone and allows the bone to grow in length. (b) The pubic portions of the right and left hip bones of the pelvis are joined together by fibrocartilage, forming the pubic symphysis. (Image credit: "Cartiliginous Joints" by OpenStax is licensed under CC BY 3.0)

Synchondrosis

A **synchondrosis** (“joined by cartilage”) is a cartilaginous joint where bones are joined together by hyaline cartilage, or where bone is united to hyaline cartilage. A synchondrosis may be temporary or permanent. A temporary synchondrosis is the epiphyseal plate (growth plate) of a growing long bone (Figure 8.4.1.a). The epiphyseal plate is the region of growing hyaline cartilage that unites the diaphysis (shaft) of the bone to the epiphysis (end of the bone). Bone lengthening involves growth of the epiphyseal plate cartilage and its replacement by bone, which adds to the diaphysis. For many years during childhood growth, the rates of cartilage growth and bone formation are equal and thus the epiphyseal plate does not change in overall thickness as the bone lengthens. During the late teens and early 20s, growth of the cartilage slows and eventually stops. The epiphyseal plate is then completely replaced by bone, and the diaphysis and epiphysis portions of the bone fuse together to form a single adult bone. This fusion of the diaphysis and epiphysis is a synostosis. Once this occurs, bone lengthening ceases. For this reason, the epiphyseal plate is considered to be a temporary synchondrosis. Because cartilage is softer than bone tissue, injury to a growing long bone can damage the epiphyseal plate cartilage, thus stopping bone growth and preventing additional bone lengthening.

Growing layers of cartilage also form synchondroses that join together the ilium, ischium, and pubic portions of the hip

bone during childhood and adolescence. When body growth stops, the cartilage disappears and is replaced by bone, forming synostoses and fusing the bony components together into the single hip (coxal) bone of the adult. Similarly, synostoses unite the sacral vertebrae that fuse together to form the adult sacrum.

Examples of permanent synchondroses are found in the thoracic cage. One example is the first sternocostal joint, where the first rib is anchored to the manubrium by its costal cartilage. (The articulations of the remaining costal cartilages to the sternum are all synovial joints.) Additional synchondroses are formed where the anterior end of the other 11 ribs is joined to its costal cartilage. Unlike the temporary synchondroses of the epiphyseal plate, these permanent synchondroses retain their hyaline cartilage and thus do not ossify with age. Due to the lack of movement between the bone and cartilage, both temporary and permanent synchondroses are functionally classified as a synarthrosis.

Symphysis

A cartilaginous joint where the bones are joined by fibrocartilage is called a **symphysis** (“growing together”). Fibrocartilage is very strong because it contains numerous bundles of thick collagen fibers, thus giving it a much greater ability to resist pulling and bending forces when compared with hyaline cartilage. This gives symphyses the ability to strongly unite the adjacent bones, but can still allow for limited movement to occur. Thus, a symphysis is functionally classified as an amphiarthrosis.

The gap separating the bones at a symphysis may be narrow or wide. Examples in which the gap between the bones is narrow include the pubic symphysis and the manubriosternal joint. At the pubic symphysis (Figure $8.4.1.b$) , the pubic portions of the right and left hip bones of the pelvis are joined together by fibrocartilage across a narrow gap. Similarly, at the manubriosternal joint, fibrocartilage unites the manubrium and body portions of the sternum.

The intervertebral symphysis is a wide symphysis located between the bodies of adjacent vertebrae of the vertebral column (Figure 9.2.2). Here, a thick pad of fibrocartilage called an intervertebral disc strongly unites the adjacent vertebrae by filling the gap between them. The width of the intervertebral symphysis is important because it allows for small movements between the adjacent vertebrae. In addition, the thick intervertebral disc provides cushioning between the vertebrae, which is important when carrying heavy objects or during high-impact activities such as running or jumping.

Concept Review

There are two types of cartilaginous joints. A synchondrosis is formed when the adjacent bones are united by hyaline cartilage. A temporary synchondrosis is formed by the epiphyseal plate of a growing long bone, which is lost when the epiphyseal plate ossifies as the bone reaches maturity. The synchondrosis is thus replaced by a synostosis. Permanent synchondroses that do not ossify are found at the first sternocostal joint and between the anterior ends of the bony ribs and the junction with their costal cartilage. A symphysis is where the bones are joined by fibrocartilage and the gap between the bones may be narrow or wide. A narrow symphysis is found at the manubriosternal joint and at the pubic symphysis. A wide symphysis is the intervertebral symphysis in which the bodies of adjacent vertebrae are united by an intervertebral disc.

Review Questions

Q. A cartilaginous joint _____.

A. has a joint cavity

B. is called a symphysis when the bones are united by fibrocartilage

C. anchors the teeth to the jaws

D. is formed by a wide sheet of fibrous connective tissue

Answer

Answer: B

Q. A synchondrosis is _____.

A. found at the pubic symphysis

B. where bones are connected together with fibrocartilage

C. a type of fibrous joint

D. found at the first sternocostal joint of the thoracic cage

Answer

Answer: D

Q. Which of the following are joined by a symphysis?

A. adjacent vertebrae

B. the first rib and the sternum

C . the end and shaft of a long bone

D. the radius and ulna bones

Answer

Answer: A

Q. The epiphyseal plate of a growing long bone in a child is classified as a _____.

A. synchondrosis

B. synostosis

C. symphysis

D. syndesmosis

Answer

Answer: A

Critical Thinking Questions

Q. Describe the two types of cartilaginous joints and give examples of each.

Answer

A. Cartilaginous joints are where the adjacent bones are joined by cartilage. At a synchondrosis, the bones are united by hyaline cartilage. The epiphyseal plate of growing long bones and the first sternocostal joint that unites the first rib to the sternum are examples of synchondroses. At a symphysis, the bones are joined by fibrocartilage, which is strong and flexible. Symphysis joints include the intervertebral symphysis between adjacent vertebrae and the pubic symphysis that joins the pubic portions of the right and left hip bones.

Q. Both functional and structural classifications can be used to describe an individual joint. Define the first sternocostal joint and the pubic symphysis using both functional and structural characteristics.

Answer

A. The first sternocostal joint is a synchondrosis type of cartilaginous joint in which hyaline cartilage unites the first rib to the manubrium of the sternum. This forms an immobile (synarthrosis) type of joint. The pubic symphysis is a slightly mobile (amphiarthrosis) cartilaginous joint, where the pubic portions of the right and left hip bones are

united by fibrocartilage, thus forming a symphysis.

Glossary

symphysis
type of cartilaginous joint where the bones are joined by fibrocartilage

synchondrosis
type of cartilaginous joint where the bones are joined by hyaline cartilage

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8.5: Synovial Joints

By the end of this section, you will be able to

- Describe the structural features of a synovial joint
- Discuss the function of additional structures associated with synovial joints
- List the six types of synovial joints and give an example of each

Synovial joints are the most common type of joint in the body (Figure 8.5.1). A key structural characteristic for a synovial joint that is not seen at fibrous or cartilaginous joints is the presence of a joint cavity. This fluid-filled space is the site at which the articulating surfaces of the bones contact each other. Also unlike fibrous or cartilaginous joints, the articulating bone surfaces at a synovial joint are not directly connected to each other with fibrous connective tissue or cartilage. This gives the bones of a synovial joint the ability to move smoothly against each other, allowing for increased joint mobility.

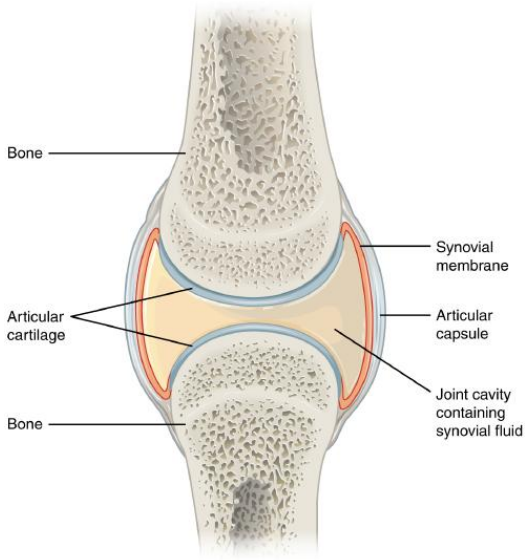


Figure 8.5.1: Synovial Joints. Synovial joints allow for smooth movements between the adjacent bones. The joint is surrounded by an articular capsule that defines a joint cavity filled with synovial fluid. The articulating surfaces of the bones are covered by a thin layer of articular cartilage. Ligaments support the joint by holding the bones together and resisting excess or abnormal joint motions. (Image credit: "Synovial Joints" by OpenStax is licensed under CC BY 3.0)

Structural Features of Synovial Joints

Synovial joints are characterized by the presence of a joint cavity. The walls of this space are formed by the **articular capsule**, a fibrous connective tissue structure that is attached to each bone just outside the area of the bone's articulating surface. The bones of the joint articulate with each other within the joint cavity.

Friction between the bones at a synovial joint is prevented by the presence of the **articular cartilage**, a thin layer of hyaline cartilage that covers the entire articulating surface of each bone. However, unlike at a cartilaginous joint, the articular cartilages of each bone are not continuous with each other. Instead, the articular cartilage acts like a coating over the bone surface, allowing the articulating bones to move smoothly against each other without damaging the underlying bone tissue. Lining the inner surface of the articular capsule is a thin **synovial membrane**. The cells of this membrane secrete **synovial fluid** (synovia = "a thick fluid"), a thick, slimy fluid that provides lubrication to further reduce friction between the bones of the joint. This fluid also provides nourishment to the articular cartilage, which does not contain blood vessels. The ability of the bones to move smoothly against each other within the joint cavity, and the freedom of joint movement this provides, means that each synovial joint is functionally classified as a diarthrosis.

Outside of their articulating surfaces, the bones are connected together by **ligaments**, which are strong bands of dense fibrous connective tissue. These strengthen and support the joint by anchoring the bones together and preventing their separation. Ligaments allow for normal movements at a joint, but limit the range of these motions, thus preventing excessive or abnormal joint movements. Ligaments are classified based on their relationship to the fibrous articular capsule. An **extrinsic ligament** is located outside of the articular capsule, an **intrinsic ligament** is fused to or incorporated into the wall of the articular capsule, and an **intracapsular ligament** is located inside of the articular capsule.

At many synovial joints, additional support is provided by the muscles and their tendons that act across the joint. A **tendon** is the dense connective tissue structure that attaches a muscle to bone. As forces acting on a joint increase, the body will automatically increase the overall strength of contraction of the muscles crossing that joint, thus allowing the muscle and its tendon to serve as a "dynamic ligament" to resist forces and support the joint. This type of indirect support by muscles is very important at the shoulder joint, for example, where the ligaments are relatively weak.

Additional Structures Associated with Synovial Joints

A few synovial joints of the body have a fibrocartilage structure located between the articulating bones. This is called an **articular disc**, which is generally small and oval-shaped, or a **meniscus**, which is larger and C-shaped. These structures can serve several functions, depending on the specific joint. In some places, an articular disc may act to strongly unite the bones of the joint to each other. Examples of this include the articular discs found at the sternoclavicular joint or between the distal ends of the radius and ulna bones. At other synovial joints, the disc can provide shock absorption and cushioning between the bones, which is the function of each meniscus within the knee joint. Finally, an articular disc can serve to smooth the movements between the articulating bones, as seen at the temporomandibular joint. Some synovial joints also have a fat pad, which can serve as a cushion between the bones.

Additional structures located outside of a synovial joint serve to prevent friction between the bones of the joint and the overlying muscle tendons or skin. A **bursa** (plural = bursae) is a thin connective tissue sac filled with lubricating liquid. They are located in regions where skin, ligaments, muscles, or muscle tendons can rub against each other, usually near a synovial articulation. Bursae reduce friction by separating the adjacent structures, preventing them from rubbing directly against each other. Bursae are classified by their location. A **subcutaneous bursa** is located between the skin and an underlying bone. It allows skin to move smoothly over the bone. Examples include the prepatellar bursa located over the kneecap (Figure 8.5.2) and the olecranon bursa at the tip of the elbow. A **submuscular bursa** is found between a muscle and an underlying bone, or between adjacent muscles. These prevent rubbing of the muscle during movements. A large submuscular bursa, the trochanteric bursa, is found at the lateral hip, between the greater trochanter of the femur and the overlying gluteus maximus muscle. A **subtendinous bursa** is found between a tendon and a bone. Examples include the subacromial bursa that protects the tendon of shoulder muscle as it passes under the acromion of the scapula, and the suprapatellar bursa that separates the tendon of the quadriceps femoris (thigh) muscle from the distal femur just above the knee (Figure 8.5.2).

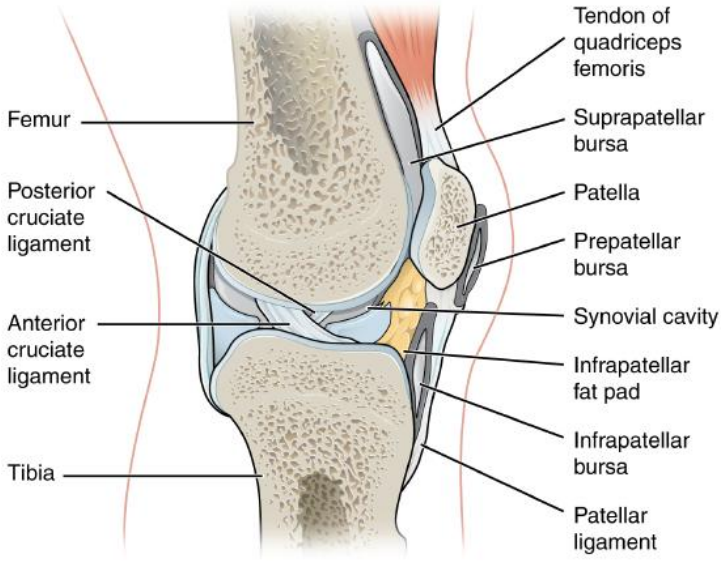


Figure 8.5.2: Bursae. Bursae are fluid-filled sacs that serve to prevent friction between skin, muscle, or tendon and an underlying bone. Three major bursae and a fat pad are part of the complex joint that unites the femur and tibia of the leg. (Image Credit: "Bursa" by OpenStax is licensed under CC BY 3.0)

A **tendon sheath** is similar in structure to a bursa, but smaller. It is a connective tissue sac that surrounds a muscle tendon at places where the tendon crosses a joint. It contains a lubricating fluid that allows for smooth motions of the tendon during muscle contraction and joint movements.

DISOERDERS OF THE ...

Joints: Bursitis

Bursitis is the inflammation of a bursa near a joint. This will cause pain, swelling, or tenderness of the bursa and surrounding area, and may also result in joint stiffness. Bursitis is most commonly associated with the bursae found at or near the shoulder, hip, knee, or elbow joints. At the shoulder, subacromial bursitis may occur in the bursa that separates the acromion of the scapula from the tendon of a shoulder muscle as it passes deep to the acromion. In the hip region, trochanteric bursitis can occur in the bursa that overlies the greater trochanter of the femur, just below the lateral side of the hip. Ischial bursitis occurs in the bursa that separates the skin from the ischial tuberosity of the pelvis, the bony structure that is weight bearing when sitting. At the knee, inflammation and swelling of the bursa located between the skin and patella bone is prepatellar bursitis ("housemaid's knee"), a condition more commonly seen today in roofers or floor and carpet installers who do not use knee pads. At the elbow, olecranon bursitis is inflammation of the bursa between the skin and olecranon process of the ulna. The olecranon forms the bony tip of the elbow, and bursitis here is also known as "student's elbow."

Bursitis can be either acute (lasting only a few days) or chronic. It can arise from muscle overuse, trauma, excessive or prolonged pressure on the skin, rheumatoid arthritis, gout, or infection of the joint. Repeated acute episodes of bursitis can result in a chronic condition. Treatments for the disorder include antibiotics if the bursitis is caused by an infection, or anti-inflammatory agents, such as nonsteroidal anti-inflammatory drugs (NSAIDs) or corticosteroids if the bursitis is due to trauma or overuse. Chronic bursitis may require that fluid be drained, but additional surgery is usually not required.

Types of Synovial Joints

Synovial joints are subdivided based on the shapes of the articulating surfaces of the bones that form each joint. The six types of synovial joints are pivot, hinge, saddle, plane, condyloid, and ball-and socket-joints (Figure 8.5.3) .

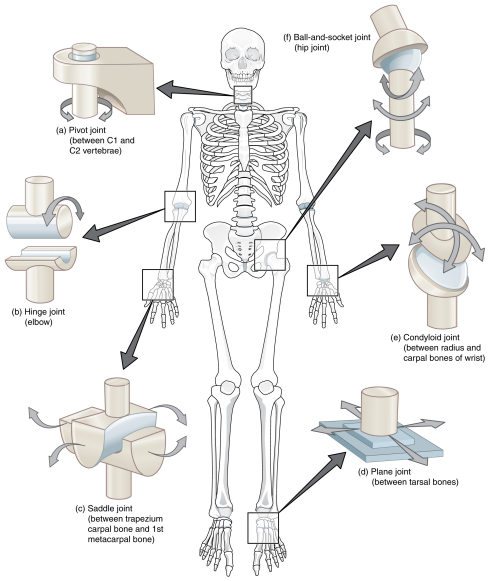


Figure 8.5.3: Types of Synovial Joints. The six types of synovial joints allow the body to move in a variety of ways. (a) Pivot joints allow for rotation around an axis, such as between the first and second cervical vertebrae, which allows for side-to-side rotation of the head. (b) The hinge joint of the elbow works like a door hinge. (c) The articulation between the trapezium carpal bone and the first metacarpal bone at the base of the thumb is a saddle joint. (d) Plane joints, such as those between the tarsal bones of the foot, allow for limited gliding movements between bones. (e) The radiocarpal joint of the wrist is a condyloid joint. (f) The hip and shoulder joints are the only ball-and-socket joints of the body. (Image credit: "Types of Synovial Joints" by OpenStax is licensed under CC BY 3.0)

Pivot Joint

At a **pivot joint**, a rounded portion of a bone is enclosed within a ring formed partially by the articulation with another bone and partially by a ligament (Figure $8.5.3.a$) . The bone rotates within this ring. Since the rotation is around a single axis, pivot joints are functionally classified as a uniaxial type of joint. An example of a pivot joint is the atlantoaxial joint, found between the C1 (atlas) and C2 (axis) vertebrae. Here, the upward projecting dens of the axis articulates with the inner aspect of the atlas, where it is held in place by the transverse ligament. Rotation at this joint allows you to turn your head from side to side. A second pivot joint is found at the **proximal radioulnar joint**. Here, the head of the radius is largely encircled by a ligament that holds it in place as it articulates with the radial notch of the ulna. Rotation of the radius allows for forearm movements.

Hinge Joint

In a **hinge joint**, the convex end of one bone articulates with the concave end of the adjoining bone (Figure $8.5.3.b$) . This type of joint allows only for bending and straightening motions along a single axis, and thus hinge joints are functionally classified as uniaxial joints. A good example is the elbow joint, with the articulation between the trochlea of the humerus and the trochlear notch of the ulna. Other hinge joints of the body include the knee, ankle, and interphalangeal joints between the phalanx bones of the fingers and toes.

Saddle Joint

At a **saddle joint**, both of the articulating surfaces for the bones have a saddle shape, which is concave in one direction and convex in the other (Figure $8.5.3.c$) . This allows the two bones to fit together like a rider sitting on a saddle. Saddle joints are functionally classified as biaxial joints. The primary example is the first carpometacarpal joint, between the trapezium (a carpal bone) and the first metacarpal bone at the base of the thumb. This joint provides the thumb the ability to move away from the palm of the hand along two planes. Thus, the thumb can move within the same plane as the palm of the hand, or it can jut out anteriorly, perpendicular to the palm. This movement of the first carpometacarpal joint is what gives humans their distinctive “opposable” thumbs. The sternoclavicular joint is also classified as a saddle joint.

Plane Joint

At a **plane joint**, also known as a gliding joint, the articulating surfaces of the bones are flat or slightly curved and of approximately

the same size, which allows the bones to slide against each other (Figure 8.5.3.d) . The motion at this type of joint is usually small and tightly constrained by surrounding ligaments. Based only on their shape, plane joints can allow multiple movements, including rotation. Thus plane joints can be functionally classified as a multiaxial joint. However, not all of these movements are available to every plane joint due to limitations placed on it by ligaments or neighboring bones. Thus, depending upon the specific joint of the body, a plane joint may exhibit only a single type of movement or several movements. Plane joints are found between the carpal bones (intercarpal joints) of the wrist or tarsal bones (intertarsal joints) of the foot, between the clavicle and acromion of the scapula (acromioclavicular joint), and between the superior and inferior articular processes of adjacent vertebrae (zygapophysial joints).

Condyloid Joint

At a **condyloid joint**, also known as an ellipsoid joint, the shallow depression at the end of one bone articulates with a rounded structure from an adjacent bone or bones (Figure 8.5.3.e) . The knuckle (metacarpophalangeal) joints of the hand between the distal end of a metacarpal bone and the proximal phalanx bone are condyloid joints. Another example is the radiocarpal joint of the wrist, between the shallow depression at the distal end of the radius bone and the rounded scaphoid, lunate, and triquetrum carpal bones. In this case, the articulation area has a more oval (elliptical) shape. Functionally, condyloid joints are biaxial joints that allow for two planes of movement. One movement involves the bending and straightening of the fingers or the anterior-posterior movements of the hand. The second movement is a side-to-side movement, which allows you to spread your fingers apart and bring them together, or to move your hand in a medial-going or lateral-going direction.

Ball-and-Socket Joint

The joint with the greatest range of motion is the **ball-and-socket joint**. At these joints, the rounded head of one bone (the ball) fits into the concave articulation (the socket) of the adjacent bone (Figure 8.5.3.f) . The coxafemoral joint (hip) and the glenohumeral (shoulder) joint are the only ball-and-socket joints of the body. At the hip joint, the head of the femur articulates with the acetabulum of the hip bone, and at the shoulder joint, the head of the humerus articulates with the glenoid cavity of the scapula.

Ball-and-socket joints are classified functionally as multiaxial joints. The femur and the humerus are able to move in both anterior-posterior and medial-lateral directions and they can also rotate around their long axis. The shallow socket formed by the glenoid cavity allows the shoulder joint an extensive range of motion. In contrast, the deep socket of the acetabulum and the strong supporting ligaments of the hip joint serve to constrain movements of the femur, reflecting the need for stability and weight-bearing ability at the hip.

AGING AND THE.....

Joints

Arthritis is a common disorder of synovial joints that involves inflammation of the joint. This often results in significant joint pain, along with swelling, stiffness, and reduced joint mobility. There are more than 100 different forms of arthritis. Arthritis may arise from aging, damage to the articular cartilage, autoimmune diseases, bacterial or viral infections, or unknown (probably genetic) causes.

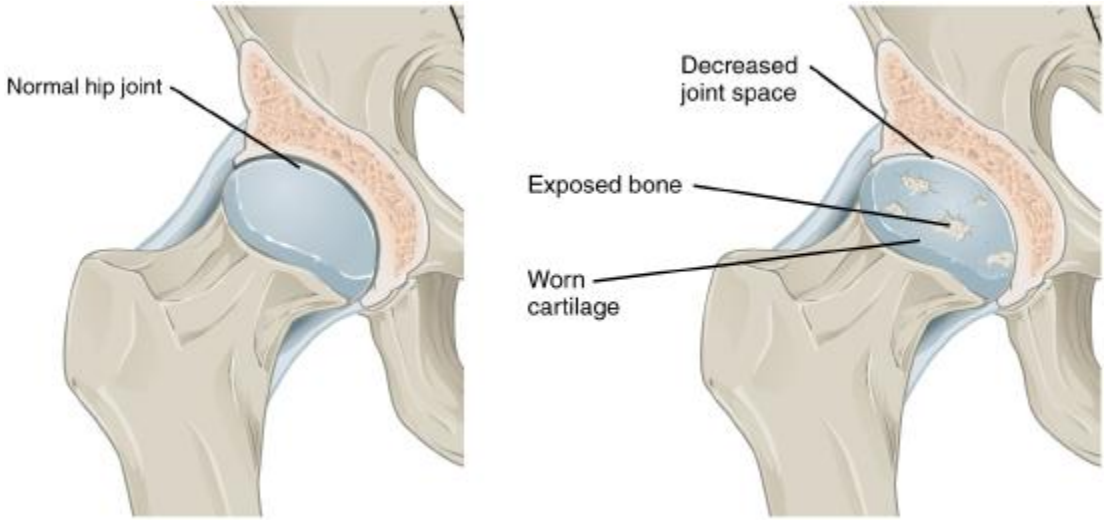
The most common type of arthritis is osteoarthritis, which is associated with aging and “wear and tear” of the articular cartilage (Figure 8.5.4) . Risk factors that may lead to osteoarthritis later in life include injury to a joint; jobs that involve physical labor; sports with running, twisting, or throwing actions; and being overweight. These factors put stress on the articular cartilage that covers the surfaces of bones at synovial joints, causing the cartilage to gradually become thinner. As the articular cartilage layer wears down, more pressure is placed on the bones. The joint responds by increasing production of the lubricating synovial fluid, but this can lead to swelling of the joint cavity, causing pain and joint stiffness as the articular capsule is stretched. The bone tissue underlying the damaged articular cartilage also responds by thickening, producing irregularities and causing the articulating surface of the bone to become rough or bumpy. Joint movement then results in pain and inflammation. In its early stages, symptoms of osteoarthritis may be reduced by mild activity that “warms up” the joint, but the symptoms may worsen following exercise. In individuals with more advanced osteoarthritis, the affected joints can become more painful and therefore are difficult to use effectively, resulting in increased immobility. There is no cure for osteoarthritis, but several treatments can help alleviate the

pain. Treatments may include lifestyle changes, such as weight loss and low-impact exercise, and over-the-counter or prescription medications that help to alleviate the pain and inflammation. For severe cases, joint replacement surgery (arthroplasty) may be required.

Joint replacement is a very invasive procedure, so other treatments are always tried before surgery. However arthroplasty can provide relief from chronic pain and can enhance mobility within a few months following the surgery. This type of surgery involves replacing the articular surfaces of the bones with prostheses (artificial components). For example, in hip arthroplasty, the worn or damaged parts of the hip joint, including the head and neck of the femur and the acetabulum of the pelvis, are removed and replaced with artificial joint components. The replacement head for the femur consists of a rounded ball attached to the end of a shaft that is inserted inside the diaphysis of the femur. The acetabulum of the pelvis is reshaped and a replacement socket is fitted into its place. The parts, which are always built in advance of the surgery, are sometimes custom made to produce the best possible fit for a patient.

Gout is a form of arthritis that results from the deposition of uric acid crystals within a body joint. Usually only one or a few joints are affected, such as the big toe, knee, or ankle. The attack may only last a few days, but may return to the same or another joint. Gout occurs when the body makes too much uric acid or the kidneys do not properly excrete it. A diet with excessive fructose has been implicated in raising the chances of a susceptible individual developing gout.

Other forms of arthritis are associated with various autoimmune diseases, bacterial infections of the joint, or unknown genetic causes. Autoimmune diseases, including rheumatoid arthritis, scleroderma, or systemic lupus erythematosus, produce arthritis because the immune system of the body attacks the body joints. In rheumatoid arthritis, the joint capsule and synovial membrane become inflamed. As the disease progresses, the articular cartilage is severely damaged or destroyed, resulting in joint deformation, loss of movement, and severe disability. The most commonly involved joints are the hands, feet, and cervical spine, with corresponding joints on both sides of the body usually affected, though not always to the same extent. Rheumatoid arthritis is also associated with lung fibrosis, vasculitis (inflammation of blood vessels), coronary heart disease, and premature mortality. With no known cure, treatments are aimed at alleviating symptoms. Exercise, anti-inflammatory and pain medications, various specific disease-modifying anti-rheumatic drugs, or surgery are used to treat rheumatoid arthritis.



(Figure 8.5.4) : Osteoarthritis. Osteoarthritis of a synovial joint results from aging or prolonged joint wear and tear. These cause erosion and loss of the articular cartilage covering the surfaces of the bones, resulting in inflammation that causes joint stiffness and pain. (Image credit: "Osteoarthritis in the Hip" by OpenStax is licensed under CC BY 3.0)

Concept Review

Synovial joints are the most common type of joints in the body. They are characterized by the presence of a joint cavity, inside of which the bones of the joint articulate with each other. The articulating surfaces of the bones at a synovial joint are not directly connected to each other by connective tissue or cartilage, which allows the bones to move freely against each other. The walls of the joint cavity are formed by the articular capsule. Friction between the bones is reduced by a thin layer of articular cartilage covering the surfaces of the bones, and by a lubricating synovial fluid, which is secreted by the synovial membrane.

Synovial joints are strengthened by the presence of ligaments, which hold the bones together and resist excessive or abnormal movements of the joint. Ligaments are classified as extrinsic ligaments if they are located outside of the articular capsule, intrinsic ligaments if they are fused to the wall of the articular capsule, or intracapsular ligaments if they are located inside the articular capsule. Some synovial joints also have an articular disc (meniscus), which can provide padding between the bones, smooth their movements, or strongly join the bones together to strengthen the joint. Muscles and their tendons acting across a joint can also increase their contractile tension when needed, thus providing indirect support for the joint.

Bursae contain a lubricating fluid that serves to reduce friction between structures. Subcutaneous bursae prevent friction between the skin and an underlying bone, submuscular bursae protect muscles from rubbing against a bone or another muscle, and a subtendinous bursa prevents friction between bone and a muscle tendon. Tendon sheaths contain a lubricating fluid and surround tendons to allow for smooth movement of the tendon as it crosses a joint.

Based on the shape of the articulating bone surfaces and the types of movement allowed, synovial joints are classified into six types. At a pivot joint, one bone is held within a ring by a ligament and its articulation with a second bone. Pivot joints only allow for rotation around a single axis. These are found at the articulation between the C1 (atlas) and the dens of the C2 (axis) vertebrae, which provides the side-to-side rotation of the head, or at the proximal radioulnar joint between the head of the radius and the radial notch of the ulna, which allows for rotation of the radius during forearm movements. Hinge joints, such as at the elbow, knee, ankle, or interphalangeal joints between phalanx bones of the fingers and toes, allow only for bending and straightening of the joint. Pivot and hinge joints are functionally classified as uniaxial joints.

Condyloid joints are found where the shallow depression of one bone receives a rounded bony area formed by one or two bones. Condyloid joints are found at the base of the fingers (metacarpophalangeal joints) and at the wrist (radiocarpal joint). At a saddle joint, the articulating bones fit together like a rider and a saddle. An example is the first carpometacarpal joint located at the base of the thumb. Both condyloid and saddle joints are functionally classified as biaxial joints.

Plane joints are formed between the small, flattened surfaces of adjacent bones. These joints allow the bones to slide or rotate against each other, but the range of motion is usually slight and tightly limited by ligaments or surrounding bones. This type of joint is found between the articular processes of adjacent vertebrae, at the acromioclavicular joint, or at the intercarpal joints of the hand and intertarsal joints of the foot. Ball-and-socket joints, in which the rounded head of a bone fits into a large depression or socket, are found at the shoulder and hip joints. Both plane and ball-and-sockets joints are classified functionally as multiaxial joints. However, ball-and-socket joints allow for large movements, while the motions between bones at a plane joint are small.

Review Questions

Q. Which type of joint provides the greatest range of motion?

A. ball-and-socket

B. hinge

C. condyloid

D. plane

Answer

Answer: A

Q. Which type of joint allows for only uniaxial movement?

A. saddle joint

B. hinge joint

C. condyloid joint

D. ball-and-socket joint

Answer

Answer: B

Q. Which of the following is a type of synovial joint?

A. a synostosis

B. a suture

C. a plane joint

D. a synchondrosis

Answer

Answer: C

Q. A bursa _____.

A. surrounds a tendon at the point where the tendon crosses a joint

B. secretes the lubricating fluid for a synovial joint

C. prevents friction between skin and bone, or a muscle tendon and bone

D. is the strong band of connective tissue that holds bones together at a synovial joint

Answer

Answer: C

Q. At synovial joints, _____.

A. the articulating ends of the bones are directly connected by fibrous connective tissue

B. the ends of the bones are enclosed within a space called a subcutaneous bursa

C. intrinsic ligaments are located entirely inside of the articular capsule

D. the joint cavity is filled with a thick, lubricating fluid

Answer

Answer: D

Q. At a synovial joint, the synovial membrane _____.

A. forms the fibrous connective walls of the joint cavity

B. is the layer of cartilage that covers the articulating surfaces of the bones

C. forms the intracapsular ligaments

D. secretes the lubricating synovial fluid

Answer

Answer: D

Q. Condyloid joints _____.

A. are a type of ball-and-socket joint

B. include the radiocarpal joint

C. are a uniaxial diarthrosis joint

D. are found at the proximal radioulnar joint

Answer

Answer: B

Q. A meniscus is _____.

A. a fibrocartilage pad that provides padding between bones

B. a fluid-filled space that prevents friction between a muscle tendon and underlying bone

C. the articular cartilage that covers the ends of a bone at a synovial joint

D. the lubricating fluid within a synovial joint

Answer

Answer: A

Critical Thinking Questions

Q. Describe the characteristic structures found at all synovial joints.

Answer

A. All synovial joints have a joint cavity filled with synovial fluid that is the site at which the bones of the joint articulate with each other. The articulating surfaces of the bones are covered by articular cartilage, a thin layer of hyaline cartilage. The walls of the joint cavity are formed by the connective tissue of the articular capsule. The synovial membrane lines the interior surface of the joint cavity and secretes the synovial fluid. Synovial joints are directly supported by ligaments, which span between the bones of the joint. These may be located outside of the articular capsule (extrinsic ligaments), incorporated or fused to the wall of the articular capsule (intrinsic ligaments), or found inside of the articular capsule (intracapsular ligaments). Ligaments hold the bones together and also serve to resist or prevent excessive or abnormal movements of the joint.

Q. Describe the structures that provide direct and indirect support for a synovial joint.

Answer

A. Direct support for a synovial joint is provided by ligaments that strongly unite the bones of the joint and serve to resist excessive or abnormal movements. Some joints, such as the sternoclavicular joint, have an articular disc that is attached to both bones, where it provides direct support by holding the bones together. Indirect joint support is provided by the muscles and their tendons that act across a joint. Muscles will increase their contractile force to help support the joint by resisting forces acting on it.

Glossary

articular capsule
connective tissue structure that encloses the joint cavity of a synovial joint

articular cartilage
thin layer of hyaline cartilage that covers the articulating surfaces of bones at a synovial joint

articular disc
meniscus; a fibrocartilage structure found between the bones of some synovial joints; provides padding or smooths movements between the bones; strongly unites the bones together

ball-and-socket joint
synovial joint formed between the spherical end of one bone (the ball) that fits into the depression of a second bone (the socket); found at the hip and shoulder joints; functionally classified as a multiaxial joint

bursa
connective tissue sac containing lubricating fluid that prevents friction between adjacent structures, such as skin and bone, tendons and bone, or between muscles

condyloid joint
synovial joint in which the shallow depression at the end of one bone receives a rounded end from a second bone or a rounded structure formed by two bones; found at the metacarpophalangeal joints of the fingers or the radiocarpal joint of the wrist; functionally classified as a biaxial joint

extrinsic ligament
ligament located outside of the articular capsule of a synovial joint

hinge joint
synovial joint at which the convex surface of one bone articulates with the concave surface of a second bone; includes the elbow, knee, ankle, and interphalangeal joints; functionally classified as a uniaxial joint

intracapsular ligament
ligament that is located within the articular capsule of a synovial joint

intrinsic ligament
ligament that is fused to or incorporated into the wall of the articular capsule of a synovial joint

meniscus
articular disc

pivot joint
synovial joint at which the rounded portion of a bone rotates within a ring formed by a ligament and an articulating bone; functionally classified as uniaxial joint

plane joint
synovial joint formed between the flattened articulating surfaces of adjacent bones; functionally classified as a multiaxial joint

proximal radioulnar joint
articulation between head of radius and radial notch of ulna; uniaxial pivot joint that allows for rotation of radius during pronation/supination of forearm

saddle joint
synovial joint in which the articulating ends of both bones are convex and concave in shape, such as at the first carpometacarpal joint at the base of the thumb; functionally classified as a biaxial joint

subcutaneous bursa
bursa that prevents friction between skin and an underlying bone

submuscular bursa
bursa that prevents friction between bone and a muscle or between adjacent muscles

subtendinous bursa
bursa that prevents friction between bone and a muscle tendon

synovial fluid
thick, lubricating fluid that fills the interior of a synovial joint

synovial membrane
: thin layer that lines the inner surface of the joint cavity at a synovial joint; produces the synovial fluid

tendon
: dense connective tissue structure that anchors a muscle to bone

tendon sheath
: connective tissue that surrounds a tendon at places where the tendon crosses a joint; contains a lubricating fluid to prevent friction and allow smooth movements of the tendon

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8.6: Types of Body Movements

By the end of this section, you will be able to

- Define the different types of body movements
- Identify the joints that allow for these motions

Synovial joints allow the body a tremendous range of movements. Each movement at a synovial joint results from the contraction or relaxation of the muscles that are attached to the bones on either side of the articulation. The type of movement that can be produced at a synovial joint is determined by its structural type. While the ball-and-socket joint gives the greatest range of movement at an individual joint, in other regions of the body, several joints may work together to produce a particular movement. Overall, each type of synovial joint is necessary to provide the body with its great flexibility and mobility. There are many types of movement that can occur at synovial joints (Table 8.6.1). Movement types are generally paired, with one being the opposite of the other. Body movements are always described in relation to the anatomical position of the body: upright stance, with upper limbs to the side of body and palms facing forward. Refer to Figure 8.6.1 and Figure 8.6.2 as you go through this section.

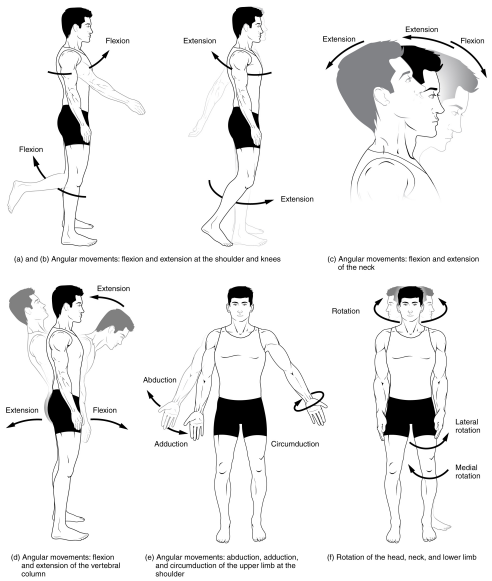

Figure 8.6.1:Movements of the Body, Part 1. Synovial joints give the body many ways in which to move. (a)–(b) Flexion and extension motions are in the sagittal (anterior–posterior) plane of motion. These movements take place at the shoulder, hip, elbow, knee, wrist, metacarpophalangeal, metatarsophalangeal, and interphalangeal joints. (c)–(d) Anterior bending of the head or vertebral column is flexion, while any posterior-going movement is extension. (e) Abduction and adduction are motions of the limbs, hand, fingers, or toes in the coronal (medial–lateral) plane of movement. Moving the limb or hand laterally away from the body, or spreading the fingers or toes, is abduction. Adduction brings the limb or hand toward or across the midline of the body, or brings the fingers or toes together. Circumduction is the movement of the limb, hand, or fingers in a circular pattern, using the sequential combination of flexion, adduction, extension, and abduction motions. Adduction/abduction and circumduction take place at the shoulder, hip, wrist, metacarpophalangeal, and metatarsophalangeal joints. (f) Turning of the head side to side or twisting of the body is rotation. Medial and lateral rotation of the upper limb at the shoulder or lower limb at the hip involves turning the anterior surface of the limb toward the midline of the body (medial or internal rotation) or away from the midline (lateral or external rotation). (Image credit: "Body Movements I" by OpenStax is licensed under CC BY 3.0)

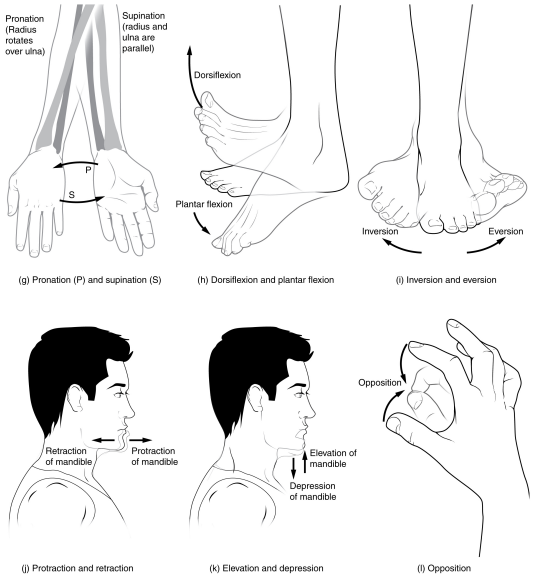

Figure 8.6.2: Movements of the Body, Part 2. (g) Supination of the forearm turns the hand to the palm forward position in which the radius and ulna are parallel, while forearm pronation turns the hand to the palm backward position in which the radius crosses over the ulna to form an "X." (h) Dorsiflexion of the foot at the ankle joint moves the top of the foot toward the leg, while plantar flexion lifts the heel and points the toes. (i) Eversion of the foot moves the bottom (sole) of the foot away from the midline of the body, while foot inversion faces the sole toward the midline. (j) Protraction of the mandible pushes the chin forward, and retraction pulls the chin back. (k) Depression of the mandible opens the mouth, while elevation closes it. (l) Opposition of the thumb brings the tip of the thumb into contact with the tip of the fingers of the same hand and reposition brings the thumb back next to the index finger. (Image credit: "Body Movements II" by OpenStax is licensed under CC BY 3.0)

Flexion and Extension

Flexion and **extension** are movements that take place within the sagittal plane and involve anterior or posterior movements of the body or limbs. In the limbs, flexion decreases the angle between the bones (bending of the joint), while extension increases the angle and straightens the joint. For the upper limb, all anterior-going motions are flexion and all posterior-going motions are extension. These include anterior-posterior movements of the arm at the shoulder, the forearm at the elbow, the hand at the wrist, and the fingers at the metacarpophalangeal and interphalangeal joints. For the thumb, extension moves the thumb away from the palm of the hand, within the same plane as the palm, while flexion brings the thumb back against the index finger or into the palm. These motions take place at the first carpometacarpal joint. In the lower limb, bringing the thigh forward and upward is flexion at the hip joint, while any posterior-going motion of the thigh is extension. Note that extension of the thigh beyond the anatomical (standing) position is greatly limited by the ligaments that support the hip joint. Knee flexion is the bending of the knee to bring the foot toward the posterior thigh, and extension is the straightening of the knee. Flexion and extension movements are seen at the hinge, condyloid, saddle, and ball-and-socket joints of the limbs (Figure $8.6.1.a-b$).

For the vertebral column, flexion (anterior flexion) is an anterior (forward) bending of the neck or body, while extension involves a posterior-directed motion, such as straightening from a flexed position or bending backward $8.6.1.c-d$). **Lateral flexion** is the bending of the neck or body toward the right or left side. These movements of the vertebral column involve both the symphysis joint formed by each intervertebral disc, as well as the plane type of synovial joint formed between the inferior articular processes of one vertebra and the superior articular processes of the next lower vertebra.

Hyperextension is the abnormal or excessive extension of a joint beyond its normal range of motion, thus resulting in injury. Similarly, **hyperflexion** is excessive flexion at a joint. Hyperextension injuries are common at hinge joints such as the knee or elbow. In cases of “whiplash” in which the head is suddenly moved backward and then forward, a patient may experience both hyperextension and hyperflexion of the cervical region.

Abduction and Adduction

Abduction and **adduction** motions occur within the coronal plane and involve medial-lateral motions of the limbs, fingers, toes, or thumb. Abduction moves the limb laterally away from the midline of the body, while adduction is the opposing movement that

brings the limb toward the body or across the midline. For example, abduction is raising the arm at the shoulder joint, moving it laterally away from the body, while adduction brings the arm down to the side of the body. Similarly, abduction and adduction at the wrist moves the hand away from or toward the midline of the body. Spreading the fingers or toes apart is also abduction, while bringing the fingers or toes together is adduction. For the thumb, abduction is the anterior movement that brings the thumb to a 90° perpendicular position, pointing straight out from the palm. Adduction moves the thumb back to the anatomical position, next to the index finger. Abduction and adduction movements are seen at condyloid, saddle, and ball-and-socket joints (Figure $8.6.1.e$) .

Circumduction

Circumduction is the movement of a body region in a circular manner, in which one end of the body region being moved stays relatively stationary while the other end describes a circle. It involves the sequential combination of flexion, adduction, extension, and abduction at a joint. This type of motion is found at biaxial condyloid and saddle joints, and at multiaxial ball-and-sockets joints (Figure $8.6.1.e$).

Rotation

Rotation can occur within the vertebral column, at a pivot joint, or at a ball-and-socket joint. Rotation of the neck or body is the twisting movement produced by the summation of the small rotational movements available between adjacent vertebrae. At a pivot joint, one bone rotates in relation to another bone. This is a uniaxial joint, and thus rotation is the only motion allowed at a pivot joint. For example, at the atlantoaxial joint, the first cervical (C1) vertebra (atlas) rotates around the dens, the upward projection from the second cervical (C2) vertebra (axis). This allows the head to rotate from side to side as when shaking the head "no." The proximal radioulnar joint is a pivot joint formed by the head of the radius and its articulation with the ulna. This joint allows for the radius to rotate along its length during pronation and supination movements of the forearm (Figure $8.6.1.f$).

Rotation can also occur at the ball-and-socket joints of the shoulder and hip. Here, the humerus and femur rotate around their long axis, which moves the anterior surface of the arm or thigh either toward or away from the midline of the body. Movement that brings the anterior surface of the limb toward the midline of the body is called **medial (internal) rotation**. Conversely, rotation of the limb so that the anterior surface moves away from the midline is **lateral (external) rotation** (Figure $8.6.1.f$). Be sure to distinguish medial and lateral rotation, which can only occur at the multiaxial shoulder and hip joints, from circumduction, which can occur at either biaxial or multiaxial joints.

Supination and Pronation

Supination and pronation are movements of the forearm. In the anatomical position, the upper limb is held next to the body with the palm facing forward. This is the **supinated position** of the forearm. In this position, the radius and ulna are parallel to each other. When the palm of the hand faces backward, the forearm is in the **pronated position**, and the radius and ulna form an X-shape.

Supination and pronation are the movements of the forearm that go between these two positions. **Pronation** is the motion that moves the forearm from the supinated (anatomical) position to the pronated (palm backward) position. This motion is produced by rotation of the radius at the proximal radioulnar joint, accompanied by movement of the radius at the distal radioulnar joint. The proximal radioulnar joint is a pivot joint that allows for rotation of the head of the radius. Because of the slight curvature of the shaft of the radius, this rotation causes the distal end of the radius to cross over the distal ulna at the distal radioulnar joint. This crossing over brings the radius and ulna into an X-shape position. **Supination** is the opposite motion, in which rotation of the radius returns the bones to their parallel positions and moves the palm to the anterior facing (supinated) position (Figure $8.6.1.f$).

Dorsiflexion and Plantar Flexion

Dorsiflexion and **plantar flexion** are movements at the ankle joint, which is a hinge joint. Lifting the front of the foot, so that the top of the foot moves toward the anterior leg is dorsiflexion, while lifting the heel of the foot from the ground or pointing the toes downward is plantar flexion. These are the only movements available at the ankle joint (Figure $8.6.2.h$).

Inversion and Eversion

Inversion and eversion are complex movements that involve the multiple plane joints among the tarsal bones of the posterior foot (intertarsal joints) and thus are not motions that take place at the ankle joint. **Inversion** is the turning of the foot to angle the bottom of the foot toward the midline, while **eversion** turns the bottom of the foot away from the midline. The foot has a greater range of inversion than eversion motion. These are important motions that help to stabilize the foot when walking or running on an uneven surface and aid in the quick side-to-side changes in direction used during active sports such as basketball, racquetball, or soccer (Figure $8.6.2.i$) .

Protraction and Retraction

Protraction and **retraction** are anterior-posterior movements of the scapula or mandible. Protraction of the scapula occurs when the shoulder is moved forward, as when pushing against something or throwing a ball. Retraction is the opposite motion, with the scapula being pulled posteriorly and medially, toward the vertebral column. For the mandible, protraction occurs when the lower jaw is pushed forward, to stick out the chin, while retraction pulls the lower jaw backward. (Figure $8.6.2.j$).

Depression and Elevation

Depression and **elevation** are downward and upward movements of the scapula or mandible. The upward movement of the scapula and shoulder is elevation, while a downward movement is depression. These movements are used to shrug your shoulders. Similarly, elevation of the mandible is the upward movement of the lower jaw used to close the mouth or bite on something, and depression is the downward movement that produces opening of the mouth (Figure $8.6.2.k$) .

Excursion

Excursion is the side to side movement of the mandible. **Lateral excursion** moves the mandible away from the midline, toward either the right or left side. **Medial excursion** returns the mandible to its resting position at the midline.

Superior Rotation and Inferior Rotation

Superior and inferior rotation are movements of the scapula and are defined by the direction of movement of the glenoid cavity. These motions involve rotation of the scapula around a point inferior to the scapular spine and are produced by combinations of muscles acting on the scapula. During **superior rotation**, the glenoid cavity moves upward as the medial end of the scapular spine moves downward. This is a very important motion that contributes to upper limb abduction. Without superior rotation of the scapula, the greater tubercle of the humerus would hit the acromion of the scapula, thus preventing any abduction of the arm above shoulder height. Superior rotation of the scapula is thus required for full abduction of the upper limb. Superior rotation is also used without arm abduction when carrying a heavy load with your hand or on your shoulder. You can feel this rotation when you pick up a load, such as a heavy book bag and carry it on only one shoulder. To increase its weight-bearing support for the bag, the shoulder lifts as the scapula superiorly rotates. **Inferior rotation** occurs during limb adduction and involves the downward motion of the glenoid cavity with upward movement of the medial end of the scapular spine.

Opposition and Reposition

Opposition is the thumb movement that brings the tip of the thumb in contact with the tip of a finger. This movement is produced at the first carpometacarpal joint, which is a saddle joint formed between the trapezium carpal bone and the first metacarpal bone. Thumb opposition is produced by a combination of flexion and abduction of the thumb at this joint. Returning the thumb to its anatomical position next to the index finger is called **reposition** (Figure $8.6.2.l$).

Table 8.6.1: Synovial Joint Movements

Type of Joint	Movement	Example
Pivot	Uniaxial joint; allows rotational movement	Atlantoaxial joint (C1–C2 vertebrae articulation); proximal radioulnar joint
Hinge	Uniaxial joint; allows flexion/extension movements	Knee; elbow; ankle; interphalangeal joints of fingers and toes
Condyloid	Biaxial joint; allows flexion/extension, abduction/adduction, and circumduction movements	Metacarpophalangeal (knuckle) joints of fingers; radiocarpal joint of wrist; metatarsophalangeal joints for toes
Saddle	Biaxial joint; allows flexion/extension, abduction/adduction, and circumduction movements	First carpometacarpal joint of the thumb; sternoclavicular joint
Plane	Multiaxial joint; allows inversion and eversion of foot, or flexion, extension, and lateral flexion of the vertebral column	Intertarsal joints of foot; superior-inferior articular process articulations between vertebrae
Ball-and-socket	Multiaxial joint; allows flexion/extension, abduction/adduction, circumduction, and medial/lateral rotation movements	Shoulder and hip joints

Concept Review

The variety of movements provided by the different types of synovial joints allows for a large range of body motions and gives you tremendous mobility. These movements allow you to flex or extend your body or limbs, medially rotate and adduct your arms and flex your elbows to hold a heavy object against your chest, raise your arms above your head, rotate or shake your head, and bend to touch the toes (with or without bending your knees).

Each of the different structural types of synovial joints also allow for specific motions. The atlantoaxial pivot joint provides side-to-side rotation of the head, while the proximal radioulnar articulation allows for rotation of the radius during pronation and supination of the forearm. Hinge joints, such as at the knee and elbow, allow only for flexion and extension. Similarly, the hinge joint of the ankle only allows for dorsiflexion and plantar flexion of the foot.

Condyloid and saddle joints are biaxial. These allow for flexion and extension, and abduction and adduction. The sequential combination of flexion, adduction, extension, and abduction produces circumduction. Multiaxial plane joints provide for only small motions, but these can add together over several adjacent joints to produce body movement, such as inversion and eversion of the foot. Similarly, plane joints allow for flexion, extension, and lateral flexion movements of the vertebral column. The multiaxial ball and socket joints allow for flexion-extension, abduction-adduction, and circumduction. In addition, these also allow for medial (internal) and lateral (external) rotation. Ball-and-socket joints have the greatest range of motion of all synovial joints.

Review Questions

Q. The joints between the articular processes of adjacent vertebrae can contribute to which movement?

A. lateral flexion

B. circumduction

C. dorsiflexion

D. abduction

Answer

Answer: A

Q. Which motion moves the bottom of the foot away from the midline of the body?

A. elevation

B. dorsiflexion

C. eversion

D. plantar flexion

Answer

Answer: C

Q. Movement of a body region in a circular movement at a condyloid joint is what type of motion?

A. rotation

B. elevation

C. abduction

D. circumduction

Answer

Answer: D

Q. Supination is the motion that moves the _____.

A. hand from the palm backward position to the palm forward position

B. foot so that the bottom of the foot faces the midline of the body

C. hand from the palm forward position to the palm backward position

D. scapula in an upward direction

Answer

Answer: A

Q. Movement at the shoulder joint that moves the upper limb laterally away from the body is called _____.

A. elevation

B. eversion

C. abduction

D. lateral rotation

Answer

Answer: C

Critical Thinking Questions

Q. Briefly define the types of joint movements available at a ball-and-socket joint.

Answer

A. Ball-and-socket joints are multiaxial joints that allow for flexion and extension, abduction and adduction, circumduction, and medial and lateral rotation.

Q. Discuss the joints involved and movements required for you to cross your arms together in front of your chest.

Answer

A. To cross your arms, you need to use both your shoulder and elbow joints. At the shoulder, the arm would need to flex and medially rotate. At the elbow, the forearm would need to be flexed.

Glossary

abduction
movement in the coronal plane that moves a limb laterally away from the body; spreading of the fingers

adduction
movement in the coronal plane that moves a limb medially toward or across the midline of the body; bringing fingers together

circumduction
circular motion of the arm, thigh, hand, thumb, or finger that is produced by the sequential combination of flexion, abduction, extension, and adduction

depression
downward (inferior) motion of the scapula or mandible

dorsiflexion
movement at the ankle that brings the top of the foot toward the anterior leg

elevation
upward (superior) motion of the scapula or mandible

eversion
foot movement involving the intertarsal joints of the foot in which the bottom of the foot is turned laterally, away from the midline

extension
movement in the sagittal plane that increases the angle of a joint (straightens the joint); motion involving posterior bending of the vertebral column or returning to the upright position from a flexed position

flexion
movement in the sagittal plane that decreases the angle of a joint (bends the joint); motion involving anterior bending of the vertebral column

hyperextension
excessive extension of joint, beyond the normal range of movement

hyperflexion
excessive flexion of joint, beyond the normal range of movement

inferior rotation
movement of the scapula during upper limb adduction in which the glenoid cavity of the scapula moves in a downward direction as the medial end of the scapular spine moves in an upward direction

inversion
foot movement involving the intertarsal joints of the foot in which the bottom of the foot is turned toward the midline

lateral excursion
side-to-side movement of the mandible away from the midline, toward either the right or left side

lateral flexion
bending of the neck or body toward the right or left side

lateral (external) rotation
movement of the arm at the shoulder joint or the thigh at the hip joint that moves the anterior surface of the limb away from the midline of the body

medial excursion
side-to-side movement that returns the mandible to the midline

medial (internal) rotation
movement of the arm at the shoulder joint or the thigh at the hip joint that brings the anterior surface of the limb toward the midline of the body

opposition
thumb movement that brings the tip of the thumb in contact with the tip of a finger

plantar flexion
foot movement at the ankle in which the heel is lifted off of the ground

pronated position
forearm position in which the palm faces backward

pronation
forearm motion that moves the palm of the hand from the palm forward to the palm backward position

protraction
anterior motion of the scapula or mandible

reposition
movement of the thumb from opposition back to the anatomical position (next to index finger)

retraction
posterior motion of the scapula or mandible

rotation
movement of a bone around a central axis (atlantoaxial joint) or around its long axis (proximal radioulnar joint; shoulder or hip joint); twisting of the vertebral column resulting from the summation of small motions between adjacent vertebrae

superior rotation
movement of the scapula during upper limb abduction in which the glenoid cavity of the scapula moves in an upward direction as the medial end of the scapular spine moves in a downward direction

supinated position
forearm position in which the palm faces anteriorly (anatomical position)

supination
forearm motion that moves the palm of the hand from the palm backward to the palm forward position

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8.7: Anatomy of Selected Synovial Joints

By the end of this section, you will be able to:

- Describe the bones that articulate together to form selected synovial joints
- Discuss the movements available at each joint
- Describe the structures that support and prevent excess movements at each joint

Each synovial joint of the body is specialized to perform certain movements. The movements that are allowed are determined by the structural classification for each joint. For example, a multiaxial ball-and-socket joint has much more mobility than a uniaxial hinge joint. However, the ligaments and muscles that support a joint may place restrictions on the total range of motion available. Thus, the ball-and-socket joint of the shoulder has little in the way of ligament support, which gives the shoulder a very large range of motion. In contrast, movements at the hip joint are restricted by strong ligaments, which reduce its range of motion but confer stability during standing and weight bearing.

This section will examine the anatomy of selected synovial joints of the body. Anatomical names for most joints are derived from the names of the bones that articulate at that joint, although some joints, such as the elbow, hip, and knee joints are exceptions to this general naming scheme.

Articulations of the Vertebral Column

In addition to being held together by the intervertebral discs, adjacent vertebrae also articulate with each other at synovial joints formed between the superior and inferior articular processes called **zygapophysial joints** (facet joints). These are plane joints that provide for only limited motions between the vertebrae. The orientation of the articular processes at these joints varies in different regions of the vertebral column and serves to determine the types of motions available in each vertebral region. The cervical and lumbar regions have the greatest ranges of motions.

In the neck, the articular processes of cervical vertebrae are flattened and generally face upward or downward. This orientation provides the cervical vertebral column with extensive ranges of motion for flexion, extension, lateral flexion, and rotation. In the thoracic region, the downward projecting and overlapping spinous processes, along with the attached thoracic cage, greatly limit flexion, extension, and lateral flexion. However, the flattened and vertically positioned thoracic articular processes allow for the greatest range of rotation within the vertebral column. The lumbar region allows for considerable extension, flexion, and lateral flexion, but the orientation of the articular processes largely prohibits rotation.

The articulations formed between the skull, the atlas (C1 vertebra), and the axis (C2 vertebra) differ from the articulations in other vertebral areas and play important roles in movement of the head. The **atlanto-occipital joint** is formed by the articulations between the superior articular processes of the atlas (Figure 8.7.1) and the occipital condyles on the base of the skull. This articulation has a pronounced U-shaped curvature, oriented along the anterior-posterior axis. This allows the skull to rock forward and backward, producing flexion and extension of the head. This moves the head up and down, as when shaking your head “yes.”

The **atlantoaxial joint**, between the atlas and axis, consists of three articulations. The paired superior articular processes of the axis articulate with the inferior articular processes of the atlas. These articulating surfaces are relatively flat and oriented horizontally. The third articulation is the pivot joint formed between the dens, which projects upward from the body of the axis, and the inner aspect of the anterior arch of the atlas (Figure 8.7.1). The strong transverse ligament passes posterior to the dens to hold it in position against the anterior arch. These articulations allow the atlas to rotate on top of the axis, moving the head toward the right or left, as when shaking your head “no.”

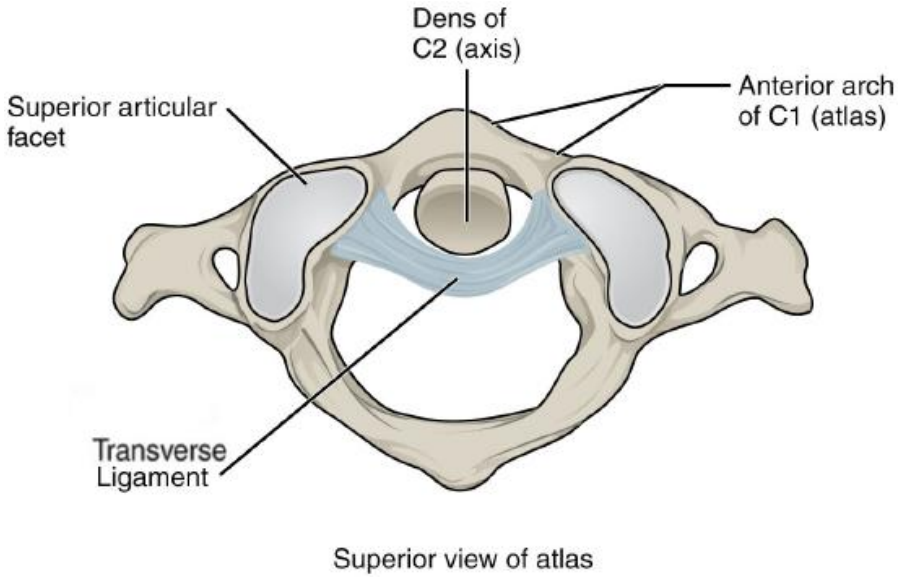

Figure 8.7.1: Atlantoaxial Joint. The atlantoaxial joint is a pivot type of joint between the dens portion of the axis (C2 vertebra) and the anterior arch of the atlas (C1 vertebra), with the dens held in place by a ligament. (Image Credit: "Atlantoaxial Joint" by Whitney Menefee is licensed under CC BY 4.0 / A derivative from the original work)

Temporomandibular Joint

The **temporomandibular joint (TMJ)** is the joint that allows for opening (mandibular depression) and closing (mandibular elevation) of the mouth, as well as lateral/medial excursion and protraction/retraction motions of the lower jaw. This joint involves the articulation between the mandibular fossa and articular tubercle of the temporal bone, with the condyle (head) of the mandible. Located between these bony structures within the joint cavity, filling the gap between the skull and mandible, is a flexible articular disc (Figure 8.7.2) . This disc serves to smooth the movements between the temporal bone and mandibular condyle.

Movement at the TMJ during opening and closing of the mouth involves both gliding and hinge motions of the mandible. With the mouth closed, the mandibular condyle and articular disc are located within the mandibular fossa of the temporal bone. During opening of the mouth, the mandible hinges downward and at the same time is pulled anteriorly, causing both the condyle and the articular disc to glide forward from the mandibular fossa onto the downward projecting articular tubercle. The net result is a forward and downward motion of the condyle and mandibular depression. The temporomandibular joint is supported by an extrinsic ligament that anchors the mandible to the skull. This ligament spans the distance between the base of the skull and the lingula on the medial side of the mandibular ramus.

Dislocation of the TMJ may occur when opening the mouth too wide (such as when taking a large bite) or following a blow to the jaw, resulting in the mandibular condyle moving beyond (anterior to) the articular tubercle. In this case, the individual would not be able to close their mouth. Temporomandibular joint disorder is a painful condition that may arise due to arthritis, wearing of the articular cartilage covering the bony surfaces of the joint, muscle fatigue from overuse or grinding of the teeth, damage to the articular disc within the joint, or jaw injury. Temporomandibular joint disorders can also cause headache, difficulty chewing, or even the inability to move the jaw (lock jaw). Pharmacologic agents for pain or other therapies, including bite guards, are used as treatments.

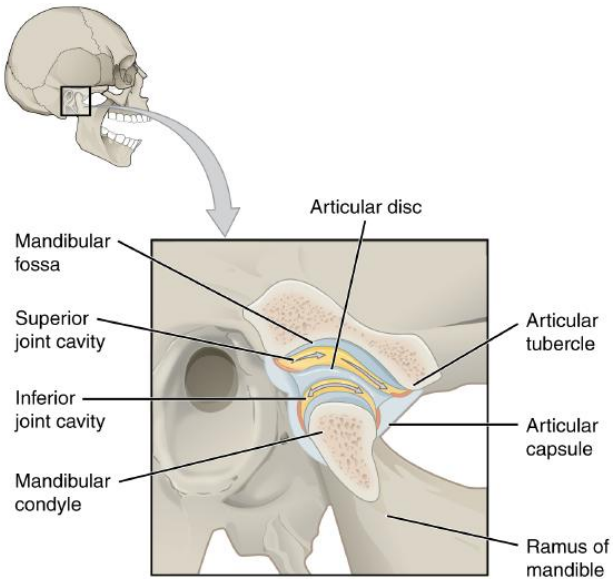

Figure 8.7.2: Temporomandibular Joint. The temporomandibular joint is the articulation between the temporal bone of the skull and the condyle of the mandible, with an articular disc located between these bones. During depression of the mandible (opening of the mouth), the mandibular condyle moves both forward and hinges downward as it travels from the mandibular fossa onto the articular tubercle. (Image credit: "Tempomandibular Joint" by OpenStax is licensed under CC BY 3.0)

Shoulder Joint

The shoulder joint is called the **glenohumeral joint**. This is a ball-and-socket joint formed by the articulation between the head of the humerus and the glenoid cavity of the scapula (Figure 8.7.3) . This joint has the largest range of motion of any joint in the body. However, this freedom of movement is due to the lack of structural support and thus the enhanced mobility is offset by a loss of stability.

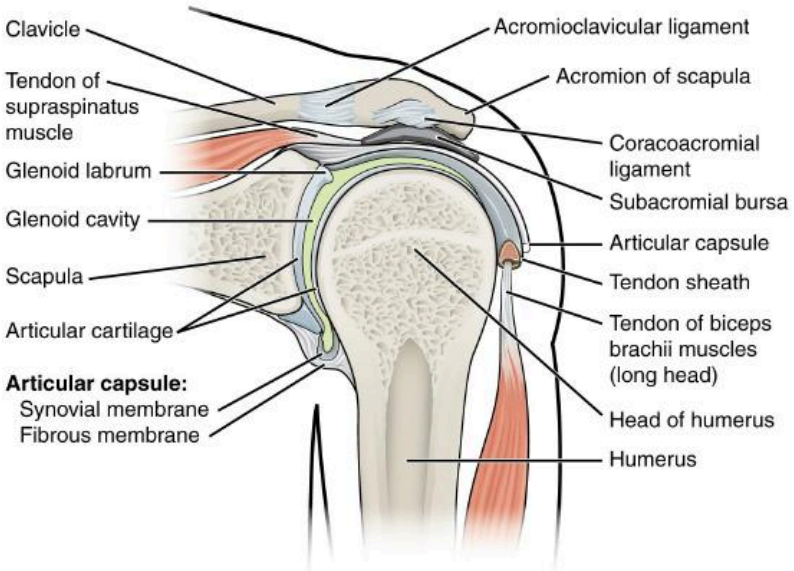

Figure 8.7.3: Glenohumeral Joint. The glenohumeral (shoulder) joint is a ball-and-socket joint that provides the widest range of motions. It has a loose articular capsule and is supported by ligaments and the rotator cuff muscles. (Image credit: "Shoulder Joint" by Whitney Menefee is licensed under CC BY 4.0 / A derivative from the original work)

The large range of motions at the shoulder joint is provided by the articulation of the large, rounded humeral head with the small and shallow glenoid cavity, which is only about one third of the size of the humeral head. Both of these structures are lined with articular cartilage. The socket formed by the glenoid cavity is deepened slightly by a small lip of fibrocartilage called the **glenoid labrum**, which extends around the outer margin of the cavity. The articular capsule that surrounds the glenohumeral

joint is composed of a synovial membrane lined by a fibrous membrane and is relatively thin and loose to allow for large motions of the upper limb. Some structural support for the joint is provided by thickenings of the articular capsule wall that form weak intrinsic ligaments. These include the **coracohumeral ligament**, running from the coracoid process of the scapula to the anterior humerus, and three ligaments, each called a **glenohumeral ligament**, located on the anterior side of the articular capsule. These ligaments help to strengthen the superior and anterior capsule walls. An accessory ligament to the joint is the **coracoacromial ligament**, which attaches the corocoid process of the scapula to the acromion, and serves to prevent the head of the humerus from being displaced superiorly.

However, the primary support for the shoulder joint is provided by muscles crossing the joint, particularly the four rotator cuff muscles. These muscles (supraspinatus, infraspinatus, teres minor, and subscapularis) arise from the scapula and attach to the greater or lesser tubercles of the humerus. As these muscles cross the shoulder joint, their tendons encircle the head of the humerus and become fused to the anterior, superior, and posterior walls of the articular capsule. The thickening of the capsule formed by the fusion of these four muscle tendons is called the **rotator cuff**. Another muscle associated with the shoulder joint is the biceps brachii muscle. While it is not part of the rotator cuff, the tendon of the long head of the biceps brachii muscle, which is surrounded by a tendon sheath for protection within the joint, attaches to the glenoid labrum. Because of this association, any damage to the glenoid labrum typically results in damage or tearing of the biceps brachii tendon.

Two bursae, the **subacromial bursa** and the **subscapular bursa**, help to prevent friction between the rotator cuff muscle tendons and the scapula as these tendons cross the glenohumeral joint. In addition to their individual actions of moving the upper limb, the rotator cuff muscles also serve to hold the head of the humerus in position within the glenoid cavity. By constantly adjusting their strength of contraction to resist forces acting on the shoulder, these muscles serve as “dynamic ligaments” and thus provide the primary structural support for the glenohumeral joint.

Injuries to the shoulder joint are common. Repetitive use of the upper limb, particularly in abduction such as during throwing, swimming, or racquet sports, may lead to acute or chronic inflammation of the bursa or muscle tendons, a tear of the glenoid labrum, or degeneration or tears of the rotator cuff. Because the humeral head is strongly supported by muscles and ligaments around its anterior, superior, and posterior aspects, most dislocations of the humerus occur in an inferior direction. This can occur when force is applied to the humerus when the upper limb is fully abducted, as when diving to catch a baseball and landing on your hand or elbow. Inflammatory responses to any shoulder injury can lead to the formation of scar tissue between the articular capsule and surrounding structures, thus reducing shoulder mobility, a condition called adhesive capsulitis (“frozen shoulder”).

Interactive Link

Shoulder Joint

QR Code representing a URL

Watch this video on the anatomy of the shoulder joint. What movements are available at the shoulder joint?

Answer available at the end of this section.

Elbow Joint

The **elbow joint** is a uniaxial hinge joint formed by the **humeroulnar joint**, the articulation between the trochlea of the humerus and the trochlear notch of the ulna. Also associated with the elbow are the **humeroradial joint** and the **proximal radioulnar joint**. All three of these joints are enclosed within a single articular capsule (Figure 8.7.4) .

The articular capsule of the elbow is thin on its anterior and posterior aspects, but is thickened along its outside margins by strong intrinsic ligaments. These ligaments prevent side-to-side movements and hyperextension. On the medial side is the triangular **ulnar collateral ligament**. This arises from the medial epicondyle of the humerus and attaches to the coronoid process on the medial side of the proximal ulna. The strongest part of this ligament is the anterior portion, which resists hyperextension of the elbow. The ulnar collateral ligament may be injured by frequent, forceful extensions of the forearm, as is seen in baseball pitchers. Reconstructive surgical repair of this ligament is referred to as Tommy John surgery, named for the former major league pitcher who was the first person to have this treatment.

The lateral side of the elbow is supported by the **radial collateral ligament**. This arises from the lateral epicondyle of the humerus and then blends into the lateral side of the annular ligament. The **annular ligament** encircles the head of the radius.

This ligament supports the head of the radius as it articulates with the radial notch of the ulna at the proximal radioulnar joint. This is a pivot joint that allows for rotation of the radius during supination and pronation of the forearm.

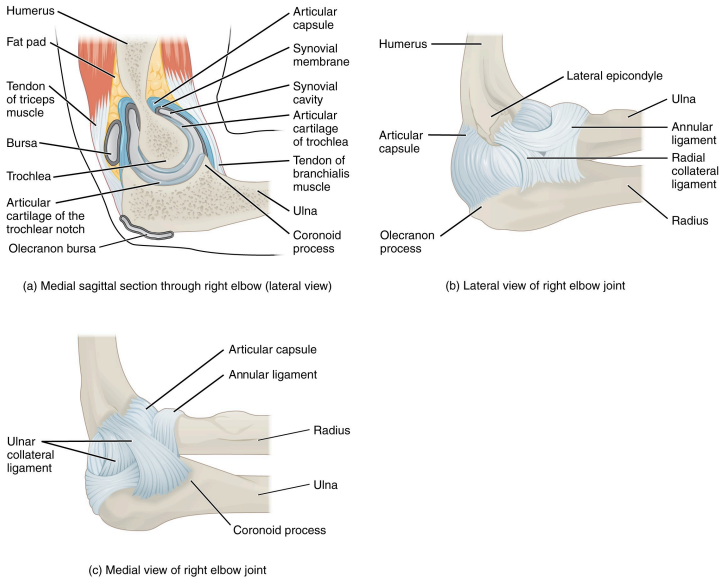

Figure 8.7.4: Elbow Joint. (a) The elbow is a hinge joint that allows only for flexion and extension of the forearm. (b) It is supported by the ulnar and radial collateral ligaments. (c) The annular ligament supports the head of the radius at the proximal radioulnar joint, the pivot joint that allows for rotation of the radius. (Image credit: "Elbow Joint" by Whitney Menefee is licensed under CC BY 4.0 / A derivative from the original work)

Hip Joint

The **hip joint**, or the coxafemoral joint, is a multiaxial ball-and-socket joint between the head of the femur and the acetabulum of the hip bone (Figure 8.7.5). The hip carries the weight of the body and thus requires strength and stability during standing and walking. For these reasons, its range of motion is more limited than that of the shoulder joint.

The acetabulum is the socket portion of the hip joint. This space is deep and has a large articulation area for the femoral head, thus giving stability and weight bearing ability to the joint. The acetabulum is further deepened by the **acetabular labrum**, a fibrocartilage lip attached to the outer margin of the acetabulum. The surrounding articular capsule is strong, with several thickened areas forming intrinsic ligaments. These ligaments arise from the hip bone, at the margins of the acetabulum, and attach to the femur at the base of the neck. The ligaments are the **iliofemoral ligament**, **pubofemoral ligament**, and **ischiofemoral ligament**, all of which spiral around the head and neck of the femur. The ligaments are tightened by extension at the hip, thus pulling the head of the femur tightly into the acetabulum when in the upright, standing position. Very little additional extension of the thigh is permitted beyond this vertical position. These ligaments thus stabilize the hip joint and allow you to maintain an upright standing position with only minimal muscle contraction. Inside of the articular capsule, the **ligament of the head of the femur** (ligamentum teres) spans between the acetabulum and femoral head. This intracapsular ligament is normally slack and does not provide any significant joint support, but it does provide a pathway for an important artery that supplies the head of the femur.

The hip is prone to osteoarthritis, and thus was the first joint for which a replacement prosthesis was developed. A common injury in elderly individuals, particularly those with weakened bones due to osteoporosis, is a “broken hip,” which is actually a fracture of the femoral neck. This may result from a fall, or it may cause the fall. This can happen as one lower limb is taking a step and all of the body weight is placed on the other limb, causing the femoral neck to break and producing a fall. Any accompanying disruption of the blood supply to the femoral neck or head can lead to necrosis of these areas, resulting in bone and cartilage death. Femoral fractures usually require surgical treatment, after which the patient will need mobility assistance for a prolonged period, either from family members or in a long-term care facility. Consequentially, the associated health care costs of “broken hips” are substantial. In addition, hip fractures are associated with increased rates of morbidity (incidences of disease) and mortality (death). Surgery for a hip fracture followed by prolonged bed rest may lead to life-threatening complications, including pneumonia, infection of pressure ulcers (bedsores), and thrombophlebitis (deep vein thrombosis; blood clot formation) that can result in a pulmonary embolism (blood clot within the lung).

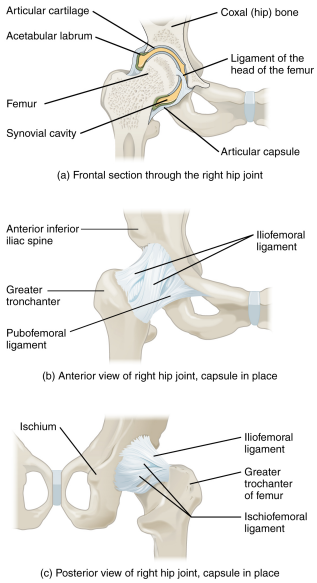

Figure 8.7.5: Hip Joint. (a) The ball-and-socket joint of the hip is a multiaxial joint that provides both stability and a wide range of motion. (b–c) When standing, the supporting ligaments are tight, pulling the head of the femur into the acetabulum. (Image credit: "Hip Joint" by OpenStax is licensed under CC BY 3.0)

Interactive Link

Hip Joint 1

QR Code representing a URL

Watch this video on the anatomy of the hip joint. What is a possible consequence following a fracture of the femoral neck within the capsule of the hip joint?

Answer available at the end of this section.

Knee Joint

The knee joint is the largest joint of the body (Figure 8.7.6) . It actually consists of three articulations. The **femoropatellar joint** is found between the patella and the distal femur. The **medial tibiofemoral joint** and **lateral tibiofemoral joint** are located between the medial and lateral condyles of the femur and the medial and lateral condyles of the tibia. All of these articulations are enclosed within a single articular capsule. The knee functions as a hinge joint, allowing flexion and extension of the leg. This action is generated by both rolling and gliding motions of the femur on the tibia. In addition, some rotation of the leg is available when the knee is flexed, but not when extended. The knee is well constructed for weight bearing in its extended position, but is vulnerable to injuries associated with hyperextension, twisting, or blows to the medial or lateral side of the joint, particularly while weight bearing.

At the femoropatellar joint, the patella slides vertically within a groove on the distal femur. The patella is a sesamoid bone incorporated into the tendon of the quadriceps femoris muscle, the large muscle of the anterior thigh. The patella serves to protect the quadriceps tendon from friction against the distal femur. Continuing from the patella to the anterior tibia just below the knee is the **patellar ligament**. Acting via the patella and patellar ligament, the quadriceps femoris is a powerful muscle that acts to extend the leg at the knee. It also serves as a “dynamic ligament” to provide very important support and stabilization for the knee joint. Surrounding the patella are the **medial patellar retinaculum** and **lateral patellar retinaculum**. Each of these structures are a thick layer of dense fibrous connective tissue that work to maintain the position of the patella in relation to the femur.

The medial and lateral tibiofemoral joints are the articulations between the rounded condyles of the femur and the relatively flat condyles of the tibia. During flexion and extension motions, the condyles of the femur both roll and glide over the surfaces of the tibia. The rolling action produces flexion or extension, while the gliding action serves to maintain the femoral condyles centered

over the tibial condyles, thus ensuring maximal bony, weight-bearing support for the femur in all knee positions. As the knee comes into full extension, the femur undergoes a slight medial rotation in relation to tibia. The rotation results because the lateral condyle of the femur is slightly smaller than the medial condyle. Thus, the lateral condyle finishes its rolling motion first, followed by the medial condyle. The resulting small medial rotation of the femur serves to “lock” the knee into its fully extended and most stable position. Flexion of the knee is initiated by a slight lateral rotation of the femur on the tibia, which “unlocks” the knee. This lateral rotation motion is produced by the popliteus muscle of the posterior leg.

Located between the articulating surfaces of the femur and tibia are two articular discs, the **medial meniscus** and **lateral meniscus** (Figure $8.7.6.b$) . Each is a C-shaped fibrocartilage structure that is thin along its inside margin and thick along the outer margin. They are attached to their tibial condyles, but do not attach to the femur. While both menisci are free to move during knee motions, the medial meniscus shows less movement because it is anchored at its outer margin to the articular capsule and tibial collateral ligament. The menisci provide padding between the bones and help to fill the gap between the round femoral condyles and flattened tibial condyles. Some areas of each meniscus lack an arterial blood supply and thus these areas heal poorly if damaged.

The knee joint has multiple ligaments that provide support, particularly in the extended position (Figure $8.7.6.c$) . Outside of the articular capsule, located at the sides of the knee, are two extrinsic ligaments. The **fibular collateral ligament** (lateral collateral ligament) is on the lateral side and spans from the lateral epicondyle of the femur to the head of the fibula. The **tibial collateral ligament** (medial collateral ligament) of the medial knee runs from the medial epicondyle of the femur to the medial tibia. As it crosses the knee, the tibial collateral ligament is firmly attached on its deep side to the articular capsule and to the medial meniscus, an important factor when considering knee injuries. In the fully extended knee position, both collateral ligaments are taut (tight), thus serving to stabilize and support the extended knee and preventing side-to-side or rotational motions between the femur and tibia.

The articular capsule of the posterior knee is thickened by intrinsic ligaments that help to resist knee hyperextension. Inside the knee are two intracapsular ligaments, the **anterior cruciate ligament** and **posterior cruciate ligament**. These ligaments are anchored inferiorly to the tibia at the intercondylar eminence, the roughened area between the tibial condyles. The cruciate ligaments are named for whether they are attached anteriorly or posteriorly to this tibial region. Each ligament runs diagonally upward to attach to the inner aspect of a femoral condyle. The cruciate ligaments are named for the X-shape formed as they pass each other (cruciate means “cross”). The posterior cruciate ligament is the stronger ligament. It serves to support the knee when it is flexed and weight bearing, as when walking downhill. In this position, the posterior cruciate ligament prevents the femur from sliding anteriorly off the top of the tibia. The anterior cruciate ligament becomes tight when the knee is extended, and thus resists hyperextension.

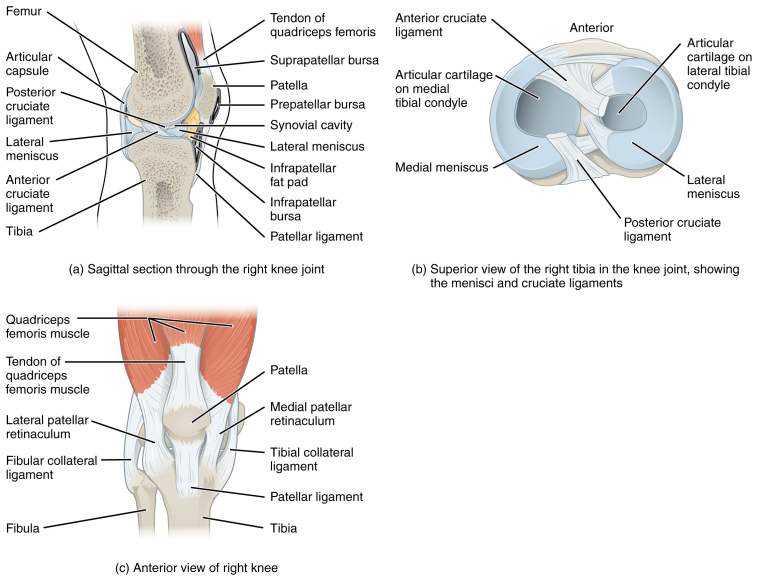

Figure $8.7.6$: Knee Joint. (a) The knee joint is the largest joint of the body. (b)–(c) It is supported by the tibial and fibular collateral ligaments located on the sides of the knee outside of the articular capsule, and the anterior and posterior cruciate ligaments found inside the capsule. The medial and lateral menisci provide padding and support between the femoral condyles and tibial condyles. (Image credit: "Knee Joint" by OpenStax is licensed under CC BY 3.0)

DISORDERS OF THE...

Joints

Injuries to the knee are common. Since this joint is primarily supported by muscles and ligaments, injuries to any of these structures will result in pain or knee instability. Injury to the posterior cruciate ligament occurs when the knee is flexed and the tibia is driven posteriorly, such as falling and landing on the tibial tuberosity or hitting the tibia on the dashboard when not wearing a seatbelt during an automobile accident. More commonly, injuries occur when forces are applied to the extended knee, particularly when the foot is planted and unable to move. Anterior cruciate ligament injuries can result with a forceful blow to the anterior knee, producing hyperextension, or when a runner makes a quick change of direction that produces both twisting and hyperextension of the knee.

A worse combination of injuries can occur with a hit to the lateral side of the extended knee (Figure 8.7.7) . A moderate blow to the lateral knee will cause the medial side of the joint to open, resulting in stretching or damage to the tibial collateral ligament. Because the medial meniscus is attached to the tibial collateral ligament, a stronger blow can tear the ligament and also damage the medial meniscus. This is one reason that the medial meniscus is 20 times more likely to be injured than the lateral meniscus. A powerful blow to the lateral knee produces a “terrible triad” injury, in which there is a sequential injury to the tibial collateral ligament, medial meniscus, and anterior cruciate ligament.

Arthroscopic surgery has greatly improved the surgical treatment of knee injuries and reduced subsequent recovery times. This procedure involves a small incision and the insertion into the joint of an arthroscope, a pencil-thin instrument that allows for visualization of the joint interior. Small surgical instruments are also inserted via additional incisions. These tools allow a surgeon to remove or repair a torn meniscus or to reconstruct a ruptured cruciate ligament. The current method for anterior cruciate ligament replacement involves using a portion of the patellar ligament. Holes are drilled into the cruciate ligament attachment points on the tibia and femur, and the patellar ligament graft, with small areas of attached bone still intact at each end, is inserted into these holes. The bone-to-bone sites at each end of the graft heal rapidly and strongly, thus enabling a rapid recovery.

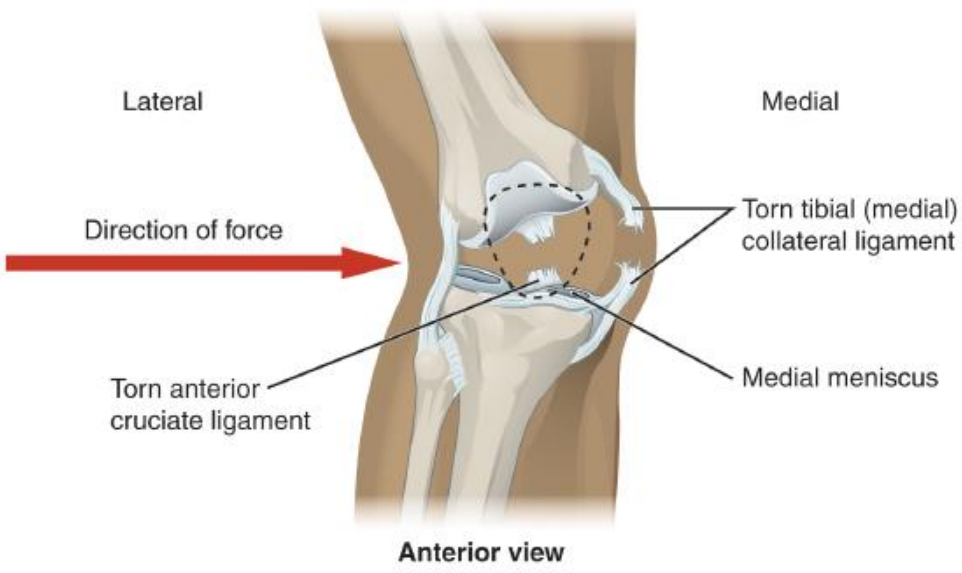

Figure 8.7.7: Knee Injury. A strong blow to the lateral side of the extended knee will cause three injuries, in sequence: tearing of the tibial collateral ligament, damage to the medial meniscus, and rupture of the anterior cruciate ligament. (Image credit: "Knee Injury" by OpenStax is licensed under CC BY 3.0)

Ankle and Foot Joints

The ankle is formed by the **talocrural joint** (Figure 8.7.8) . It consists of the articulations between the talus bone of the foot and the distal ends of the tibia and fibula of the leg (crural = “leg”). The superior aspect of the talus bone is square-shaped and has three areas of articulation. The top of the talus articulates with the inferior tibia. This is the portion of the ankle joint that carries the body weight between the leg and foot. The sides of the talus are firmly held in position by the articulations with the medial

malleolus of the tibia and the lateral malleolus of the fibula, which prevent any side-to-side motion of the talus. The ankle is thus a uniaxial hinge joint that allows only for dorsiflexion and plantar flexion of the foot.

Additional joints between the tarsal bones of the posterior foot allow for the movements of foot inversion and eversion. Most important for these movements is the **subtalar joint**, located between the talus and calcaneus bones. The joints between the talus and navicular bones and the calcaneus and cuboid bones are also important contributors to these movements. All of the joints between tarsal bones are plane joints. Together, the small motions that take place at these joints all contribute to the production of inversion and eversion foot motions and are helpful for maintaining balance.

Like the hinge joints of the elbow and knee, the talocrural joint of the ankle is supported by several strong ligaments located on the sides of the joint. These ligaments extend from the medial malleolus of the tibia or lateral malleolus of the fibula and anchor to the talus and calcaneus bones. Since they are located on the sides of the ankle joint, they allow for dorsiflexion and plantar flexion of the foot. They also prevent abnormal side-to-side and twisting movements of the talus and calcaneus bones during eversion and inversion of the foot. On the medial side is the broad **deltoid ligament,** named for its triangular shape. The deltoid ligament supports the ankle joint and also resists excessive eversion of the foot. The lateral side of the ankle has several smaller ligaments. These include the **anterior talofibular ligament** and the **posterior talofibular ligament**, both of which span between the talus bone and the lateral malleolus of the fibula, and the **calcaneofibular ligament**, located between the calcaneus bone and fibula. These ligaments support the ankle and also resist excess inversion of the foot.

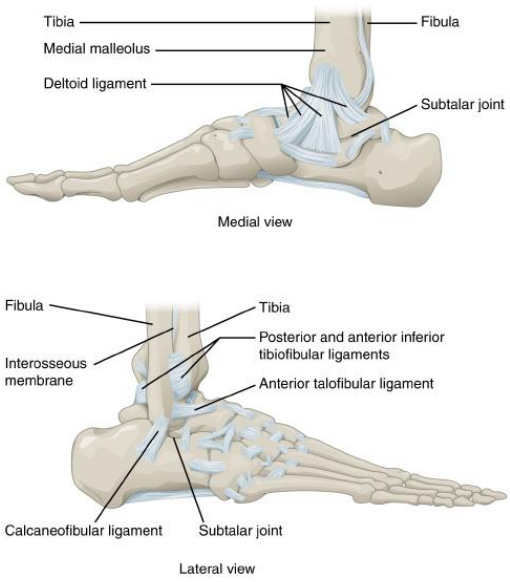

Figure 8.7.8: Ankle Joint. The talocrural (ankle) joint is a uniaxial hinge joint that only allows for dorsiflexion or plantar flexion of the foot. Movements at the subtalar joint, between the talus and calcaneus bones, combined with motions at other intertarsal joints, enables eversion/inversion movements of the foot. Ligaments that unite the medial or lateral malleolus with the talus and calcaneus bones serve to support the talocrural joint and to resist excess eversion or inversion of the foot. (Image credit: "Ankle Feet Joint" by OpenStax is licensed under CC BY 3.0)

Interactive Link

Ankle Joint 1

QR Code representing a URL

Watch this video on the anatomy of the ankle joint. What are the three ligaments found on the lateral side of the ankle joint?

Answer available at the end of this section.

DISORDERS OF THE...

Joints

The ankle is the most frequently injured joint in the body, with the most common injury being an inversion ankle sprain. A sprain is the stretching or tearing of the supporting ligaments. Excess inversion causes the talus bone to tilt laterally, thus damaging the ligaments on the lateral side of the ankle. The anterior talofibular ligament is most commonly injured, followed by the calcaneofibular ligament. In severe inversion injuries, the forceful lateral movement of the talus not only ruptures the lateral ankle ligaments, but also fractures the distal fibula.

Less common are eversion sprains of the ankle, which involve stretching of the deltoid ligament on the medial side of the ankle. Forcible eversion of the foot, for example, with an awkward landing from a jump or when a football player has a foot planted and is hit on the lateral ankle, can result in a Pott's fracture and dislocation of the ankle joint. In this injury, the very strong deltoid ligament does not tear, but instead shears off the medial malleolus of the tibia. This frees the talus, which moves laterally and fractures the distal fibula. In extreme cases, the posterior margin of the tibia may also be sheared off.

Above the ankle, the distal ends of the tibia and fibula are united by a strong syndesmosis formed by the interosseous membrane and ligaments at the distal tibiofibular joint. These connections prevent separation between the distal ends of the tibia and fibula and maintain the talus locked into position between the medial malleolus and lateral malleolus. Injuries that produce a lateral twisting of the leg on top of the planted foot can result in stretching or tearing of the tibiofibular ligaments, producing a syndesmotic ankle sprain or "high ankle sprain."

Most ankle sprains can be treated using the RICE technique: Rest, Ice, Compression, and Elevation. Reducing joint mobility using a brace or cast may be required for a period of time. More severe injuries involving ligament tears or bone fractures may require surgery.

Concept Review

Although synovial joints share many common features, each joint of the body is specialized for certain movements and activities. The joints of the upper limb provide for large ranges of motion, which give the upper limb great mobility, thus enabling actions such as the throwing of a ball or typing on a keyboard. The joints of the lower limb are more robust, giving them greater strength and the stability needed to support the body weight during running, jumping, or kicking activities.

The joints of the vertebral column include the symphysis joints formed by each intervertebral disc and the plane synovial joints between the superior and inferior articular processes of adjacent vertebrae. Each of these joints provide for limited motions, but these sum together to produce flexion, extension, lateral flexion, and rotation of the neck and body. The range of motions available in each region of the vertebral column varies, with all of these motions available in the cervical region. Only rotation is allowed in the thoracic region, while the lumbar region has considerable extension, flexion, and lateral flexion, but rotation is prevented. The atlanto-occipital joint allows for flexion and extension of the head, while the atlantoaxial joint is a pivot joint that provides for rotation of the head.

The temporomandibular (jaw) joint is the articulation between the condyle of the mandible and the mandibular fossa and articular tubercle of the skull temporal bone. An articular disc is located between the bony components of this joint. A combination of gliding and hinge motions of the mandibular condyle allows for elevation/depression, protraction/retraction, and side-to-side motions of the lower jaw.

The glenohumeral (shoulder) joint is a multiaxial ball-and-socket joint that provides flexion/extension, abduction/adduction, circumduction, and medial/lateral rotation of the humerus. The head of the humerus articulates with the glenoid cavity of the scapula. The glenoid labrum extends around the margin of the glenoid cavity. Intrinsic ligaments, including the coracohumeral ligament and glenohumeral ligaments, provide some support for the shoulder joint. However, the primary support comes from muscles crossing the joint whose tendons form the rotator cuff. These muscle tendons are protected from friction against the scapula by the subacromial bursa and subscapular bursa.

The elbow is a uniaxial hinge joint that allows for flexion/extension of the forearm. It includes the humeroulnar joint and the humeroradial joint. The medial elbow is supported by the ulnar collateral ligament and the radial collateral ligament supports the lateral side. These ligaments prevent side-to-side movements and resist hyperextension of the elbow. The proximal radioulnar joint is a pivot joint that allows for rotation of the radius during pronation/supination of the forearm. The annular ligament surrounds the head of the radius to hold it in place at this joint.

The hip joint is a ball-and-socket joint whose motions are more restricted than at the shoulder to provide greater stability

during weight bearing. The hip joint is the articulation between the head of the femur and the acetabulum of the hip bone. The acetabulum is deepened by the acetabular labrum. The iliofemoral, pubofemoral, and ischiofemoral ligaments strongly support the hip joint in the upright, standing position. The ligament of the head of the femur provides little support but carries an important artery that supplies the femur.

The knee includes three articulations. The femoropatellar joint is between the patella and distal femur. The patella, a sesamoid bone incorporated into the tendon of the quadriceps femoris muscle of the anterior thigh, serves to protect this tendon from rubbing against the distal femur during knee movements. The medial and lateral tibiofemoral joints, between the condyles of the femur and condyles of the tibia, are modified hinge joints that allow for knee extension and flexion. During these movements, the condyles of the femur both roll and glide over the surface of the tibia. As the knee comes into full extension, a slight medial rotation of the femur serves to “lock” the knee into its most stable, weight-bearing position. The reverse motion, a small lateral rotation of the femur, is required to initiate knee flexion. When the knee is flexed, some rotation of the leg is available.

Two extrinsic ligaments, the tibial collateral ligament on the medial side and the fibular collateral ligament on the lateral side, serve to resist hyperextension or rotation of the extended knee joint. Two intracapsular ligaments, the anterior cruciate ligament and posterior cruciate ligament, span between the tibia and the inner aspects of the femoral condyles. The anterior cruciate ligament resists hyperextension of the knee, while the posterior cruciate ligament prevents anterior sliding of the femur, thus supporting the knee when it is flexed and weight bearing. The medial and lateral menisci, located between the femoral and tibial condyles, are articular discs that provide padding and improve the fit between the bones.

The talocrural joint forms the ankle. It consists of the articulation between the talus bone and the medial malleolus of the tibia, the distal end of the tibia, and the lateral malleolus of the fibula. This is a uniaxial hinge joint that allows only dorsiflexion and plantar flexion of the foot. Gliding motions at the subtalar and intertarsal joints of the foot allow for inversion/eversion of the foot. The ankle joint is supported on the medial side by the deltoid ligament, which prevents side-to-side motions of the talus at the talocrural joint and resists excessive eversion of the foot. The lateral ankle is supported by the anterior and posterior talofibular ligaments and the calcaneofibular ligament. These support the ankle joint and also resist excess inversion of the foot. An inversion ankle sprain, a common injury, will result in injury to one or more of these lateral ankle ligaments.

Review Questions

Q. The primary support for the glenohumeral joint is provided by the _____.

A. coracohumeral ligament

B. glenoid labrum

C. rotator cuff muscles

D. subacromial bursa

Answer

Answer: C

Q. The proximal radioulnar joint _____.

A. is supported by the annular ligament

B. contains an articular disc that strongly unites the bones

C. is supported by the ulnar collateral ligament

D. is a hinge joint that allows for flexion/extension of the forearm

Answer

Answer: A

Q. Which statement is true concerning the knee joint?

A. The lateral meniscus is an intrinsic ligament located on the lateral side of the knee joint.

B. Hyperextension is resisted by the posterior cruciate ligament.

C. The anterior cruciate ligament supports the knee when it is flexed and weight bearing.

D. The medial meniscus is attached to the tibial collateral ligament.

Answer

Answer: D

Q. The ankle joint _____.

A. is also called the subtalar joint

B. allows for gliding movements that produce inversion/eversion of the foot

C. is a uniaxial hinge joint

D. is supported by the tibial collateral ligament on the lateral side

Answer

Answer: C

Q. Which region of the vertebral column has the *greatest* range of motion for rotation?

A. cervical

B. thoracic

C. lumbar

D. sacral

Answer

Answer: B

Critical Thinking Questions

Q. Discuss the structures that contribute to support of the shoulder joint.

Answer

A. The shoulder joint allows for a large range of motion. The primary support for the shoulder joint is provided by the four rotator cuff muscles. These muscles serve as “dynamic ligaments” and thus can modulate their strengths of contraction as needed to hold the head of the humerus in position at the glenoid fossa. Additional but weaker support comes from the coracohumeral ligament, an intrinsic ligament that supports the superior aspect of the shoulder joint, and the glenohumeral ligaments, which are intrinsic ligaments that support the anterior side of the joint.

Q. Describe the sequence of injuries that may occur if the extended, weight-bearing knee receives a very strong blow to the lateral side of the knee.

Answer

A. A strong blow to the lateral side of the extended knee will cause the medial side of the knee joint to open, resulting in a sequence of three injuries. First will be damage to the tibial collateral ligament. Since the medial

meniscus is attached to the tibial collateral ligament, the meniscus is also injured. The third structure injured would be the anterior cruciate ligament.

Glossary

acetabular labrum
lip of fibrocartilage that surrounds outer margin of the acetabulum on the hip bone

annular ligament
intrinsic ligament of the elbow articular capsule that surrounds and supports the head of the radius at the proximal radioulnar joint

anterior cruciate ligament
intracapsular ligament of the knee; extends from anterior, superior surface of the tibia to the inner aspect of the lateral condyle of the femur; resists hyperextension of knee

anterior talofibular ligament
intrinsic ligament located on the lateral side of the ankle joint, between talus bone and lateral malleolus of fibula; supports talus at the talocrural joint and resists excess inversion of the foot

atlantoaxial joint
series of three articulations between the atlas (C1) vertebra and the axis (C2) vertebra, consisting of the joints between the inferior articular processes of C1 and the superior articular processes of C2, and the articulation between the dens of C2 and the anterior arch of C1

atlanto-occipital joint
articulation between the occipital condyles of the skull and the superior articular processes of the atlas (C1 vertebra)

calcaneofibular ligament
intrinsic ligament located on the lateral side of the ankle joint, between the calcaneus bone and lateral malleolus of the fibula; supports the talus bone at the ankle joint and resists excess inversion of the foot

coracoacromial ligament
accessory ligament of the shoulder joint; connects the coracoid process of the scapula to the acromion

coracohumeral ligament
intrinsic ligament of the shoulder joint; runs from the coracoid process of the scapula to the anterior humerus

deltoid ligament
broad intrinsic ligament located on the medial side of the ankle joint; supports the talus at the talocrural joint and resists excess eversion of the foot

elbow joint
humeroulnar joint

femoropatellar joint
portion of the knee joint consisting of the articulation between the distal femur and the patella

fibular collateral ligament
extrinsic ligament of the knee joint that spans from the lateral epicondyle of the femur to the head of the fibula; resists hyperextension and rotation of the extended knee

glenohumeral joint
shoulder joint; articulation between the glenoid cavity of the scapula and head of the humerus; multiaxial ball-and-socket joint that allows for flexion/extension, abduction/adduction, circumduction, and medial/lateral rotation of the humerus

glenohumeral ligament
one of the three intrinsic ligaments of the shoulder joint that strengthen the anterior articular capsule

glenoid labrum
: lip of fibrocartilage located around the outside margin of the glenoid cavity of the scapula

hip joint
: also known as the coxafemoral joint; articulation between the head of the femur and the acetabulum of the hip (coxal) bone

humeroradial joint
: articulation between the capitulum of the humerus and head of the radius

humeroulnar joint
: articulation between the trochlea of humerus and the trochlear notch of the ulna; uniaxial hinge joint that allows for flexion/extension of the forearm

iliofemoral ligament
: intrinsic ligament spanning from the ilium of the hip bone to the femur, on the superior-anterior aspect of the hip joint

ischiofemoral ligament
: intrinsic ligament spanning from the ischium of the hip bone to the femur, on the posterior aspect of the hip joint

lateral meniscus
: C-shaped fibrocartilage articular disc located at the knee, between the lateral condyle of the femur and the lateral condyle of the tibia

lateral patellar retinaculum
: thick layer of dense fibrous connective tissue that anchors the patella in position on its lateral side

lateral tibiofemoral joint
: portion of the knee consisting of the articulation between the lateral condyle of the tibia and the lateral condyle of the femur; allows for flexion/extension at the knee

ligament of the head of the femur
: intracapsular ligament that runs from the acetabulum of the hip bone to the head of the femur

medial meniscus
: C-shaped fibrocartilage articular disc located at the knee, between the medial condyle of the femur and medial condyle of the tibia

medial patellar retinaculum
: thick layer of dense fibrous connective tissue that anchors the patella in position on its medial side

medial tibiofemoral joint
: portion of the knee consisting of the articulation between the medial condyle of the tibia and the medial condyle of the femur; allows for flexion/extension at the knee

patellar ligament
: ligament spanning from the patella to the anterior tibia; serves as the final attachment for the quadriceps femoris muscle

posterior cruciate ligament
: intracapsular ligament of the knee; extends from the posterior, superior surface of the tibia to the inner aspect of the medial condyle of the femur; prevents anterior displacement of the femur when the knee is flexed and weight bearing

posterior talofibular ligament
: intrinsic ligament located on the lateral side of the ankle joint, between the talus bone and lateral malleolus of the fibula; supports the talus at the talocrural joint and resists excess inversion of the foot

proximal radioulnar joint
: articulation between the radius and ulna at the elbow joint

pubofemoral ligament
: intrinsic ligament spanning from the pubis of the hip bone to the femur, on the anterior-inferior aspect of the hip joint

radial collateral ligament
: intrinsic ligament on the lateral side of the elbow joint; runs from the lateral epicondyle of humerus to merge with the annular ligament

rotator cuff
: strong connective tissue structure formed by the fusion of four rotator cuff muscle tendons to the articular capsule of the shoulder joint; surrounds and supports superior, anterior, lateral, and posterior sides of the humeral head

subacromial bursa
: bursa that protects the supraspinatus muscle tendon and superior end of the humerus from rubbing against the acromion of the scapula

subscapular bursa
: bursa that prevents rubbing of the subscapularis muscle tendon against the scapula

subtalar joint
: articulation between the talus and calcaneus bones of the foot; allows motions that contribute to inversion/eversion of the foot

talocrural joint
: ankle joint; articulation between the talus bone of the foot and medial malleolus of the tibia, distal tibia, and lateral malleolus of the fibula; a uniaxial hinge joint that allows only for dorsiflexion and plantar flexion of the foot

temporomandibular joint (TMJ)
: articulation between the condyle of the mandible and the mandibular fossa and articular tubercle of the temporal bone of the skull; allows for depression/elevation (opening/closing of mouth), protraction/retraction, and side-to-side motions of the mandible

tibial collateral ligament
: extrinsic ligament of knee joint that spans from the medial epicondyle of the femur to the medial tibia; resists hyperextension and rotation of extended knee

ulnar collateral ligament
: intrinsic ligament on the medial side of the elbow joint; spans from the medial epicondyle of the humerus to the medial ulna

zygapophysial joints
: facet joints; plane joints between the superior and inferior articular processes of adjacent vertebrae that provide for only limited motions between the vertebrae

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Answers

Interactive Link

Answer: The shoulder joint is a ball-and-socket joint that allows for flexion-extension, abduction-adduction, medial rotation, lateral rotation, and circumduction of the humerus.

Interactive Link

Answer: An intracapsular fracture of the neck of the femur can result in disruption of the arterial blood supply to the head of the femur, which may lead to avascular necrosis of the femoral head.

Interactive Link

Answer: The ligaments of the lateral ankle are the anterior and posterior talofibular ligaments and the calcaneofibular ligament. These ligaments support the ankle joint and resist excess inversion of the foot.

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8.8: Development of Joints

By the end of this section, you will be able to:

- Describe the two processes by which mesenchyme can give rise to bone
- Discuss the process by which joints of the limbs are formed

Joints form during embryonic development in conjunction with the formation and growth of the associated bones. The embryonic tissue that gives rise to all bones, cartilages, and all other connective tissues of the body is called mesenchyme. In the head, mesenchyme will accumulate at the areas that will become the bones that form the top and sides of the skull. The mesenchyme in these areas will develop directly into bone through the process of intramembranous ossification, in which mesenchymal cells differentiate into bone-producing cells that then generate bone tissue. The mesenchyme between the areas of bone production will become the fibrous connective tissue that fills the spaces between the developing bones. Initially, the connective tissue-filled gaps between the bones are wide, and are called fontanelles. After birth, as the skull bones grow and enlarge, the gaps between them decrease in width and the fontanelles are reduced to suture joints in which the bones are united by a narrow layer of fibrous connective tissue.

The bones that form the base and facial regions of the skull develop through the process of endochondral ossification. In this process, mesenchyme accumulates and differentiates into hyaline cartilage, which forms a model of the future bone. The hyaline cartilage model is then gradually, over a period of many years, displaced by bone. The mesenchyme between these developing bones becomes the fibrous connective tissue of the suture joints between the bones in these regions of the skull.

A similar process of endochondral ossification gives rises to the bones and joints of the limbs. The limbs initially develop as small limb buds that appear on the sides of the embryo around the end of the fourth week of development. Starting during the sixth week, as each limb bud continues to grow and elongate, areas of mesenchyme within the bud begin to differentiate into the hyaline cartilage that will form models of each of the future bones. The synovial joints will form between the adjacent cartilage models, in an area called the **joint interzone**. Cells at the center of this interzone region undergo cell death to form the joint cavity, while surrounding mesenchymal cells will form the articular capsule, supporting ligaments, and other synovial structures (e.g. bursae, menisci). The process of endochondral ossification, which converts the cartilage models into bone, begins by the twelfth week of embryonic development. At birth, ossification of much of the bone has occurred, but the hyaline cartilage of the epiphyseal plate will remain throughout childhood and adolescence to allow for bone lengthening. Hyaline cartilage is also retained as the articular cartilage that covers the surfaces of the bones at synovial joints.

Concept Review

During embryonic growth, bones and joints develop from mesenchyme, an embryonic tissue that gives rise to bone, cartilage, and all other connective tissues. In the skull, the bones develop either directly from mesenchyme through the process of intramembranous ossification, or indirectly through endochondral ossification, which initially forms a hyaline cartilage model of the future bone, which is later converted into bone. In both cases, the mesenchyme between the developing bones differentiates into fibrous connective tissue that will unite the skull bones at suture joints. In the limbs, mesenchyme accumulations within the growing limb bud will become a hyaline cartilage model for each of the limb bones. A joint interzone will develop between these areas of cartilage. Mesenchymal cells at the margins of the interzone will give rise to the articular capsule, while cell death at the center forms the space that will become the joint cavity of the future synovial joint. The hyaline cartilage model of each limb bone will eventually be converted into bone via the process of endochondral ossification. However, hyaline cartilage will remain, forming the protective articular cartilage at the ends of the adult.

Review Questions

Q. Intramembranous ossification _____.

A. gives rise to the bones of the limbs

B. produces the bones of the top and sides of the skull

C. produces the bones of the face and base of the skull

D. involves the conversion of a hyaline cartilage model into bone

Answer

Answer: B

Q. Synovial joints _____.

A. are derived from fontanelles

B. are produced by intramembranous ossification

C. develop at an interzone site

D. are produced by endochondral ossification

Answer

Answer: C

Q. Endochondral ossification is _____.

A. the process that replaces hyaline cartilage with bone tissue

B. the process by which mesenchyme differentiates directly into bone tissue

C. completed before birth

D. the process that gives rise to the joint interzone and future joint cavity

Answer

Answer: A

Critical Thinking Questions

Q. Describe how synovial joints develop within the embryonic limb.

Answer

A. Mesenchyme gives rise to cartilage models of the future limb bones. An area called the joint interzone located between adjacent cartilage models will become a synovial joint. The cells at the center of the interzone die, thus producing the joint cavity. Additional mesenchyme cells at the periphery of the interzone become the articular capsule.

Q. Differentiate between endochondral and intramembranous ossification.

Answer

A. Intramembranous ossification is the process by which mesenchymal cells differentiate directly into bone producing cells. This process produces the bones that form the top and sides of the skull. The remaining skull bones and the bones of the limbs are formed by endochondral ossification. In this, mesenchymal cells differentiate into hyaline cartilage cells that produce a cartilage model of the future bone. The cartilage is then gradually replaced by bone tissue over a period of many years, during which the cartilage of the epiphyseal plate can continue to grow to allow for enlargement or lengthening of the bone.

Glossary

joint interzone
: site within a growing embryonic limb bud that will become a synovial joint

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9: SKELETAL MUSCLE TISSUE

9.1: Introduction to Muscle Tissue
9.2: Overview of Muscle Tissues
9.3: Skeletal Muscle
9.4: Muscle Fiber Contraction and Relaxation
9.5: Types of Muscle Fibers
9.6: Development and Regeneration of Muscle Tissue

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9.1: Introduction to Muscle Tissue

Chapter Learning Objectives

After studying this chapter, you will be able to:

- Explain the organization of muscle tissue
- Describe the function and structure of skeletal, cardiac muscle, and smooth muscle
- Explain how muscles work with tendons to move the body
- Describe how muscles contract and relax
- Explain the development and regeneration of muscle tissue

When most people think of muscles, they think of the muscles that are visible just under the skin, particularly of the limbs. These are skeletal muscles, so-named because most of them move the skeleton. But there are two other types of muscle in the body, with distinctly different jobs. Cardiac muscle, found in the heart, functions to pump blood through the circulatory system. Smooth muscle functions in various involuntary movements, such as having one's hair stand on end when cold or frightened, or moving food through the digestive system. This chapter will focus on the structure and function of skeletal muscles.

Figure 9.1.1: Tennis Player. Athletes rely on toned skeletal muscles to supply the force required for movement. (Image credit: "Tennis Player" by Emmanuel Huybrechts is licensed under CC BY 4.0)

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9.2: Overview of Muscle Tissues

By the end of this section, you will be able to:

- Describe the different types of muscle
- Explain contractility and extensibility

Muscle is one of the four primary tissue types of the body, and the body contains three types of muscle tissue: skeletal muscle, cardiac muscle, and smooth muscle (Figure $9.2.1$). All muscle tissues have four functional properties in common which include **excitability**, **contractility**, **extensibility**, and **elasticity**.

They all exhibit a quality called **excitability** as their plasma membranes can change their electrical states (from polarized to depolarized) and send an electrical wave called an action potential along the entire surface of each cell. While the nervous system can influence the excitability of cardiac and smooth muscle to some degree, skeletal muscle completely depends on signaling from the nervous system to work properly. On the other hand, both cardiac muscle and smooth muscle can respond to other stimuli, such as hormones and local stimuli.

Muscles begin the process of contracting (shortening) when a protein called actin is pulled by a protein called myosin. This occurs in striated muscle (skeletal and cardiac) in the presence of calcium ions (Ca^{++}) which is regulated by electrical signaling. Ca^{++} also is required for the contraction of smooth muscle, although its role is different: here Ca^{++} activates enzymes, which in turn activate myosin heads. All muscles require adenosine triphosphate (ATP) to continue the process of contracting, and they all relax when the Ca^{++} is removed.

Contractility allows muscle tissue to pull on its attachment points and shorten with force. Muscle tissue also has the quality of **extensibility**; it can stretch or extend. Following contraction or extension, a muscle can return to its original length when relaxed due to a quality of muscle tissue called **elasticity**. It can recoil back to its original length due to elastic proteins.

Differences among the three muscle types include the microscopic organization of their contractile proteins—actin and myosin. The actin and myosin proteins are arranged very regularly in the cytoplasm of individual muscle cells (referred to as fibers) in both skeletal muscle and cardiac muscle, which creates a pattern, or stripes, called striations. The striations are visible with a light microscope under high magnification (see Figure $9.2.1.a, c$). **Skeletal muscle** fibers are multinucleated cells that compose the skeletal muscle. **Cardiac muscle** fibers each have one to two nuclei and are physically and electrically connected to each other so that the entire heart contracts as one unit (called a syncytium).

Because the actin and myosin are not arranged in such regular fashion in smooth muscle, the cytoplasm of a **smooth muscle** fiber (which has only a single nucleus) has a uniform, nonstriated appearance (resulting in the name smooth muscle). However, the less organized appearance of smooth muscle should not be interpreted as less efficient. Smooth muscle in the walls of arteries is a critical component that regulates blood pressure necessary to push blood through the circulatory system; and smooth muscle in the skin, visceral organs, and internal passageways is essential for moving all materials through the body and maintaining homeostasis.

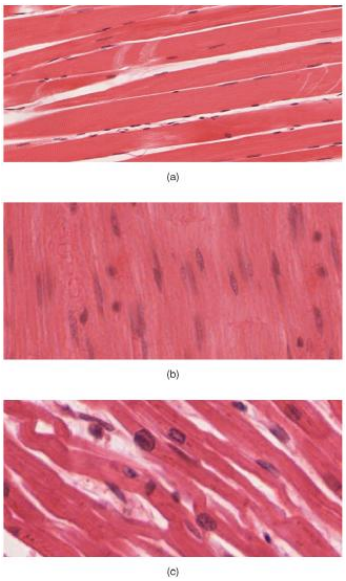

Figure 9.2.1. The Three Types of Muscle Tissue. The body contains three types of muscle tissue: (a) skeletal muscle, LM × 1600 (b) smooth muscle, LM × 1600 (c) cardiac muscle, LM × 1600. (Image credit: "Skeletal Smooth Cardiac" by OpenStax is licensed under CC BY 3.0/Micrographs provided by the Regents of University of Michigan Medical School © 2012)

Concept Review

Muscle is the tissue in animals that allows for active movement of the body or materials within the body. There are three types of muscle tissue: skeletal muscle, cardiac muscle, and smooth muscle. Most of the body's skeletal muscle produces movement by acting on the skeleton. Cardiac muscle is found in the wall of the heart and pumps blood through the circulatory system. Smooth muscle is found in the skin, where it is associated with hair follicles; it also is found in the walls of internal organs, blood vessels, and internal passageways, where it assists in moving materials.

Review Questions

Q. Muscle that has a striped appearance is described as being _____.

A. elastic

B. nonstriated

C. excitable

D. striated

Answer

Answer: D

Q. Which element is important in directly triggering contraction?

A. sodium (Na^+)

B. calcium (Ca^{++})

C. potassium (K^+)

D. chloride (Cl^-)

Answer

Answer: B

Q. Which of the following properties is *not* common to all three muscle tissues?

A. excitability

B. the need for ATP

C. polarity

D. elasticity

Answer

Answer: C

Critical Thinking Questions

Q. Why is elasticity an important quality of muscle tissue?

Answer

A. It allows muscle to return to its original length during relaxation after contraction.

Glossary

cardiac muscle
striated muscle found in the heart; joined to one another at intercalated discs and under the regulation of pacemaker cells, which contract as one unit to pump blood through the circulatory system. Cardiac muscle is under involuntary control.

contractility
ability to shorten (contract) forcibly

elasticity
ability to stretch and rebound

excitability
ability to undergo neural stimulation

extensibility
ability to lengthen (extend)

skeletal muscle
striated, multinucleated muscle that requires signaling from the nervous system to trigger contraction; most skeletal muscles are referred to as voluntary muscles that move bones and produce movement

smooth muscle
nonstriated, mononucleated muscle in the skin that is associated with hair follicles; assists in moving materials in the walls of internal organs, blood vessels, and internal passageways

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9.3: Skeletal Muscle

By the end of this section, you will be able to:

- Describe the layers of connective tissues that package skeletal muscle
- Explain how muscles work with tendons to move the body
- Identify and describe the microscopic anatomy of a muscle fiber
- Describe excitation-contraction coupling

The best-known feature of skeletal muscle is its ability to contract and cause movement. Skeletal muscles act not only to produce movement but also to stop movement, such as resisting gravity to maintain posture. Small, constant adjustments of skeletal muscles are needed to hold a body upright or balanced in any position. Muscles also prevent excess movement of the bones and joints, maintaining skeletal stability and preventing structural damage or deformation. Joints can become misaligned or dislocated by excessive or inappropriate forces applied to associated bones; muscles work to keep joints stable. Skeletal muscles are located throughout the body at the openings of internal tracts to control the movement of various substances. These muscles allow functions, such as swallowing, urination, and defecation, to be under voluntary control. Skeletal muscles also protect internal organs (particularly abdominal and pelvic organs) by acting as an external barrier or shield to external trauma and by supporting the weight of the organs.

Skeletal muscles contribute to the maintenance of homeostasis in the body by generating heat. Muscle contraction requires energy, and when ATP is broken down, heat is produced. This heat is very noticeable during exercise, when sustained muscle movement causes body temperature to rise, and in cases of extreme cold, when shivering produces random skeletal muscle contractions to generate heat.

Each skeletal muscle is an organ that consists of various integrated tissues. These tissues include the skeletal muscle fibers, blood vessels, nerve fibers, and connective tissue. Each skeletal muscle has three layers of connective tissue (called “mysia”) that enclose it and provide structure to the muscle as a whole, and also compartmentalize the muscle fibers within the muscle (Figure 9.3.1). Each muscle is wrapped in a sheath of dense, irregular connective tissue called the **epimysium**, which allows a muscle to contract and move powerfully while maintaining its structural integrity. The epimysium also separates muscle from other tissues and organs in the area, allowing the muscle to move independently.

Inside each skeletal muscle, muscle fibers are organized into bundles, called a **fascicle**, by a middle layer of dense irregular connective tissue called the **perimysium**. This fascicular organization is common in muscles of the limbs; it allows the nervous system to trigger a specific movement of a muscle by activating a subset of muscle fibers within a bundle, or fascicle, of the muscle. Inside each fascicle, each muscle fiber is encased in a thin areolar connective tissue layer of collagen and reticular fibers called the **endomysium**. The endomysium contains the extracellular fluid and nutrients to support the muscle fiber. These nutrients are supplied via blood capillaries located in the endomysium.

Three levels of skeletal muscle arrangement

Figure 9.3.1: The Three Connective Tissue Layers. Bundles of muscle fibers, called fascicles, are covered by the perimysium. Muscle fibers are covered by the endomysium. (Image credit: "The Three Connective Tissue Layers" by Openstax is licensed under CC BY 4.0)

In skeletal muscles that work with tendons to pull on bones, the collagen in the three tissue layers intertwines and integrates with the collagen of a tendon, straightening to form a cord of dense regular connective tissue. At the other end of the tendon, the collagen incorporates into periosteum becoming dense irregular connective tissue once more. Tension created by contraction of the muscle fibers is transferred though the mysia, to the tendon, and then to the periosteum to pull on the bone to move the skeleton. In other places, the mysia may fuse with a broad, tendon-like sheet called an **aponeurosis**, or to fascia, the connective tissue between skin and bones. The broad sheet of connective tissue in the lower back that the latissimus dorsi muscles (the “lats”) fuse into is an example of an aponeurosis.

Every skeletal muscle is richly supplied by blood vessels for nourishment, oxygen delivery, and waste removal. In addition, every muscle fiber in a skeletal muscle is supplied by the axon branch of a somatic motor neuron, which signals the fiber to contract.

Unlike cardiac and smooth muscle, the only way to functionally contract a skeletal muscle is through signaling from the nervous system.

The Neuromuscular Junction

The specialized site of the skeletal muscle where a motor neuron's axon terminal meets the muscle fiber is called the **neuromuscular junction (NMJ)** (Figure 9.3.2). This is where the muscle fiber first responds to signaling by the motor neuron. The sarcolemma (plasma membrane) in the region of a neuromuscular junction, known as the **motor end-plate**, contains special transmembrane proteins that receive a signal from the motor neuron and begin the electrical signal in the muscle fiber (Figure 9.3.5). Every skeletal muscle fiber in every skeletal muscle is innervated by a motor neuron at the NMJ. Excitation signals from the neuron are the only way to functionally activate the fiber to contract.

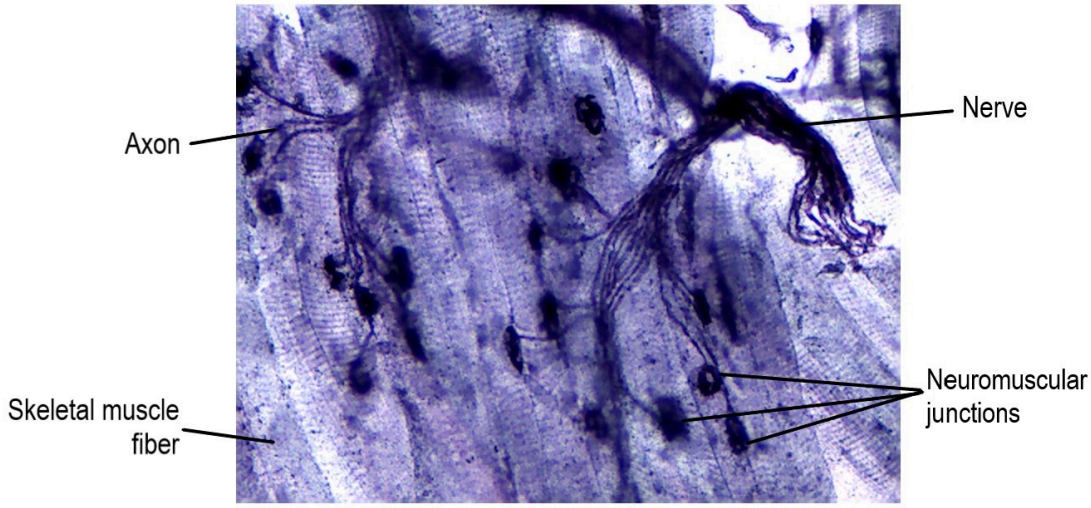

Figure 9.3.2: Neuromuscular Junctions. Every skeletal muscle fiber is innervated by a motor neuron at the neuromuscular junction. Signals from motor neurons initiate the process of muscle contraction. (Image credit: "Motor End Plate - Labeled" by Whitney Menefee is licensed under CC BY-SA 4.0 / A derivative from the original work)

Skeletal Muscle Fibers

Because skeletal muscle cells are long and cylindrical, they are commonly referred to as **skeletal muscle fibers**. Specific terminology associated with muscle fibers is rooted in the Greek *sarco*, which means "flesh." The plasma membrane of muscle fibers is called the **sarcolemma** and the cytoplasm is referred to as **sarcoplasm.** Skeletal muscle fibers can be quite large for human cells, with diameters up to 100 μm and lengths up to 30 cm (11.8 in). During early development, embryonic myoblasts, each with its own nucleus, fuse with up to hundreds of other myoblasts to form the multinucleated skeletal muscle fibers. Multiple nuclei mean multiple copies of genes, permitting the production of the large amounts of proteins and enzymes needed for muscle contraction along the length of the entire muscle fiber.

Within the sarcoplasm of each muscle fiber are **myofibrils** that run the entire length of the muscle fiber and attach to the sarcolemma at its end (Figure 9.3.1). Each myofibril is composed of a bundle of contractile **myofilaments** (known as actin and myosin), along with other support proteins. As myofibrils contract, the entire muscle cell contracts. Because myofibrils are only approximately 1.2 μm in diameter, hundreds to thousands can be found inside one muscle fiber. Surrounding each myofibril is the **sarcoplasmic reticulum (SR),** the specialized smooth endoplasmic reticulum of muscle fibers, which stores, releases, and retrieves calcium ions (Ca^{++}) (Figure 9.3.3).

As will be discussed, the signal from a motor neuron actually stimulates the release of calcium ions (Ca^{++}) from its storage in the cell's SR. For the action potential to reach the membrane of the SR from the motor end plate, there are periodic invaginations in the sarcolemma, called **T-tubules** ("T" stands for "transverse"). You will recall that the diameter of a muscle fiber can be up to 100 μm, so these T-tubules ensure that the membrane can get close to the SR in the sarcoplasm. On each side of the T-tubule is a **terminal cisterna** (plural - cisternae), an enlarged region of the SR that contains high concentrations of calcium ions. The

arrangement of a T-tubule with the terminal cisternae of the SR on either side is called a **triad** (Figure 9.3.3). The triad surrounds the cylindrical structure of the myofibril.

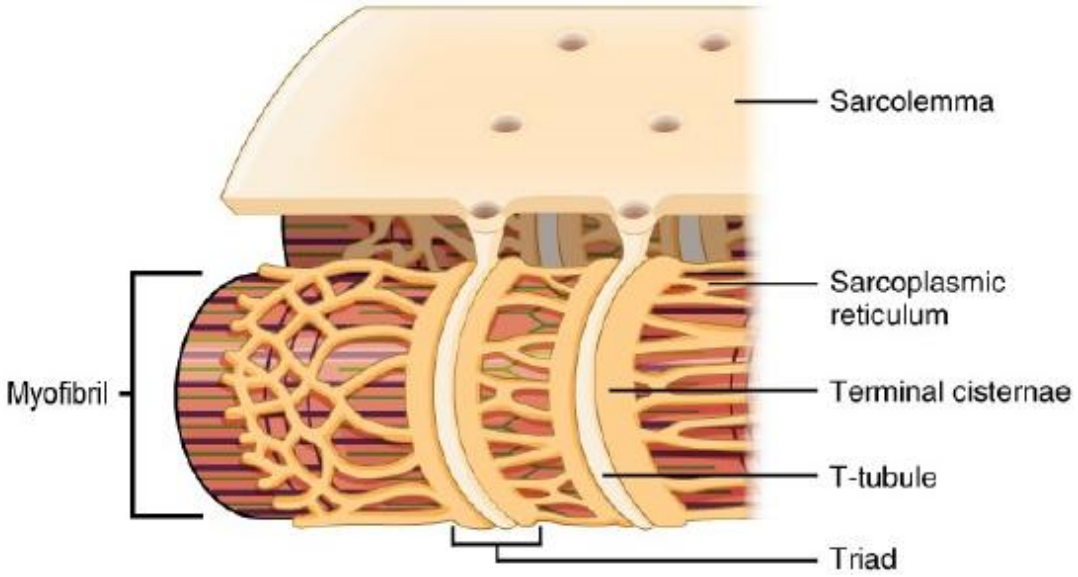

Figure 9.3.3: The Triad. Narrow T-tubules permit the conduction of electrical impulses. The SR functions to regulate intracellular levels of calcium. Two terminal cisternae (where enlarged SR connects to the T-tubule) and one T-tubule comprise a triad—a “threesome” of membranes, with those of SR on two sides and the T-tubule sandwiched between them. (Image credit: "The Triad" by Whitney Menefee is licensed under CC BY 4.0 / A derivative from the original work)

The Sarcomere

The striated appearance of skeletal muscle fibers is due to the arrangement of the myofilaments **actin** and **myosin** in sequential order from one end of the muscle fiber to the other. Each segment of these myofilaments and their regulatory proteins, **troponin** and **tropomyosin** (along with other proteins), is called a **sarcomere**. The sarcomere is the functional unit of the muscle fiber. A chain of thousands of repeating sarcomeres forms the long tube-like myofibrils.

Each sarcomere is approximately 2 μm in length with a three-dimensional cylinder-like arrangement. The repeating pattern of the myofilaments, along with other proteins, within the sarcomere gives rise to very distinctive regions and structures (Figure 9.3.4). Each sarcomere is bordered by structures called **Z-discs** (also called Z-lines, because pictures are two-dimensional), to which the actin myofilaments are anchored. Because the actin forms strands that are thinner than the myosin, it is called the **thin filament** of the sarcomere. Likewise, because the myosin strands have more mass and are thicker, they are called the **thick filament** of the sarcomere. This difference in thickness, is what causes the striated appearance of skeletal muscle fibers. The area immediately surrounding the Z-discs, is known as the **I band**, or light band, because only actin is present. The thin composition of actin makes it difficult to see, hence the name the light band. The myosin is anchored in the center of the sarcomere, to a structure known as the **M line,** where is projects toward but not all to way to, the Z-discs. The area of the sarcomere where myosin is present is known as the **A band**, or dark band. Opposite to thin composition of actin, myosin is thick, which makes this area dark in appearance. There are some areas, where actin and myosin myofilaments are both present, known as the zone of overlap. Immediately surrounding the M line is the **H zone,** where there is no overlap and only myosin is present.

Microscopic view of muscle fiber organization

Figure 9.3.4: The Sarcomere. Myofibrils within the sarcoplasm are composed of chains of thousands of repeating sarcomeres. (Image credit: "Muscle Fibers" by Openstax is licensed under CC BY 4.0)

Myofilaments

As mentioned above, actin is known as the thin filament and myosin as the thick filament. The structural differences between these two myofilaments not only leads to the striated appearance of skeletal muscle tissue, but also to the ability of the two to work together to produce the overall function of muscle contraction.

Actin myofilaments are formed by multiple actin subunits, each of which contain a myosin binding site (Figure 9.3.5). In a relaxed muscle, the binding sites remain shielded by the troponin-tropomyosin regulatory complex. The **tropomyosin** filaments run the length of the actin, covering all of the binding sites and are held in place by **troponin**.

Myosin myofilaments have two specific regions, the tail and the heads (Figure 9.3.5). Connecting these two regions is a flexible hinge region. The tails function to cluster many myosin myofilaments together, while the heads take an active role in the muscle contraction process. The heads contain an actin-binding site, as well as an ATP binding site. The importance of these binding sites will be discussed in the next section of this book.

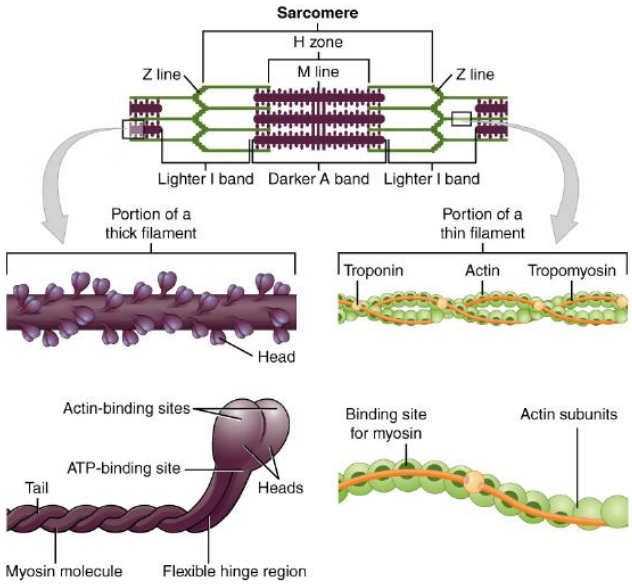

Figure 9.3.5: Myofilaments. The sarcomere, the region from one Z-line to the next Z-line, is the functional unit of a skeletal muscle fiber and is composed of a repeating arrangements of actin and myosin, along with other proteins. (Image credit: "Thick and Thin Filaments" by Openstax is licensed under CC BY 4.0)

Excitation-Contraction Coupling

All living cells have membrane potentials, or electrical gradients across their membranes. The inside of the membrane is usually around -60 to -90 mV, relative to the outside. This is referred to as a cell's membrane potential. Neurons and muscle cells can use their membrane potentials to generate electrical signals. They do this by controlling the movement of charged particles, called ions, across their membranes to create electrical currents. This is achieved by opening and closing specialized proteins in the membrane called ion channels. Although the currents generated by ions moving through these channel proteins are very small, they form the basis of both neural signaling and muscle contraction.

Both neurons and skeletal muscle cells are electrically excitable, meaning that they are able to generate action potentials. An action potential is a special type of electrical signal that can travel along a cell membrane as a wave. This allows a signal to be transmitted quickly and faithfully over long distances.

Although the term **excitation-contraction coupling** confuses or scares some students, it comes down to this: for a skeletal muscle fiber to contract, its membrane must first be "excited"—in other words, it must be stimulated to fire an action potential. The muscle fiber action potential, which sweeps along the sarcolemma as a wave, is "coupled" to the actual contraction through the release of calcium ions (Ca^{++}) from the SR. Once released, the Ca^{++} interacts with the shielding proteins, forcing them to move aside so that the actin-binding sites are available for attachment by myosin heads. The myosin then pulls the actin filaments toward the center, shortening the muscle fiber.

In skeletal muscle, this sequence begins with signals from the somatic motor division of the nervous system. In other words, the "excitation" step in skeletal muscles is always triggered by signaling from the nervous system (Figure 9.3.6).

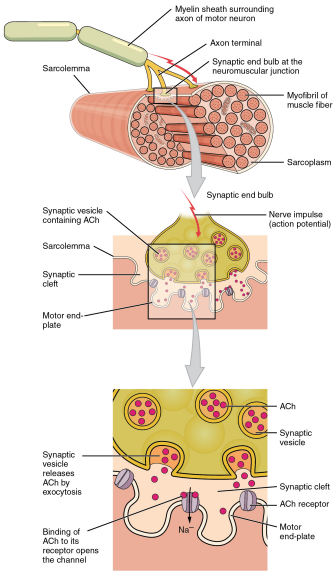

Figure 9.3.6: Motor End-Plate and Innervation. At the NMJ, the axon terminal releases ACh. The motor end-plate is the location of the ACh-receptors in the muscle fiber sarcolemma. When ACh molecules are released, they diffuse across a minute space called the synaptic cleft and bind to the receptors. (Image credit: "Motor Endplate and Innervation" by Openstax is licensed under CC BY 4.0)

The motor neurons that tell the skeletal muscle fibers to contract originate in the spinal cord, with a smaller number located in the brainstem for activation of skeletal muscles of the face, head, and neck. These neurons have long processes, called axons, which are specialized to transmit action potentials long distances— in this case, all the way from the spinal cord to the muscle itself (which may be up to three feet away). The axons of multiple neurons bundle together to form nerves, like wires bundled together in a cable.

Signaling begins when a neuronal **action potential** travels along the axon of a motor neuron, and then along the individual branches to terminate at the NMJ. At the NMJ, the axon terminal releases a chemical messenger, or **neurotransmitter**, called **acetylcholine (ACh)**. The ACh molecules diffuse across a minute space called the **synaptic cleft** and bind to ACh receptors located within the **motor end-plate** of the sarcolemma on the other side of the synapse. Once ACh binds, a channel in the ACh receptor opens and positively charged ions can pass through into the muscle fiber, causing it to **depolarize**, meaning that the membrane potential of the muscle fiber becomes less negative (closer to zero.)

As the membrane depolarizes, another set of ion channels called **voltage-gated sodium channels** are triggered to open. Sodium ions enter the muscle fiber, and an action potential rapidly spreads (or “fires”) along the entire membrane to initiate excitation-contraction coupling.

Things happen very quickly in the world of excitable membranes (just think about how quickly you can snap your fingers as soon as you decide to do it). Immediately following depolarization of the membrane, it repolarizes, re-establishing the negative membrane potential. Meanwhile, the ACh in the synaptic cleft is degraded by the enzyme acetylcholinesterase (AChE) so that the ACh cannot rebind to a receptor and reopen its channel, which would cause unwanted extended muscle excitation and contraction. Propagation of an action potential along the sarcolemma is the excitation portion of excitation-contraction coupling. The T-tubules carry the action potential into the interior of the cell, which triggers the opening of calcium channels in the membrane of the adjacent SR, causing Ca^{++} to diffuse out of the SR and into the sarcoplasm. It is the arrival of Ca^{++} in the sarcoplasm that initiates contraction of the muscle fiber by its contractile units, or sarcomeres.

Concept Review

Skeletal muscles contain connective tissue, blood vessels, and nerves. There are three layers of connective tissue: epimysium, perimysium, and endomysium. Skeletal muscle fibers are organized into groups called fascicles. Blood vessels and nerves enter the connective tissue and branch. Muscles attach to bones directly or through tendons or aponeuroses. Skeletal muscles maintain posture, stabilize joints, support organs, control internal movement, and generate heat.

Skeletal muscle fibers are long, multinucleated cells. The membrane of the cell is the sarcolemma; the cytoplasm of the cell is the sarcoplasm. The sarcoplasmic reticulum (SR) is a form of endoplasmic reticulum that specializes in storing and releasing calcium.

Muscle fibers are composed of myofibrils. The banding pattern of myofibrils, called striations, are created by the organization of actin and myosin proteins in functional units called sarcomeres.

Review Questions

Q. The correct order for the smallest to the largest unit of organization in muscle tissue is _____.

A. fascicle, myofilament, muscle fiber, myofibril

B. myofilament, myofibril, muscle fiber, fascicle

C. muscle fiber, fascicle, myofilament, myofibril

D. myofibril, muscle fiber, myofilament, fascicle

Answer

Answer: B

Q. Depolarization of the sarcolemma means _____.

A. the inside of the membrane has become less negative as sodium ions accumulate

B. the outside of the membrane has become less negative as sodium ions accumulate

C. the inside of the membrane has become more negative as sodium ions accumulate

D. the sarcolemma has completely lost any electrical charge

Answer

Answer: A

Critical Thinking Questions

Q. What would happen to skeletal muscle if the epimysium were destroyed?

Answer

A. Muscles would lose their integrity during powerful movements, resulting in muscle damage.

Q. Describe how tendons facilitate body movement.

Answer

A. When a muscle contracts, the force of movement is transmitted through the tendon, which pulls on the bone to produce skeletal movement.

Q. What are the five primary functions of skeletal muscle?

Answer

A. Produce movement of the skeleton, maintain posture and body position, support soft tissues, encircle openings of the digestive, urinary, and other tracts, and maintain body temperature.

Q. What are the opposite roles of voltage-gated sodium channels and voltage-gated potassium channels?

Answer

A. The opening of voltage-gated sodium channels, followed by the influx of Na^+, transmits an Action Potential after the membrane has sufficiently depolarized. The delayed opening of potassium channels allows K^+ to exit the cell, to repolarize the membrane.

Glossary

A band
region of the sarcomere where myosin is present

acetylcholine (ACh)
neurotransmitter that binds at a motor end-plate to trigger depolarization

actin
protein that makes up most of the thin myofilaments in a sarcomere muscle fiber

action potential
change in voltage of a cell membrane in response to a stimulus that results in transmission of an electrical signal; unique to neurons and muscle fibers

aponeurosis
broad, tendon-like sheet of connective tissue that attaches a skeletal muscle to another skeletal muscle or to a bone

depolarize
to reduce the voltage difference between the inside and outside of a cell's plasma membrane (the sarcolemma for a muscle fiber), making the inside less negative than at rest

endomysium
loose, and well-hydrated connective tissue covering each muscle fiber in a skeletal muscle

epimysium
outer layer of connective tissue around a skeletal muscle

excitation-contraction coupling
sequence of events from motor neuron signaling to a skeletal muscle fiber to contraction of the fiber's sarcomeres

fascicle
bundle of muscle fibers within a skeletal muscle

H zone
region of the sarcomere surrounding the M line where only myosin is present

I band
also known as the light band; region of the sarcomere where only actin is present

M line
center structure of a sarcomere that serves to anchor myosin filaments

motor end-plate
sarcolemma of muscle fiber at the neuromuscular junction, with receptors for the neurotransmitter acetylcholine

myofibril
long, cylindrical groups of myofilaments (actin and myosin) that run parallel within the muscle fiber and contains the sarcomeres

myofilament
proteins, actin and myosin, that make up myofibrils

myosin
protein that makes up most of the thick cylindrical myofilament within a sarcomere muscle fiber

neuromuscular junction (NMJ)
synapse between the axon terminal of a motor neuron and the section of the membrane of a muscle fiber with receptors for the acetylcholine released by the terminal

neurotransmitter
signaling chemical released by nerve terminals that bind to and activate receptors on target cells

perimysium
connective tissue that bundles skeletal muscle fibers into fascicles within a skeletal muscle

sarcomere
longitudinally, repeating functional unit of skeletal muscle, with all of the contractile and associated proteins involved in contraction

sarcolemma
plasma membrane of a skeletal muscle fiber

sarcoplasm
cytoplasm of a muscle cell

sarcoplasmic reticulum (SR)
specialized smooth endoplasmic reticulum, which stores, releases, and retrieves Ca^{++}

skeletal muscle fiber
multinucleated skeletal muscle cells

synaptic cleft
space between a nerve (axon) terminal and a motor end-plate

T-tubule
projection of the sarcolemma into the interior of the cell

terminal cisternae
enlarged regions of the sarcoplamic reticulum found on either side of the t-tubules

thick filament
the thick myosin strands and their multiple heads projecting from the center of the sarcomere toward, but not all to way to, the Z-discs

thin filament
thin strands of actin and its troponin-tropomyosin complex projecting from the Z-discs toward the center of the sarcomere

triad
the grouping of one T-tubule and two terminal cisternae

troponin
regulatory protein that binds to actin, tropomyosin, and calcium

tropomyosin
regulatory protein that covers myosin-binding sites to prevent actin from binding to myosin

voltage-gated sodium channels
membrane proteins that open sodium channels in response to a sufficient voltage change, and initiate and transmit the action potential as Na^{+} enters through the channel

Z-disc
also Z-line; structure that forms the border of a sarcomere and serves as the anchor site for actin.

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9.4: Muscle Fiber Contraction and Relaxation

By the end of this section, you will be able to:

- Describe the components involved in a muscle contraction
- Explain how muscles contract and relax
- Describe the sliding filament model of muscle contraction

The sequence of events that result in the contraction of an individual muscle fiber begins with a signal — the neurotransmitter, acetylcholine (ACh) — from the motor neuron innervating that fiber. When an action potential traveling down the motor neuron arrives at the neuromuscular junction ACh is released from the axon terminal. These ACh molecules bind to receptors on the motor end plate (the specialized sarcolemma at the neuromuscular junction). This binding leads to the opening of sodium ion channels on the motor end plate and causes the sarcolemma to depolarize as positively charged sodium ions (Na^{+}) enter, triggering an action potential that spreads to the rest of the membrane, including the T-tubules. This triggers the release of calcium ions (Ca^{++}) from storage in the sarcoplasmic reticulum (SR). The Ca^{++} then initiates contraction by binding to a thin filament regulatory protein (troponin) causing a molecular interaction that moves another thin filament regulatory protein (tropomyosin) off the myosin binding sites on actin. As soon as the myosin binding sites are exposed, myosin heads bind to actin and move through a “cross-bridge cycle”, that leads to muscle contraction (Figure 9.4.1). As long as Ca^{++} ions remain in the sarcoplasm to bind to troponin, which keeps the actin-binding sites “unshielded,” and as long as ATP is available to drive the cross-bridge cycling and the pulling of actin strands by myosin, the muscle fiber will continue to shorten to an anatomical limit.

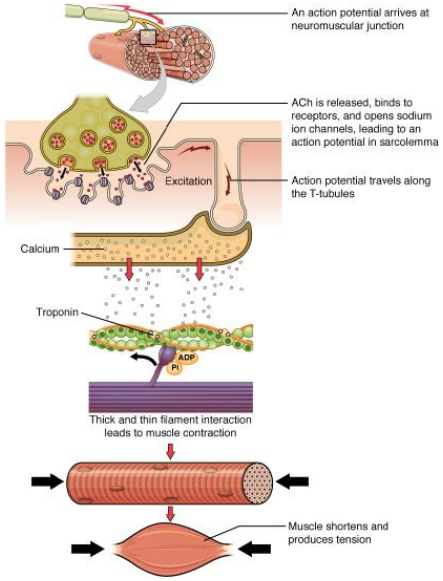

Figure 9.4.1: Contraction of a Muscle Fiber. A cross-bridge forms between actin and the myosin heads initiating contraction. As long as Ca^{++} ions remain in the sarcoplasm to bind to troponin, and as long as ATP is available, the muscle fiber will continue to shorten. (Image credit: "Contraction" by Openstax is licensed under CC BY 4.0)

Muscle contraction usually stops when signaling from the motor neuron ends, which repolarizes the sarcolemma and T-tubules, and closes the voltage-gated calcium channels in the SR. Ca^{++} ions are then pumped back into the SR, through the process of active transport, which requires ATP. The lack of Ca^{++} ions causes the tropomyosin to reshield (or re-cover) the binding sites on the actin strands, allowing the actin (thin) and myosin (thick) interaction to relax, ending the cross-bridge cycle. This leads to the muscle relaxing and lengthening. A muscle also can stop contracting when it runs out of ATP and becomes fatigued (Figure 9.4.2).

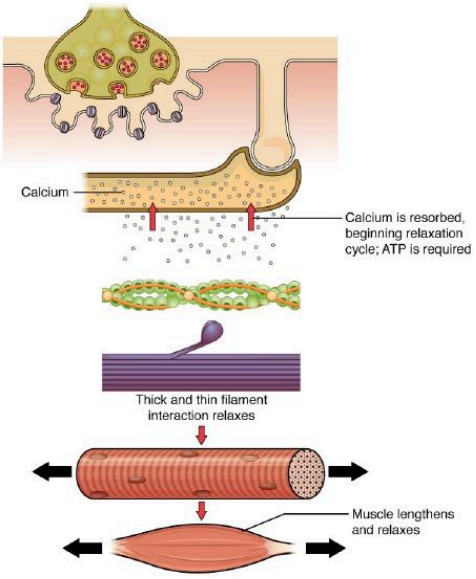

Figure 9.4.2: Relaxation of a Muscle Fiber. Ca^{++} ions are pumped back into the SR, which causes the tropomyosin to reshield the myosin binding sites on actin strands. A muscle may also stop contracting when it runs out of ATP and becomes fatigued. (Image credit: "Relaxation" by Whitney Menefee is licensed under CC BY 4.0 / A derivative from the original work)

The molecular events of muscle fiber shortening occur within the fiber's sarcomeres (see Figure 9.4.3). The contraction of a striated muscle fiber occurs as the sarcomeres, linearly arranged within myofibrils, shorten as myosin heads pull on the actin filaments.

The region where thick and thin filaments overlap has a dense appearance, as there is little space between the filaments. This zone where thin and thick filaments overlap is very important to muscle contraction, as it is the site where filament movement starts. Thin filaments, anchored at their ends by the Z-discs, do not extend completely into the central region that only contains thick filaments (H-zone), anchored at their bases at the M-line. A myofibril is composed of many sarcomeres running along its length; thus, myofibrils and muscle cells contract as the sarcomeres contract.

The Sliding Filament Model of Contraction

When signaled by a motor neuron, a skeletal muscle fiber contracts as the thin filaments are pulled and then slide past the thick filaments within the fiber's sarcomeres. This process is known as the sliding filament model of muscle contraction (Figure 9.4.3). The sliding can only occur when myosin-binding sites on the actin filaments are exposed by a series of steps that begins with Ca^{++} entry into the sarcoplasm.

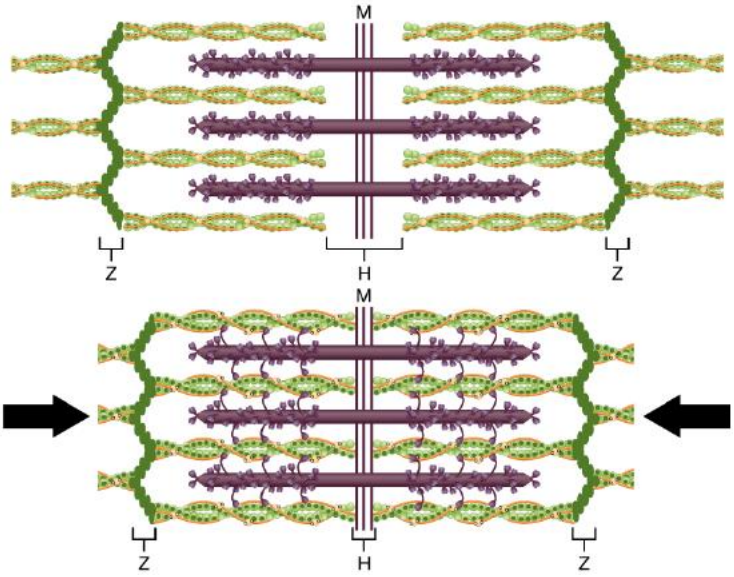

Figure 9.4.3: The Sliding Filament Model of Muscle Contraction. When a sarcomere contracts, the Z lines move closer together, and the I band becomes smaller. The A band stays the same width, but the H-zone shortens or disappears. At full contraction, the thin and thick filaments overlap. (Image credit: "Sliding Filament Model of Muscle Contraction" by Openstax is licensed under CC BY 4.0)

Tropomyosin is a protein that winds around the chains of the actin filament and covers the myosin-binding sites to prevent actin from binding to myosin. Tropomyosin binds to **troponin**, which anchors the tropomyosin in place, to form a troponin-tropomyosin complex. In a relaxed muscle, the troponin-tropomyosin complex prevents the myosin heads from binding to the active sites on the actin microfilaments. Troponin also has a binding site for Ca^{++} ions.

These two regulatory proteins work together to respond to calcium and thus “regulate” sarcomere contraction. To initiate muscle contraction, the position of tropomyosin is shifted to expose the myosin-binding site on an actin filament to allow cross-bridge formation between the actin and myosin microfilaments. The first step in the process of contraction is for Ca^{++} to bind to troponin causing an interaction that slides tropomyosin away from the binding sites on actin filaments. This allows the myosin heads to bind to these exposed binding sites and form cross-bridges. The thin filaments are then pulled by the myosin heads to slide past the thick filaments toward the center of the sarcomere. But each head can only pull a very short distance before it has reached its limit and must be “re-cocked” before it can pull again, a step that requires ATP.

ATP and The Cross-Bridge Cycle

For thin filaments to continue to slide past thick filaments during muscle contraction, myosin heads must pull the actin at the binding sites, detach, re-cock, attach to more binding sites, pull, detach, re-cock, etc. This repeated movement is known as the cross-bridge cycle. This motion of the myosin heads is similar to the oars when an individual rows a boat: The paddle of the oars (the myosin heads) pull, are lifted from the water (detach), repositioned (re-cocked) and then immersed again to pull (Figure 9.4.4). Each cycle requires energy, and the action of the myosin heads in the sarcomeres repetitively pulling on the thin filaments also requires energy, which is provided by ATP.

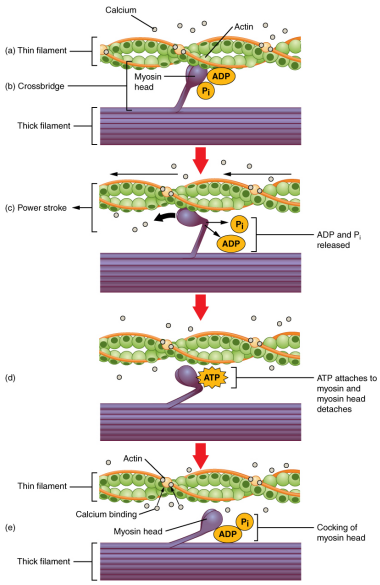

Figure 9.4.4: Skeletal Muscle Contraction. (a) The active site on actin is exposed as calcium binds to troponin. (b) The myosin head is attracted to actin, and myosin binds actin at its actin-binding site, forming the cross-bridge. (c) During the power stroke, the myosin head pivots toward the center of the sarcomere, and ADP and the phosphate group are released. (d) A new molecule of ATP attaches to the myosin head, causing the cross-bridge to detach. (e) The myosin head hydrolyzes ATP to ADP and phosphate, which returns the myosin to the cocked position. (Image credit: "Skeletal Muscle Contraction" by Openstax is licensed under CC BY 4.0)

Cross-bridge formation occurs when the myosin head attaches to actin while adenosine diphosphate (ADP) and inorganic phosphate (P_i) are still bound to myosin (Figure 9.4.4.a,b.). P_i is then released, causing myosin to form a stronger attachment to the actin, after which the myosin head moves toward the M-line, pulling the actin along with it. As actin is pulled, the filaments move approximately 10 nm toward the M-line. This movement is called the **power stroke**, as movement of the thin filament occurs at this step (Figure 9.4.4.c.). In the absence of ATP, the myosin head will not detach from actin.

In addition to the actin binding sites on myosin heads, there is also an ATP binding site. When ATP binds in this location, it causes the myosin head to detach from the actin (Figure 9.4.4.d). After this occurs, ATP is converted to ADP and P_i by the intrinsic **ATPase** activity of myosin. The energy released during ATP hydrolysis changes the angle of the myosin head into a cocked position (Figure 9.4.4.e). The myosin head is now in position for further movement.

When the myosin head is cocked, myosin is in a high-energy configuration. This energy is expended as the myosin head moves through the power stroke, and at the end of the power stroke, the myosin head is in a low-energy position. After the power stroke, ADP is released; however, the formed cross-bridge is still in place, and actin and myosin are bound together. As long as ATP is available, it readily attaches to myosin, the cross-bridge cycle can recur, and muscle contraction can continue.

Note that each thick filament of roughly 300 myosin molecules has multiple myosin heads, and many cross-bridges form and break continuously during muscle contraction. Multiply this by all of the sarcomeres in one myofibril, all the myofibrils in one muscle fiber, and all of the muscle fibers in one skeletal muscle, and you can understand why so much energy (ATP) is needed to keep skeletal muscles working. In fact, it is the loss of ATP that results in the rigor mortis observed soon after someone dies. With no further ATP production possible, there is no ATP available for myosin heads to detach from the actin-binding sites, so the cross-bridges stay in place, causing the rigidity in the skeletal muscles.

Relaxation of a Skeletal Muscle

Relaxing skeletal muscle fibers, and ultimately, the skeletal muscle, begins with the motor neuron, which stops releasing its chemical signal, ACh, into the synapse at the NMJ. The muscle fiber will repolarize, which closes the gates in the SR where Ca^{++} was being released. ATP-driven pumps will move Ca^{++} out of the sarcoplasm back into the SR. This results in the “reshielding” of the actin-binding sites on the thin filaments. Without the ability to form cross-bridges between the thin and thick filaments, the muscle fiber loses its tension and relaxes.

Muscle Strength

The number and type of skeletal muscle fibers in a given muscle is genetically determined and does not change. Muscle strength is directly related to the amount of myofibrils and sarcomeres within each fiber. Factors, such as hormones and stress (and artificial anabolic steroids), acting on the muscle can increase the production of sarcomeres and myofibrils within the muscle fibers, a change called hypertrophy, which results in an increased mass and bulk of a skeletal muscle. Likewise, decreased use of a skeletal muscle results in atrophy, where the number of sarcomeres and myofibrils decrease (but not the number of muscle fibers). It is common for a limb in a cast to result in dramatically atrophied muscles and certain diseases, such as polio, present with muscular atrophy as a comorbidity.

DISORDERS OF THE...

Muscular System

Duchenne muscular dystrophy (DMD) is a progressive weakening of the skeletal muscles. It is one of several diseases collectively referred to as "muscular dystrophy." DMD is caused by a lack of the protein dystrophin, which helps the thin filaments of myofibrils bind to the sarcolemma. Without sufficient dystrophin, muscle contractions cause the sarcolemma to tear, causing an influx of Ca++, leading to cellular damage and muscle fiber degradation. Over time, as muscle damage accumulates, muscle mass is lost, and greater functional impairments develop.

DMD is an inherited disorder caused by an abnormal X chromosome. It primarily affects males, and it is usually diagnosed in early childhood. DMD usually first appears as difficulty with balance and motion, and then progresses to an inability to walk. It continues progressing upward in the body from the lower extremities to the upper body, where it affects the muscles responsible for breathing and circulation. It ultimately causes death due to respiratory failure, and those afflicted do not usually live past their 20s.

Because DMD is caused by a mutation in the gene that codes for dystrophin, it was thought that introducing healthy myoblasts into patients might be an effective treatment. Myoblasts are the embryonic cells responsible for muscle development, and ideally, they would carry healthy genes that could produce the dystrophin needed for normal muscle contraction. This approach has been largely unsuccessful in humans. A more recent approach has involved attempting to boost the muscle's production of utrophin, a protein similar to dystrophin that may be able to assume the role of dystrophin and prevent cellular damage from occurring.

Concept Review

A muscle cell is filled with thousands of myofibrils, chains of sarcomeres attached from Z-disc to Z-disc. Sarcomeres are the smallest contractile portion of a muscle. Myofibrils are composed of thick and thin filaments. Thick filaments are composed of the protein myosin; thin filaments are composed of the protein actin. Troponin and tropomyosin are regulatory proteins affiliated with the thin filament.

Muscle contraction is described by the sliding filament model of contraction. ACh is the neurotransmitter that binds at the neuromuscular junction (NMJ) to trigger depolarization, and an action potential travels along the sarcolemma to trigger calcium release from the SR. The myosin binding sites on actin sites are exposed after calcium enters the sarcoplasm and activates the troponin-tropomyosin complex to shift. The latching of myosin heads docking onto actin-binding sites begins the "cross bridge cycle" a process that continues as long as calcium and ATP are present. During the "power stroke" myosin pulls thin filaments towards the M-line and as thin filaments slide over thick filaments, the Z-discs throughout a myofibril draw closer together to shorten the entire muscle fiber. Ultimately, the sarcomeres, myofibrils, and muscle fibers shorten to produce skeletal muscle contraction.

Review Questions

Q. In relaxed muscle, the myosin-binding site on actin is blocked by _____.

A. titin

B. troponin

C. myoglobin

D. tropomyosin

Answer

Answer: D

Q. According to the sliding filament model, binding sites on actin open when _____.

A. creatine phosphate levels rise

B. ATP levels rise

C. acetylcholine levels rise

D. calcium ion levels rise

Answer

Answer: D

Q. The cell membrane of a muscle fiber is called _____.

A. myofibril

B. sarcolemma

C. sarcoplasm

D. myofilament

Answer

Answer: B

Q. Muscle relaxation occurs when _____.

A. calcium ions are actively transported out of the sarcoplasmic reticulum

B. calcium ions diffuse out of the sarcoplasmic reticulum

C. calcium ions are actively transported into the sarcoplasmic reticulum

D. calcium ions diffuse into the sarcoplasmic reticulum

Answer

Answer: C

Q. During muscle contraction, the cross-bridge detaches when _____.

A. an ADP molecule binds to the myosin head

B. an ATP molecule binds to the myosin head

C. calcium ions bind to troponin

D. calcium ions bind to actin

Answer

Answer: B

Q. Thin and thick filaments are organized into functional units called _____.

A. myofibrils

B. myofilaments

C. T-tubules

D. sarcomeres

Answer

Answer: D

Critical Thinking Questions

Q. How would muscle contractions be affected if skeletal muscle fibers did not have T-tubules?

Answer

A. Without T-tubules, action potential conduction into the interior of the cell would happen much more slowly, causing delays between neural stimulation and muscle contraction, resulting in slower, weaker contractions.

Q. What causes the striated appearance of skeletal muscle tissue?

Answer

A. The microscopic arrangement of myofilaments within sarcomeres results in dark A bands and light I bands. These bands repeat along myofibrils, and the alignment of myofibrils in the cell cause the entire cell to appear striated.

Q. How would muscle contractions be affected if ATP was completely depleted in a muscle fiber?

Answer

A. Without ATP, the myosin heads cannot detach from the actin-binding sites. All of the “stuck” cross-bridges result in muscle stiffness. In a live person, this can cause a condition like “writer’s cramps.” In a recently dead person, it results in rigor mortis.

Glossary

aerobic respiration
production of ATP in the presence of oxygen

ATPase
enzyme that hydrolyzes ATP to ADP

creatine phosphate
phosphagen used to store energy from ATP and transfer it to muscle

glycolysis
anaerobic breakdown of glucose to ATP

lactic acid
product of anaerobic glycolysis

oxygen debt
: amount of oxygen needed to compensate for ATP produced without oxygen during muscle contraction

power stroke
: action of myosin pulling actin inward (toward the M line)

pyruvic acid
: product of glycolysis that can be used in aerobic respiration or converted to lactic acid

troponin
: regulatory protein that binds to actin, tropomyosin, and calcium

tropomyosin
: regulatory protein that covers myosin-binding sites to prevent actin from binding to myosin

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9.5: Types of Muscle Fibers

By the end of this section, you will be able to:

- Describe the types of skeletal muscle fibers
- Explain fast and slow muscle fibers

Two criteria to consider when classifying the types of muscle fibers are how fast some fibers contract relative to others, and how fibers produce ATP. Using these criteria, there are three main types of skeletal muscle fibers. **Slow oxidative (SO)** fibers contract relatively slowly and use aerobic respiration (using oxygen) to produce ATP. **Fast oxidative (FO)** fibers have fast contractions and primarily use aerobic respiration, but because they may switch to anaerobic respiration (a process called glycolysis that does not require oxygen), can fatigue more quickly than SO fibers. Lastly, **fast glycolytic (FG)** fibers have fast contractions and primarily use anaerobic glycolysis. The FG fibers fatigue more quickly than the others. Most skeletal muscles in a human contain(s) all three types, although in varying proportions.

The speed of contraction is dependent on how quickly myosin's ATPase hydrolyzes ATP to produce cross-bridge action. Fast fibers hydrolyze ATP approximately twice as quickly as slow fibers, resulting in much quicker cross-bridge cycling (which pulls the thin filaments toward the center of the sarcomeres at a faster rate). The primary metabolic pathway used by a muscle fiber determines whether the fiber is classified as oxidative or glycolytic. If a fiber primarily produces ATP through aerobic pathways it is oxidative. More ATP can be produced during each metabolic cycle, making the fiber more resistant to fatigue. Glycolytic fibers primarily create ATP through anaerobic glycolysis, which produces less ATP per cycle. As a result, glycolytic fibers fatigue at a quicker rate.

Anatomical distinctions in oxidative fibers reflect the fact that they use and need more oxygen. The oxidative fibers contain many more mitochondria than the glycolytic fibers, because aerobic metabolism, which uses oxygen (O_2) in the metabolic pathway, occurs in the mitochondria. The SO fibers possess a large number of mitochondria and are capable of contracting for longer periods because of the large amount of ATP they can produce, but they have a relatively small diameter to facilitate oxygen delivery and thus have fewer myofibrils and do not produce a large amount of tension or power. SO fibers are extensively supplied with blood capillaries to supply O_2 from the red blood cells in the bloodstream. The SO fibers also possess myoglobin, an O_2-carrying molecule similar to O_2-carrying hemoglobin in the red blood cells. The myoglobin stores some of the needed O_2 within the fibers themselves (and gives SO fibers their red color). All of these features allow SO fibers to produce large quantities of ATP, which can sustain muscle activity without fatiguing for long periods of time.

The fact that SO fibers can function for long periods without fatiguing makes them useful in maintaining posture, producing isometric contractions, stabilizing bones and joints, and making small movements that happen often but do not require large amounts of energy. They do not produce high tension, and thus they are not used for powerful, fast movements that require high amounts of energy and rapid cross-bridge cycling.

FG fibers primarily use anaerobic glycolysis as their ATP source. They have a large diameter and possess high amounts of glycogen, which is used in glycolysis to generate ATP quickly to produce high levels of tension. Because they do not primarily use aerobic metabolism, they do not possess substantial numbers of mitochondria or significant amounts of myoglobin and therefore have a white color. FG fibers are used to produce rapid, forceful contractions to make quick, powerful movements. These fibers fatigue quickly, permitting them to only be used for short periods. Most muscles possess a mixture of each fiber type. The predominant fiber type in a muscle is determined by the primary function of the muscle.

FO fibers are sometimes called intermediate fibers because they possess characteristics that are intermediate between fast fibers and slow fibers. They hydrolyze ATP relatively quickly, more quickly than SO fibers, and thus can produce relatively high amounts of tension. They are oxidative because they produce ATP aerobically, possess high amounts of mitochondria, and do not fatigue quickly. However, FO fibers do not possess significant myoglobin, giving them a lighter color than the red SO fibers. FO fibers are used primarily for movements, such as walking, that require more energy than postural control but less energy than an explosive movement, such as sprinting. FO fibers are useful for this type of movement because they produce more tension than SO fibers but they are more fatigue-resistant than FG fibers.

Concept Review

The three types of muscle fiber are slow oxidative (SO), fast oxidative (FO) and fast glycolytic (FG). SO fibers use aerobic metabolism to produce low power contractions over long periods and are slow to fatigue. FO fibers use aerobic metabolism to produce ATP but produce higher tension contractions than SO fibers. FG fibers use anaerobic metabolism to produce powerful, high-tension contractions but fatigue quickly.

Review Questions

Q. A sprinter would experience muscle fatigue sooner than a marathon runner due to _____.

A. anaerobic metabolism in the muscles of the sprinter

B. anaerobic metabolism in the muscles of the marathon runner

C. aerobic metabolism in the muscles of the sprinter

D. glycolysis in the muscles of the marathon runner

Answer

Answer: A

Q. Drug X blocks ATP regeneration from ADP and phosphate. How will muscle cells respond to this drug?

A. by absorbing ATP from the bloodstream

B. by using ADP as an energy source

C. by using glycogen as an energy source

D. none of the above

Answer

Answer: D

Critical Thinking Questions

Q. Compare the anatomical differences between SO and FG muscle fibers. How do these differences relate to their function?

Answer

A. Anatomical Differences.

Glossary

fast glycolytic (FG)
muscle fiber that primarily uses anaerobic glycolysis

fast oxidative (FO)
intermediate muscle fiber that is between slow oxidative and fast glycolytic fibers

slow oxidative (SO)
muscle fiber that primarily uses aerobic respiration

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9.6: Development and Regeneration of Muscle Tissue

By the end of this section, you will be able to:

- Describe the function of satellite cells
- Define fibrosis
- Explain which muscle type has the greatest regeneration ability

Most muscle tissue of the body arises from embryonic mesoderm. Paraxial mesodermal cells adjacent to the neural tube form blocks of cells called **somites**. Skeletal muscles, excluding those of the head and limbs, develop from mesodermal somites, whereas skeletal muscle in the head and limbs develop from general mesoderm. Somites give rise to myoblasts. A **myoblast** is a muscle-forming stem cell that migrates to different regions in the body and then fuse(s) to form a syncytium, or **myotube**. As a myotube is formed from many different myoblast cells, it contains many nuclei, but has a continuous cytoplasm. This is why skeletal muscle cells are multinucleate, as the nucleus of each contributing myoblast remains intact in the mature skeletal muscle cell. However, cardiac and smooth muscle cells are not multinucleate because the myoblasts that form their cells do not fuse.

Gap junctions develop in cardiac and single-unit smooth muscle in the early stages of development. In skeletal muscles, ACh receptors are initially present along most of the sarcolemma of myoblasts, but spinal nerve innervation causes the release of growth factors that stimulate their concentration during the formation of motor end-plates. As neurons become active, electrical signals that are sent through myocytes influence the distribution of slow and fast fibers in the muscle.

Although the number of muscle cells is set during development, satellite cells help to repair skeletal muscle cells. A **satellite cell** is similar to a myoblast because it is a type of stem cell; however, satellite cells are incorporated into muscle cells and facilitate the protein synthesis required for repair and growth. These cells are located outside the sarcolemma, in the endomysium, and are stimulated to grow and fuse with muscle cells by growth factors that are released by muscle fibers under certain forms of stress. Satellite cells primarily help to repair damage in living cells, but they can regenerate muscle fibers to a limited extent. If a cell is damaged to a greater extent than can be repaired by satellite cells, the muscle fibers are replaced by scar tissue in a process called **fibrosis**. Because scar tissue cannot contract, muscle that has sustained significant damage loses strength and cannot produce the same amount of power or endurance as it could before being damaged.

Smooth muscle tissue can regenerate from a type of stem cell called a **pericyte**, which is found in some small blood vessels. Pericytes allow smooth muscle cells to regenerate and repair much more readily than skeletal and cardiac muscle tissue. Similar to skeletal muscle tissue, cardiac muscle does not regenerate to a great extent. Dead cardiac muscle tissue is replaced by scar tissue, which cannot contract. As scar tissue accumulates, the heart loses its ability to pump because of the loss of contractile power. Fibrosis within cardiac tissue can cause electrical signaling disturbances and arrhythmias as well as cardiac failure from the decrease in contractile force. However, some minor regeneration may occur due to stem cells found in the blood that occasionally enter cardiac tissue.

CAREER CONNECTION

Physical Therapist

As muscle cells die, they are not regenerated but instead are replaced by connective tissue and adipose tissue, which do not possess the contractile abilities of muscle tissue. Muscles atrophy when they are not used, and over time if atrophy is prolonged, muscle cells die. It is therefore important that those who are susceptible to muscle atrophy exercise to maintain muscle function and prevent the complete loss of muscle tissue. In extreme cases, when movement is not possible, electrical stimulation can be introduced to a muscle from an external source. This acts as a substitute for endogenous (naturally originating from within) neural stimulation, stimulating the muscle to contract and preventing the loss of proteins that occurs with a lack of use.

Physical therapists work with patients to maintain muscle health. They are trained to target muscles susceptible to atrophy, and to prescribe and monitor exercises designed to stimulate those muscles. There are various causes of atrophy, including mechanical injury, disease, and age. After breaking a limb or undergoing surgery, inflammation and impaired muscle use

can lead to atrophy. If the muscles are not exercised, this atrophy can lead to long-term muscle weakness. A stroke can also cause muscle impairment by interrupting neural stimulation to certain muscles. Without neural inputs, these muscles do not contract and thus begin to lose structural proteins. Exercising these muscles can help to restore muscle function and minimize functional impairments. Age-related muscle loss (sarcopenia) is also a target of physical therapy, as exercise can reduce the effects of age-related atrophy and improve muscle function.

The goal of a physical therapist is to improve physical functioning and reduce functional impairments; this is achieved by understanding the cause of muscle impairment and assessing the capabilities of a patient, after which a program to enhance these capabilities is designed. Some factors that are assessed include strength, balance, and endurance, which are continually monitored as exercises are introduced to track improvements in muscle function. Physical therapists can also instruct patients on the proper use of equipment, such as crutches, and assess whether someone has sufficient strength to use them.

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10: MUSCULAR SYSTEM

10.1: Introduction to the Muscular System
10.2: Interactions of Skeletal Muscles, Their Fascicle Arrangement, and Their Lever Systems
10.3: Naming Skeletal Muscle
10.4: Axial Muscles of the Head, Neck, and Back
10.5: Axial Muscles of the Abdominal Wall and Thorax
10.6: Appendicular Muscles of the Pectoral Girdle and Upper Limbs
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs

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10.1: Introduction to the Muscular System

Chapter Learning Objectives

After studying this chapter, you will be able to:

- Describe the actions and roles of agonists and antagonists
- Explain the structure and organization of muscle fascicles and their role in generating force
- Explain the criteria used to name skeletal muscles
- Identify the skeletal muscles and their actions on the skeleton and soft tissues of the body
- Identify the origins and insertions of skeletal muscles and the prime movements

Think about the things that you do each day—talking, walking, sitting, standing, and running—all of these activities require movement of particular skeletal muscles. Skeletal muscles are even used during sleep. The diaphragm is a sheet of skeletal muscle that has to contract and relax for you to breathe day and night. If you recall from your study of the skeletal system and joints, body movement occurs around the joints in the body. The focus of this chapter is on skeletal muscle organization. The system to name skeletal muscles will be explained; in some cases, the muscle is named by its shape, and in other cases it is named by its location or attachments to the skeleton. If you understand the meaning of the name of the muscle, often it will help you remember its location and/or what it does. This chapter also will describe how skeletal muscles are arranged to accomplish movement, and how other muscles may assist, or be arranged on the skeleton to resist or carry out the opposite movement. The actions of the skeletal muscles will be covered in a regional manner, working from the head down to the toes.

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10.2: Interactions of Skeletal Muscles, Their Fascicle Arrangement, and Their Lever Systems

By the end of this section, you will be able to:

- Compare and contrast agonist and antagonist muscles
- Describe how fascicles are arranged within a skeletal muscle
- Explain the major events of a skeletal muscle contraction within a muscle in generating force

To move the skeleton, the tension created by the contraction of the fibers in most skeletal muscles is transferred to the tendons. The tendons are strong bands of dense, regular connective tissue that connect muscles to bones. The bone connection is why this muscle tissue is called skeletal muscle.

Interactions of Skeletal Muscles in the Body

To pull on a bone, that is, to change the angle at its synovial joint, which essentially moves the skeleton, a skeletal muscle must also be attached to a fixed part of the skeleton. The end of the muscle attached to a fixed (stabilized) bone is called the **origin** and the moveable end of the muscle that attaches to the bone being pulled is called the muscle's **insertion**.

Although a number of muscles may be involved in an action, the principal muscle involved is called the **prime mover**, or **agonist**. During forearm **flexion** (bending the elbow), such as lifting a cup, a muscle called the biceps brachii is actually the prime mover; however, because it can be assisted by the brachialis, the brachialis is called a **synergist** in this action (Figure 10.2.1). Also involved is the brachioradialis which assists the brachialis, and is also considered a synergist. A synergist can also be a **fixator** that stabilizes the bone that is the attachment for the prime mover's origin.

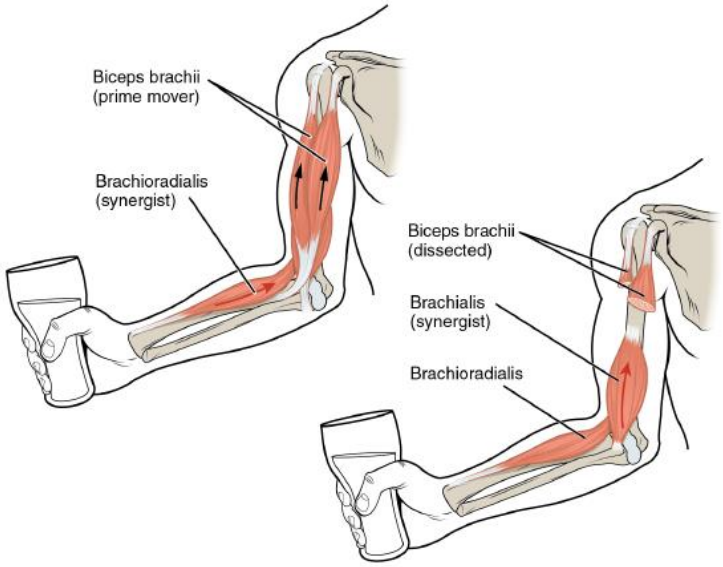

Figure 10.2.1: Prime Movers and Synergists. The biceps brachii flexes the lower arm. The brachoradialis, in the forearm, and brachialis, located deep to the biceps in the upper arm, are both synergists that aid in this motion. (Image credit:"Biceps Muscle" by Openstax is licensed under CC BY 4.0)

A muscle with the opposite action of the prime mover is called an **antagonist**. Antagonists play two important roles in muscle function: (1) they maintain body or limb position, such as holding the arm out or standing erect; and (2) they control rapid movement, as in shadow boxing without landing a punch or the ability to check the motion of a limb.

For example, to extend the knee, a group of four muscles called the quadriceps femoris in the anterior compartment of the thigh

are activated (and would be called the agonists of knee extension). However, to flex the knee joint, an opposite or antagonistic set of muscles called the hamstrings is activated.

As you can see, these terms would also be reversed for the opposing action. If you consider the first action as the knee bending, the hamstrings would be called the agonists and the quadriceps femoris would then be called the antagonists. See Table 10.2.1 for a list of some agonists and antagonists.

Table 10.2.1***:*** Agonist and Antagonist Skeletal Muscle Pairs

Agonist	Antagonist	Movement
Biceps brachii: in the anterior compartment of the arm	Triceps brachii: in the posterior compartment of the arm	The biceps brachii flexes the forearm, whereas the triceps brachii extends it.
Hamstrings: group of three muscles in the posterior compartment of the thigh	Quadriceps femoris: group of four muscles in the anterior compartment of the thigh	The hamstrings flex the leg, whereas the quadriceps femoris extend it.
Flexor digitorum superficialis and flexor digitorum profundus: in the anterior compartment of the forearm	Extensor digitorum: in the posterior compartment of the forearm	The flexor digitorum superficialis and flexor digitorum profundus flex the fingers and the hand at the wrist, whereas the extensor digitorum extends the fingers and the hand at the wrist.

There are also skeletal muscles that do not pull against the skeleton for movements. For example, there are the muscles that produce facial expressions. The insertions and origins of facial muscles are in the skin, so that certain individual muscles contract to form a smile or frown, form sounds or words, and raise the eyebrows. There also are skeletal muscles in the tongue, and the external urinary and anal sphincters that allow for voluntary regulation of urination and defecation, respectively. In addition, the diaphragm contracts and relaxes to change the volume of the pleural cavities but it does not move the skeleton to do this.

EVERYDAY CONNECTIONS

Exercise and Stretching

When exercising, it is important to first warm up the muscles. Stretching pulls on the muscle fibers and it also results in an increased blood flow to the muscles being worked. Without a proper warm-up, it is possible that you may either damage some of the muscle fibers or pull a tendon. A pulled tendon, regardless of location, results in pain, swelling, and diminished function; if it is moderate to severe, the injury could immobilize you for an extended period.

Recall the discussion about muscles crossing joints to create movement. Most of the joints you use during exercise are synovial joints, which have synovial fluid in the joint space between two bones. Exercise and stretching may also have a beneficial effect on synovial joints. Synovial fluid is a thin, but viscous film with the consistency of egg whites. When you first get up and start moving, your joints feel stiff for a number of reasons. After proper stretching and warm-up, the synovial fluid may become less viscous, allowing for better joint function.

Patterns of Fascicle Organization

Skeletal muscle is enclosed in connective tissue scaffolding at three levels. Each muscle fiber (cell) is covered by endomysium and the entire muscle is covered by epimysium. When a group of muscle fibers is “bundled” as a unit within the whole muscle by an additional covering of a connective tissue called perimysium, that bundled group of muscle fibers is called a **fascicle**. Fascicle arrangement by perimysia is correlated to the force generated by a muscle; it also affects the range of motion of the muscle. Based on the patterns of fascicle arrangement, skeletal muscles can be classified in several ways. Figure 10.2.2 shows some of the most common fascicle arrangements.

Parallel muscles have fascicles that are arranged in the same direction as the long axis of the muscle. The majority of skeletal muscles in the body have this type of organization. Some parallel muscles are flat sheets that expand at the ends to make broad

attachments. Other parallel muscles are rotund with tendons at one or both ends. Muscles that seem to be plump have a large mass of tissue located in the middle of the muscle, between the insertion and the origin, which is known as the central body, or **belly**. When a muscle contracts, the contractile fibers shorten it to an even larger bulge. For example, extend and then flex your biceps brachii muscle; the large, middle section is the belly (Figure 10.2.3). When a parallel muscle has a central, large belly that is spindle-shaped, meaning it tapers as it extends to its origin and insertion, it sometimes is called **fusiform**. Parallel muscles that do not have have a spindle-shape, but instead have a more consistent diameter throughout the length of the muscle, such as sartorius of the upper leg, are non-fusiform.

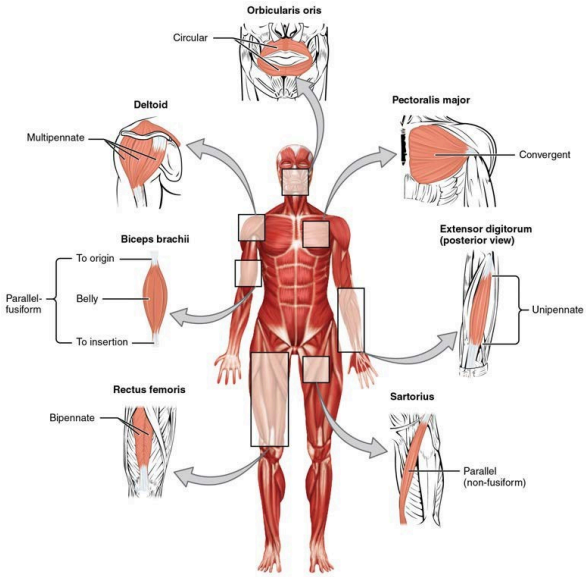

Figure 10.2.2: Muscle Shapes and Fascicle Arrangement. The skeletal muscles of the body typically come in seven different general shapes. (Image credit: "Fascicle Muscle Shapes" by Openstax is licensed under CC BY 4.0)

Figure 10.2.3: Biceps Brachii Muscle Contraction. The large mass at the center of a muscle is called the belly. Tendons emerge from both ends of the belly and connect the muscle to the bones, allowing the skeleton to move. The tendons of the bicep brachii connect to the upper arm and the forearm. (Image credit: "Biceps Brachii Muscle Contraction" by OpenStax College/Victoria Garcia is licensed under CC BY-SA 3.0)

Circular muscles are also called sphincters (Figure 10.2.2). When they relax, the sphincters' concentrically arranged bundles of muscle fibers increase the size of the opening, and when they contract, the size of the opening shrinks to the point of closure. The orbicularis oris muscle is a circular muscle that goes around the mouth. When it contracts, the oral opening becomes smaller, as when puckering the lips for whistling. Another example is the orbicularis oculi, one of which surrounds each eye. Consider, for example, the names of the two orbicularis muscles (orbicularis oris and oribicularis oculi), where part of the first name of both muscles is the same. The first part of orbicularis, orb (orb = "circular"), is a reference to a round or circular structure; it may also make one think of orbit, such as the moon's path around the earth. The word oris (oris = "oral") refers to the oral cavity, or the

mouth. The word oculi (ocular = “eye”) refers to the eye.

When a muscle has a widespread expansion over a sizable area, but then the fascicles come to a single, common attachment point, the muscle is called **convergent**. The attachment point for a convergent muscle could be a tendon, an aponeurosis (a flat, broad tendon), or a raphe (a very slender tendon). The large muscle on the chest, the pectoralis major, is an example of a convergent muscle because it converges on the greater tubercle of the humerus via a tendon. The temporalis muscle of the cranium is another.

Pennate muscles (penna = “feathers”) blend into a tendon that runs through the central region of the muscle for its whole length, somewhat like the quill of a feather with the muscle arranged similar to the feathers. Due to this design, the muscle fibers in a pennate muscle can only pull at an angle, and as a result, contracting pennate muscles do not move their tendons very far. However, because a pennate muscle generally can hold more muscle fibers within it, it can produce relatively more tension for its size. There are three subtypes of pennate muscles.

In a **unipennate** muscle, the fascicles are located on one side of the tendon. The extensor digitorum of the forearm is an example of a unipennate muscle. A **bipennate** muscle has fascicles on both sides of the tendon, as seen in rectus femoris of the upper leg. In some pennate muscles, the muscle fibers wrap around the tendon, sometimes forming individual fascicles in the process. This arrangement is referred to as **multipennate**. A common example is the deltoid muscle of the shoulder, which covers the shoulder but has a single tendon that inserts on the deltoid tuberosity of the humerus.

Because of the fascicle arrangement, a portion of a multipennate muscle like the deltoid can be stimulated by the nervous system to change the direction of the pull. For example, when the deltoid muscle contracts, the arm **abducts** (moves away from midline in the sagittal plane), but when only the anterior fascicles are stimulated, the arm will abduct and flex (move anteriorly at the shoulder joint).

The Lever System of Muscle and Bone Interactions

Skeletal muscles do not work by themselves. Muscles are arranged in pairs based on their functions. For muscles attached to the bones of the skeleton, the connection determines the force, speed, and range of movement. These characteristics depend on each other and can explain the general organization of the muscular and skeletal systems.

The skeleton and muscles act together to move the body. Have you ever used the back of a hammer to remove a nail from wood? The handle acts as a lever and the head of the hammer acts as a fulcrum, the fixed point that the force is applied to when you pull back or push down on the handle. The effort applied to this system is the pulling or pushing on the handle to remove the nail, which is the load, or “resistance” to the movement of the handle in the system. Our musculoskeletal system works in a similar manner, with bones being stiff levers and the articular endings of the bones—encased in synovial joints—acting as fulcrums. The load would be an object being lifted or any resistance to a movement (your head is a load when you are lifting it), and the effort, or applied force, comes from contracting skeletal muscle.

Lever systems in the human body are classified based on the arrangement pattern of the fulcrum, resistance, and the applied force (Figure $10.2.4$). When the fulcrum lies between the resistance and the applied force, it is considered to be a first class lever (Figure $10.2.4.a$). Tilting your head back uses a first class lever. In this motion the atlanto-occipital joint is the fulcrum, the head is the resistance, and the applied force is generated by the trapezius muscle of the neck.

A second class lever is arranged with the resistance between the fulcrum and the applied force (Figure $10.2.4.b$). When you stand on your tip toes, a second class lever is in use. The the body (resistance), lies between the metatarsophalangeal joints (fulcrum), and the applied forced from several lower leg muscles including gastrocnemius.

The arrangement of a third class lever has the applied force between the fulcrum and the resistance (Figure $10.2.4.c$). Flexion at the elbow, with the biceps brachii muscle (applied force) between the elbow joint (fulcrum) and the lower arm (resistance), is an example of motion using a third class lever.

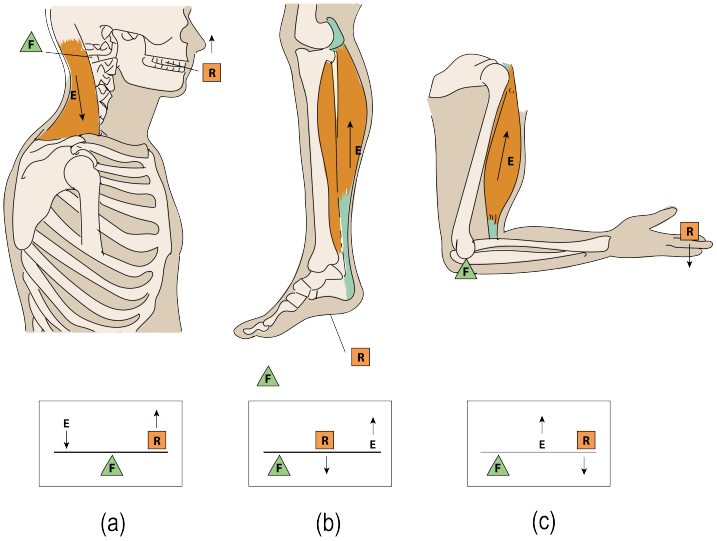

Figure 10.2.4: Lever Systems of the Human Body. (a) First class lever. (b) Second class lever. (c) Third class lever. The arrangement of the fulcrum (F), resistance (R), and effort, or applied force (E), determines the lever type found in the human body. (Image credit: “Lever Systems of the Human Body" by Daniel Donnelly is licensed under CC BY 4.0)

Concept Review

Skeletal muscles each have an origin and an insertion. The end of the muscle that attaches to the bone being pulled is called the muscle’s insertion and the end of the muscle attached to a fixed, or stabilized, bone is called the origin. The muscle primarily responsible for a movement is called the prime mover, and muscles that assist in this action are called synergists. A synergist that makes the insertion site more stable is called a fixator. Meanwhile, a muscle with the opposite action of the prime mover is called an antagonist. Several factors contribute to the force generated by a skeletal muscle. One is the arrangement of the fascicles in the skeletal muscle. Fascicles can be parallel, circular, convergent, or pennate. Each arrangement has its own range of motion and ability to do work.

Review Questions

Q. Which of the following is unique to the muscles of facial expression?

A. They all originate from the scalp musculature.

B. They insert onto the cartilage found around the face.

C. They only insert onto the facial bones.

D. They insert into the skin.

Answer

Answer; D

Q. Which of the following helps an agonist work?

A. a synergist

B. a fixator

C. an insertion

D. an antagonist

Answer

Answer: A

Q. Which of the following statements is correct about what happens during flexion?

A. The angle between bones is increased.

B. The angle between bones is decreased.

C. The bone moves away from the body.

D. The bone moves toward the center of the body.

Answer

Answer: B

Q. Which is moved the *least* during muscle contraction?

A. the origin

B. the insertion

C. the ligaments

D. the joints

Answer

Answer: A

Q. Which muscle has a convergent pattern of fascicles?

A. biceps brachii

B. gluteus maximus

C. pectoralis major

D. rectus femoris

Answer

Answer: C

Q. A muscle that has a pattern of fascicles running along the long axis of the muscle has which of the following fascicle arrangements?

A. circular

B. pennate

C. parallel

D. rectus

Answer

Answer: C

Q. Which arrangement *best* describes a bipennate muscle?

A. The muscle fibers feed in on an angle to a long tendon from both sides.

B. The muscle fibers feed in on an angle to a long tendon from all directions.

C. The muscle fibers feed in on an angle to a long tendon from one side.

D. The muscle fibers on one side of a tendon feed into it at a certain angle and muscle fibers on the other side of the tendon feed into it at the opposite angle.

Answer

Answer: A

Critical Thinking Questions

Q. What effect does fascicle arrangement have on a muscle's action?

Answer

A. Fascicle arrangements determine what type of movement a muscle can make. For instance, circular muscles act as sphincters, closing orifices.

Q. Movements of the body occur at joints. Describe how muscles are arranged around the joints of the body.

Answer

A. Muscles work in pairs to facilitate movement of the bones around the joints. Agonists are the prime movers while antagonists oppose or resist the movements of the agonists. Synergists assist the agonists, and fixators stabilize a muscle's origin.

Q. Explain how a synergist assists an agonist by being a fixator.

Answer

A. Agonists are the prime movers while antagonists oppose or resist the movements of the agonists. Synergists assist the agonists, and fixators stabilize a muscle's origin.

Glossary

abduct
move away from midline in the sagittal plane

agonist
(also, prime mover) muscle whose contraction is responsible for producing a particular motion

antagonist
muscle that opposes the action of an agonist

belly
bulky central body of a muscle

bipennate
pennate muscle that has fascicles that are located on both sides of the tendon

circular
(also, sphincter) fascicles that are concentrically arranged around an opening

convergent
fascicles that extend over a broad area and converge on a common attachment site

fascicle
muscle fibers bundled by perimysium into a unit

fixator
synergist that assists an agonist by preventing or reducing movement at another joint, thereby stabilizing the origin of the agonist

flexion
movement that decreases the angle of a joint

fusiform
muscle that has fascicles that are spindle-shaped to create large bellies

insertion
end of a skeletal muscle that is attached to the structure (usually a bone) that is moved when the muscle contracts

multipennate
pennate muscle that has a tendon branching within it

origin
end of a skeletal muscle that is attached to another structure (usually a bone) in a fixed position

parallel
fascicles that extend in the same direction as the long axis of the muscle

pennate
fascicles that are arranged differently based on their angles to the tendon

prime mover
(also, agonist) principle muscle involved in an action

synergist
muscle whose contraction helps a prime mover in an action

unipennate
pennate muscle that has fascicles located on one side of the tendon

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10.3: Naming Skeletal Muscle

By the end of this section, you will be able to:

- Describe the criteria used to name skeletal muscles
- Explain how understanding the muscle names helps describe shapes, location, and actions of various muscles

The Greeks and Romans conducted the first studies done on the human body in Western culture. The educated class of subsequent societies studied Latin and Greek, and therefore the early pioneers of anatomy continued to apply Latin and Greek terminology or roots when they named the skeletal muscles. The large number of muscles in the body and unfamiliar words can make learning the names of the muscles in the body seem daunting, but understanding the etymology can help. Etymology is the study of how the root of a particular word entered a language and how the use of the word evolved over time. Taking the time to learn the root of the words is crucial to understanding the vocabulary of anatomy and physiology. When you understand the names of muscles it will help you remember where the muscles are located and what they do (Figure 10.3.1, Table 10.3.1, and Table 10.3.2). Pronunciation of words and terms will take a bit of time to master, but after you have some basic information the correct names and pronunciations will become easier.

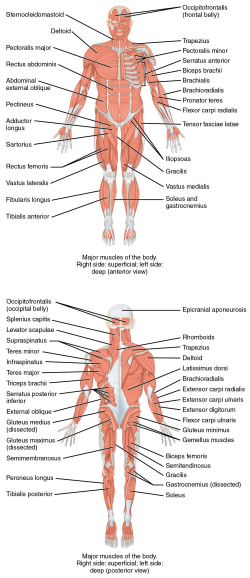

Figure 10.3.1: Overview of the Muscular System. On the anterior and posterior views of the muscular system above, superficial muscles (those at the surface) are shown on the right side of the body while deep muscles (those underneath the superficial muscles) are shown on the left half of the body. For the legs, superficial muscles are shown in the anterior view while the posterior view shows both superficial and deep muscles. (Image Credit: "The Muscular System" by Whitney Menefee is licensed under CC BY 4.0 / A derivative from the original work)

Table 10.3.1: Understanding a Muscle Name from the Latin

Example	Word	Latin Root 1	Latin Root 2	Meaning	Translation
abductor digiti minimi	abductor	ab = away from	duct = to move	a muscle that moves away from	A muscle that moves the little finger or toe away
	digiti	digitus = digit		refers to a finger or toe	
	minimi	minimus = mini, tiny		little	
adductor digiti minimi	adductor	ad = to, toward	duct = to move	a muscle that moves toward	A muscle that moves the little finger or toe toward

Example	Word	Latin Root 1	Latin Root 2	Meaning	Translation
	digiti	digitus = digit		refers to finger or toe	
	minimi	minimus = mini, tiny		little	

Table 10.3.2: Mnemonic Device for Latin Roots

Example	Latin or Greek Translation	Mnemonic Device
ad	to; toward	ADvance toward your goal
ab	away from	n/a
sub	under	SUBmarines move under water.
ductor	something that moves	A conDUCTOR makes a train move.
anti	against	If you are antisocial, you are against engaging in social activities.
epi	on top of	n/a
apo	to the side of	n/a
longissimus	longest	“Longissimus” is longer than the word “long.”
longus	long	long
brevis	short	brief
maximus	large	max
medius	medium	“Medius” and “medium” both begin with “med.”
minimus	tiny; little	mini
rectus	straight	To RECTify a situation is to straighten it out.
multi	many	If something is MULTIcolored, it has many colors.
uni	one	A UNIcorn has one horn.
bi/di	two	If a ring is DIcast, it is made of two metals.
tri	three	TRIple the amount of money is three times as much.
quad	four	QUADruplets are four children born at one birth.
externus	outside	EXternal
internus	inside	INternal

Anatomists name the skeletal muscles according to a number of criteria, each of which describes the muscle in some way. These include naming the muscle after its shape, its size compared to other muscles in the area, its location in the body or the location of its attachments to the skeleton, how many origins it has, or its action.

The skeletal muscle’s anatomical location or its relationship to a particular bone often determines its name. For example, the frontalis muscle is located on top of the frontal bone of the skull. Similarly, the shapes of some muscles are very distinctive and the names, such as orbicularis, reflect the shape ('orb' = circular). The deltoid is a large, triangular-shaped muscle that covers the shoulder. It is so-named because the Greek letter delta looks like a triangle. For the buttocks, the size of the muscles influences the names: gluteus **maximus** (largest), gluteus **medius** (medium), and the gluteus **minimus** (smallest). Names were given to indicate length—**brevis** (short), **longus** (long)—and to identify position relative to the midline: **lateralis** (to the outside away from the midline), and **medialis** (toward the midline). The direction of the muscle fibers and fascicles are used to describe muscles relative to the midline, such as the **rectus** (straight) abdominis, or the **oblique** (at an angle) muscles of the abdomen.

Some muscle names indicate the number of muscles in a group. One example of this is the quadriceps, a group of four muscles located on the anterior (front) thigh. Other muscle names can provide information as to how many origins a particular muscle has,

such as the biceps brachii. The prefix **bi** indicates that the muscle has two origins and **tri** indicates three origins.

The location of a muscle's attachment can also appear in its name. When the name of a muscle is based on the attachments, the origin is always named first. For instance, the sternocleidomastoid muscle of the neck has a dual origin on the sternum (sterno) and clavicle (cleido), and it inserts on the mastoid process of the temporal bone. The last feature by which to name a muscle is its action. When muscles are named for the movement they produce, one can find action words in their name. Some examples are **flexor** (decreases the angle at the joint), **extensor** (increases the angle at the joint), **abductor** (moves the bone away from the midline), or **adductor** (moves the bone toward the midline).

Concept Review

Muscle names are based on many characteristics. The location of a muscle in the body is important. Some muscles are named based on their size and location, such as the gluteal muscles of the buttocks. Other muscle names can indicate the location in the body or bones with which the muscle is associated, such as the tibialis anterior. The shapes of some muscles are distinctive; for example, the direction of the muscle fibers is used to describe muscles of the body midline. The origin and/or insertion can also be features used to name a muscle; examples are the biceps brachii, triceps brachii, and the pectoralis major.

Review Questions

Q. The location of a muscle's insertion and origin can determine _____.

A. action

B. the force of contraction

C. muscle name

D. the load a muscle can carry

Answer

Answer: A

Q. Where is the temporalis muscle located?

A. on the forehead

B. in the neck

C. on the side of the head

D. on the chin

Answer

Answer: C

Q. Which muscle name does *not* make sense?

A. extensor digitorum

B. gluteus minimus

C. biceps femoris

D. extensor minimus longus

Answer

Answer: D

Q. Which of the following terms would be used in the name of a muscle that moves the leg away from the body?

A. flexor

B. adductor

C. extensor

D. abductor

Answer

Answer: D

Critical Thinking Questions

Q. Describe the different criteria that contribute to how skeletal muscles are named.

Answer

A. In anatomy and physiology, many word roots are Latin or Greek. Portions, or roots, of the word give us clues about the function, shape, action, or location of a muscle.

Glossary

abductor
moves the bone away from the midline

adductor
moves the bone toward the midline

bi
two

brevis
short

extensor
muscle that increases the angle at the joint

flexor
muscle that decreases the angle at the joint

lateralis
to the outside

longus
long

maximus
largest

medialis
to the inside

medius
: medium

minimus
: smallest

oblique
: at an angle

rectus
: straight

tri
: three

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10.4: Axial Muscles of the Head, Neck, and Back

By the end of this section, you will be able to:

- Identify the axial muscles of the face, head, and neck
- Identify the movement and function of the face, head, and neck muscles

The skeletal muscles are divided into **axial** (muscles of the trunk and head) and **appendicular** (muscles of the arms and legs) categories. This system reflects the bones of the skeleton system, which are also arranged in this manner. The axial muscles are grouped based on location, function, or both. Some of the axial muscles may seem to blur the boundaries because they cross over to the appendicular skeleton. The first grouping of the axial muscles you will review includes the muscles of the head and neck, then you will review the muscles of the vertebral column, and finally you will review the oblique and rectus muscles.

Muscles That Create Facial Expression

The origins of the muscles of facial expression are on the surface of the skull (remember, the origin of a muscle does not move). The insertions of these muscles have fibers intertwined with connective tissue and the dermis of the skin. Because the muscles insert in the skin rather than on bone, when they contract, the skin moves to create facial expression (Figure 10.4.1).

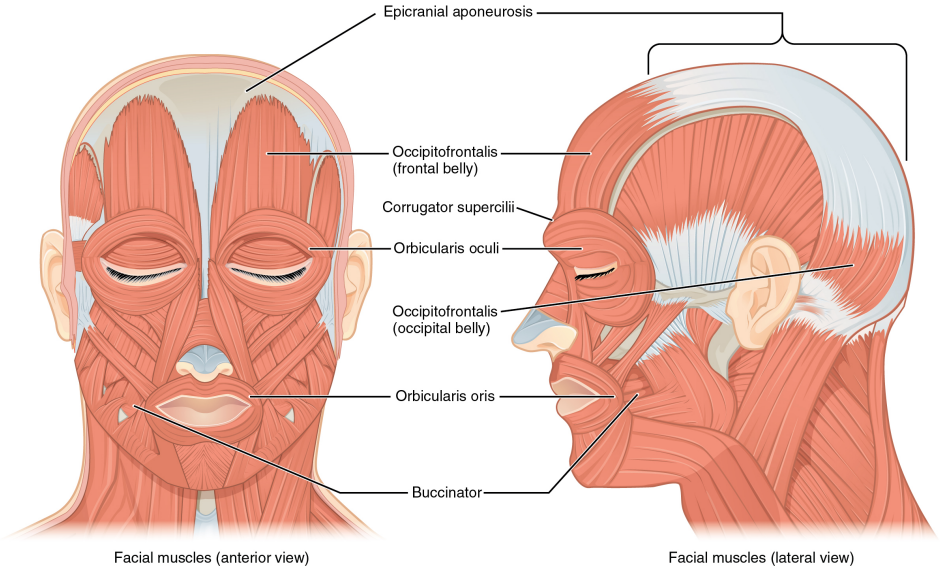

Figure 10.4.1: Muscles of Facial Expression. Many of the muscles of facial expression insert into the skin surrounding the eyelids, nose and mouth, producing facial expressions by moving the skin rather than bones. (Image credit: "Front and Side Views of the Muscles of Facial Expressions" by Openstax is licensed under CC BY 4.0)

The **orbicularis oris** is a circular muscle that moves the lips, and the **orbicularis oculi** is a circular muscle that closes the eye. The **occipitofrontalis** muscle moves up the scalp and eyebrows. The muscle has a frontal belly and an occipital (near the occipital bone on the posterior part of the skull) belly. In other words, there is a muscle on the forehead (**frontalis**) and one on the back of the head (**occipitalis**), but there is no muscle across the top of the head. Instead, the two bellies are connected by a broad tendon called the **epicranial aponeurosis**, or galea aponeurosis (galea = “apple”). The physicians originally studying human anatomy thought the skull looked like an apple.

The majority of the face is composed of the **buccinator** muscle, which compresses the cheek. This muscle allows you to whistle, blow, and suck; and it contributes to the action of chewing. There are several small facial muscles, one of which is the **corrugator supercilii**, which is the prime mover of the eyebrows. Place your finger on your eyebrows at the point of the bridge of the nose. Raise your eyebrows as if you were surprised and lower your eyebrows as if you were frowning. With these movements, you can feel the action of the corrugator supercilli. Additional muscles of facial expression are presented in Table 10.4.1.

Table 10.4.1*: Muscles of Facial Expression*

Primer Mover	Origin	Insertion	Movement	Target	Target Motion Direction
Brow					
Corrugator supercilii	Frontal bone	Skin underneath eyebrow	Lowering eyebrows (e.g. scowling, frowning)	Skin underneath eyebrows	Inferior
Occipitofrontalis (front belly)	Epicraneal aponeurosis	Underneath skin of forehead	Furrowing brow	Skin of scalp	Anterior
Occipitofrontalis (occipital belly)	Occipital bone; mastoid process (temporal bone)	Epicraneal aponeurosis	Unfurrowing brow	Skin of scalp	Posterior
Nose					
Nasalis	Maxilla	Nasal Bone	Flaring nostrils	Nasal cartilage (pushes nostrils open when cartilage is compressed)	Inferior compression; posterior compression
Mouth					
Buccinator	Maxilla, mandible; sphenoid bone (via pterygomandibular raphe)	Orbicularis oris	Lateral movement of cheeks (e.g. sucking on a straw; also used to compress air in mouth while blowing)	Cheeks	Lateral
Depressor angulus oris	Mandible	Underneath skin at corners of mouth	Opening mouth and sliding lower jaw left and right	Lower jaw	Depression, lateral
Depressor labii inferioris	Mandible	Underneath skin of lower lip	Lowering lower lip	Lower lip	Depression
Levator labii superioris	Maxilla	Underneath skin at corners of the mouth; orbicularis oris	Raising upper lip	Upper lip	Elevation
Mentalis	Mandible	Underneath skin of chin	Protrusion of lower lip (e.g. pouting expression)	Lower lip and skin of chin	Protraction
Orbicularis oris	Tissue surrounding lips	Underneath skin at corners of mouth	Shaping of lips (during speech)	Lips	Multiple
Risorius	Fascia of parotid salivary gland	Underneath skin at corners of mouth	Pursing of lips by straightening them laterally	Corners of mouth	Lateral
Zygomaticus major	Zygomatic bone	Underneath skin at corners of mouth (dimple area); orbicularis oris	Smiling	Corners of mouth	Lateral elevation

Muscles That Move the Eyes

The movement of the eyeball is under the control of the **extrinsic eye muscles**, which originate outside the eye and insert onto the outer surface of the white of the eye. These muscles are located inside the eye socket and cannot be seen on any part of the visible eyeball (Figure 10.4.2 and Table 10.4.2). If you have ever been to a doctor who held up a finger and asked you to follow it

up, down, and to both sides, he or she is checking to make sure your eye muscles are acting in a coordinated pattern.

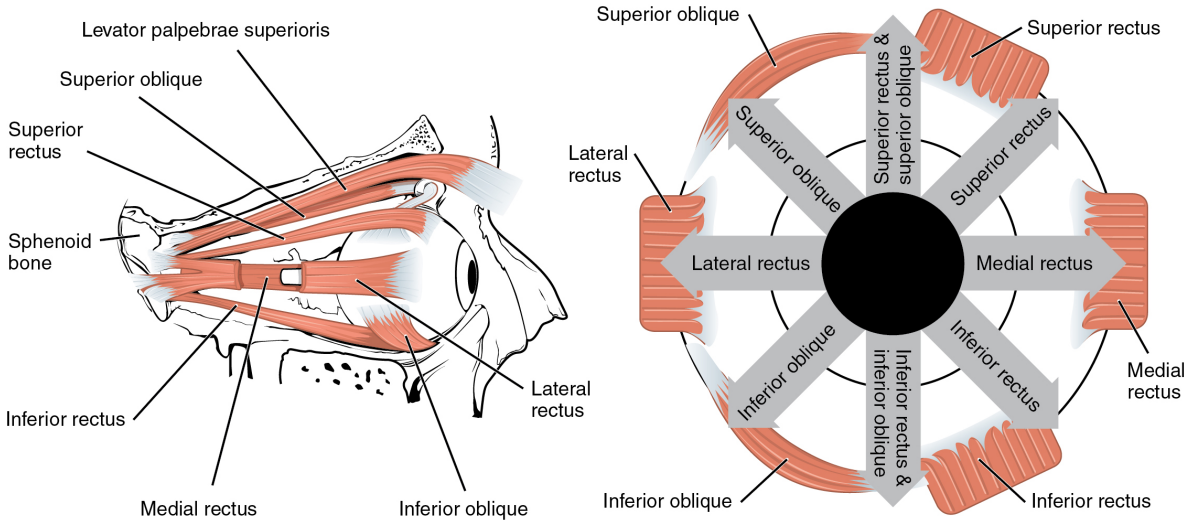

Figure 10.4.2: Muscles of the Eyes. (a) The extrinsic eye muscles originate outside of the eye on the skull. (b) Each muscle inserts onto the eyeball. (Image credit: "The Extrinsic Eye Muscles" by Openstax is licensed under CC BY 4.0)

Table 10.4.2: Muscles of the Eyes

Prime mover	Origin	Insertion	Movement	Target	Target Motion Direction
Inferior oblique	Floor of orbit (maxilla)	Surface of eyeball between inferior rectus and lateral rectus	Moves eyes up and away from nose; rotates eyeball from 12 o'clock to 9 o'clock	Eyeballs	Superior (elevates); lateral (abducts)
Inferior rectus	Common tendinous ring (ring attaches to optic foramen)	Inferior surface of eyeball	Moves eyes down and toward nose; rotates eyes from 6 o'clock to 3 o'clock	Eyeballs	Inferior (depresses); medial (adducts)
Lateral rectus	Common tendinous ring (ring attaches to optic foramen)	Lateral surface of eyeball	Moves eyes away from nose	Eyeballs	Lateral (abducts)
Levator palpabrae superioris	Roof of orbit (sphenoid bone)	Skin of upper eyelids	Opens eyes	Upper eyelid	Superior (elevates)
Medial rectus	Common tendinous ring (ring attaches to optic foramen)	Medial surface of eyeball	Moves eyes toward nose	Eyeballs	Medial (adducts)
Orbicularis oculi	Medial bones composing the orbit	Circumference of orbit	Closes eyelids	Eyelid skin	Compression along superior-inferior axis
Superior oblique	Sphenoid bone	Surface of eyeball between superior rectus and lateral rectus	Moves eyes down and away from nose; rotates eyeball from 6 o'clock to 9 o'clock	Eyeballs	Superior (elevates); lateral (abducts)
Superior rectus	Common tendinous ring (ring attaches to optic foramen)	Superior surface of eyeball	Moves eyes up and toward nose; rotates eyes from 1 o'clock to 3 o'clock	Eyeballs	Superior (elevates); medial (adducts)

Muscles That Move the Lower Jaw

In anatomical terminology, chewing is called **mastication**. Muscles involved in chewing must be able to exert enough pressure to bite through and then chew food before it is swallowed (Figure 10.4.3 and Table 10.4.3). The **masseter** muscle is the main muscle used for chewing because it elevates the mandible (lower jaw) to close the mouth, and it is assisted by the **temporalis** muscle, which retracts the mandible. You can feel the temporalis move by putting your fingers to your temple as you chew.

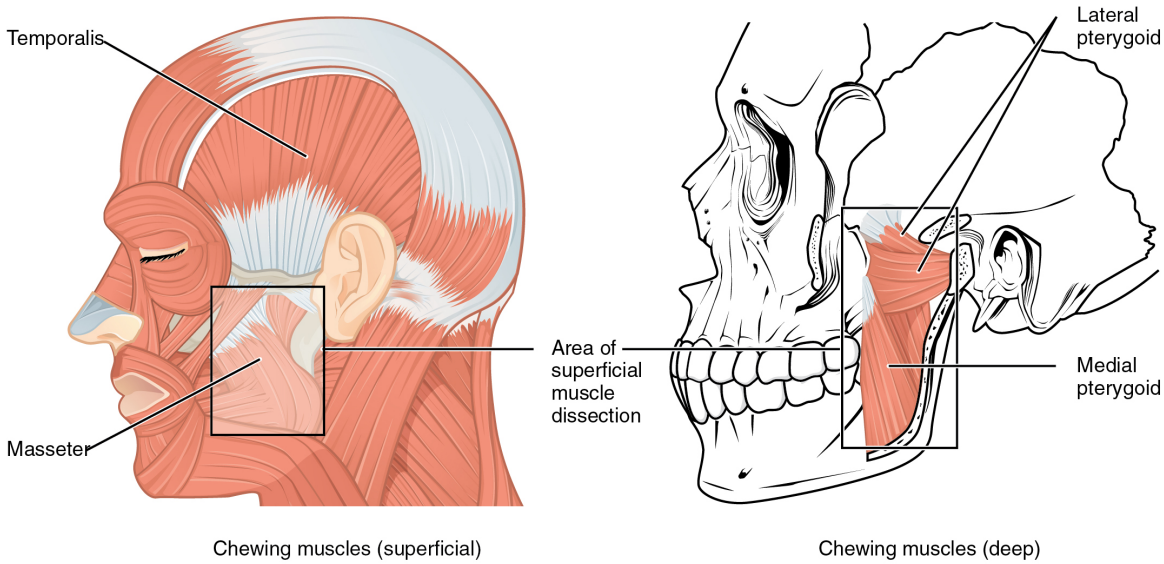

Figure 10.4.3: Muscles That Move the Lower Jaw. The muscles that move the lower jaw are typically located within the cheek and originate from processes in the skull. This provides the jaw muscles with the large amount of leverage needed for chewing. (Image credit: "Muscle that Move the Lower Jaw" by Openstax is licensed under CC BY 4.0)

Table 10.4.3: Muscles of the Lower Jaw

Primer Mover	Origin	Insertion	Movement	Target	Target motion direction
Lateral pterygoid	Pterygoid process of sphenoid bone	Mandible	Opens mouth; pushes lower jaw out under upper jaw; moves lower jaw side-to-side	Mandible	Inferior (depresses); posterior (protracts); lateral (abducts); medial (adducts)
Masseter	Maxilla arch; zygomatic arch (for masseter)	Mandible	Closes mouth; aids chewing	Mandible	Superior (elevates)
Medial pterygoid	Sphenoid bone; maxilla	Mandible; temporomandibular joint	Closes mouth; pushes lower jaw out under upper jaw; moves lower jaw side-to-side	Mandible	Superior (elevates); posterior (protracts); lateral (abducts); medial (adducts)
Temporalis	Temporal bone	Mandible	Closes mouth; pulls lower jaw in under upper jaw	Mandible	Superior (elevates); posterior (retracts)

Although the masseter and temporalis are responsible for elevating and closing the jaw to break food into digestible pieces, the **medial pterygoid** and **lateral pterygoid** muscles provide assistance in chewing and moving food within the mouth.

Muscles That Move the Tongue

Although the tongue is obviously important for tasting food, it is also necessary for mastication, **deglutition** (swallowing), and speech (Figure 10.4.4 and Table 10.4.4). Because it is so moveable, the tongue facilitates complex speech patterns and sounds.

Lateral view showing extrinsic muscle of the tongue and anterior view of the oral cavity showing the surface of the tongue

Figure 10.4.4: Muscles the Move the Tongue. The muscles that move the tongue allow for deglutition and speech. (Image credit: "Muscle that Move the Tongue" by Openstax is licensed under CC BY 4.0)

Table 10.4.4: Muscles for Tongue Movement, Swallowing, and Speech

Primer Mover	Origin	Insertion	Movement	Target	Target Motion Direction
Tongue					
Genioglossus	Mandible	Tongue undersurface; hyoid bone	Moves tongue down; sticks tongue out of mouth	Tongue	Inferior (depresses); anterior (protracts)
Hyoglossus	Hyoid Bone	Sides of tongue	Flattens tongue	Tongue	Inferior (depresses)
Palatoglossus	Soft palate	Sides of tongue	Bulges tongue	Tongue	Superior (elevation)
Styloglossus	Styloid process of temporal bone	Tongue undersurface and sides	Moves tongue up; retracts tongue back into mouth	Tongue	Superior (elevates); posterior (retracts)
Swallowing and Speaking					
Digastric	Mandible; temporal bone	Hyoid bone	Raises hyoid bone in a way that also raises the larynx, allowing the epiglottis to cover the glottis during deglutition; also assists in opening the mouth by depressing the mandible	Hyoid bone; larynx	Superior (elevates)
Geniohyoid	Mandible	Hyoid bone	Raises and moves hyoid bone forward, widening pharynx during deglutition	Hyoid bone	Superior (elevates); anterior (protracts)
Mylohyoid	Mandible	Hyoid bone; median raphe	Raises hyoid bone in a way that presses the tongue against the roof of the mouth, pushing food back into the pharynx during deglutition	Hyoid bone	Superior (elevates)
Omohyoid	Scapula	Hyoid bone	Retracts hyoid bone and moves it down during later phases of deglutition	Hyoid bone	Inferior (depresses); posterior (retracts)
Splenius capitis; longissumus capitis	Spinous processes of vertebrae C7-T3; nuchal ligament	Lateral superior nuchal line of occipital bone, mastoid process of temporal bone	Rotates and tilts head to the side; tilts head backwards	Skull; cervical vertebrae	Individually: lateral rotation; lateral flexion; Bilaterally: anterior (flexes)

Primer Mover	Origin	Insertion	Movement	Target	Target Motion Direction
Sternocleidomastoid; semispinalis capitis	Sternum; clavicle	Mastoid process of temporal bone	Rotates and tilts head to the side; tilts head forward	Skull; cervical vertebrae	Individually: medial rotation; lateral flexion; Bilaterally: anterior (flexes)
Sternohyoid	Clavicle	Hyoid bone	Depresses the hyoid bone during swallowing and speaking	Hyoid bone	Inferior (depresses)
Sternothyroid	Sternum	Thyroid cartilage	Depresses larynx, thyroid cartilage, and hyoid bone to create different vocal tones	Larynx; thyroid cartilage; hyoid bone	Inferior (depresses)
Stylohyoid	Styloid process of temporal bone	Hyoid bone	Raises and retracts the hyoid bone in a way that elongates the oral cavity during deglutition	Hyoid bone	Superior (elevates); posterior (retracts)
Thyrohyoid	Thyroid cartilage	Hyoid bone	Shrinks distance between thyroid cartilage and hyoid bone, allowing production of high-pitch vocalization	Hyoid bone; thyroid cartilage	Hyoid bone: inferior (depresses) Thyroid cartilage: superior (elevates)

Tongue muscles can be extrinsic or intrinsic. Extrinsic tongue muscles insert into the tongue from outside origins, and the intrinsic tongue muscles insert into the tongue from origins within it. The extrinsic muscles move the whole tongue in different directions, whereas the intrinsic muscles allow the tongue to change its shape (such as, curling the tongue in a loop or flattening it).

The extrinsic muscles all include the word root glossus (glossus = “tongue”), and the muscle names are derived from where the muscle originates. The **genioglossus** (genio = “chin”) originates on the mandible and allows the tongue to move downward and forward. The **styloglossus** originates on the styloid bone, and allows upward and backward motion. The **palatoglossus** originates on the soft palate to elevate the back of the tongue, and the **hyoglossus** originates on the hyoid bone to move the tongue downward and flatten it.

EVERYDAY CONNECTIONS

Anesthesia and the Tongue Muscles

Before surgery, a patient must be made ready for general anesthesia. The normal homeostatic controls of the body are put “on hold” so that the patient can be prepped for surgery. Control of respiration must be switched from the patient’s homeostatic control to the control of the anesthesiologist. The drugs used for anesthesia relax a majority of the body’s muscles.

Among the muscles affected during general anesthesia are those that are necessary for breathing and moving the tongue. Under anesthesia, the tongue can relax and partially or fully block the airway, and the muscles of respiration may not move the diaphragm or chest wall. To avoid possible complications, the safest procedure to use on a patient is called endotracheal intubation. Placing a tube into the trachea allows the doctors to maintain a patient's (open) airway to the lungs and seal the airway off from the oropharynx. Post-surgery, the anesthesiologist gradually changes the mixture of the gases that keep the patient unconscious, and when the muscles of respiration begin to function, the tube is removed. It still takes about 30 minutes for a patient to wake up, and for breathing muscles to regain control of respiration. After surgery, most people have a sore or scratchy throat for a few days.

Muscles of the Anterior Neck

The muscles of the anterior neck assist in deglutition (swallowing) and speech by controlling the positions of the larynx (voice box), and the hyoid bone, a horseshoe-shaped bone that functions as a solid foundation on which the tongue can move. The muscles of the neck are categorized according to their position relative to the hyoid bone (Figure 10.4.5). **Suprahyoid muscles** are superior to it, and the **infrahyoid muscles** are located inferiorly.

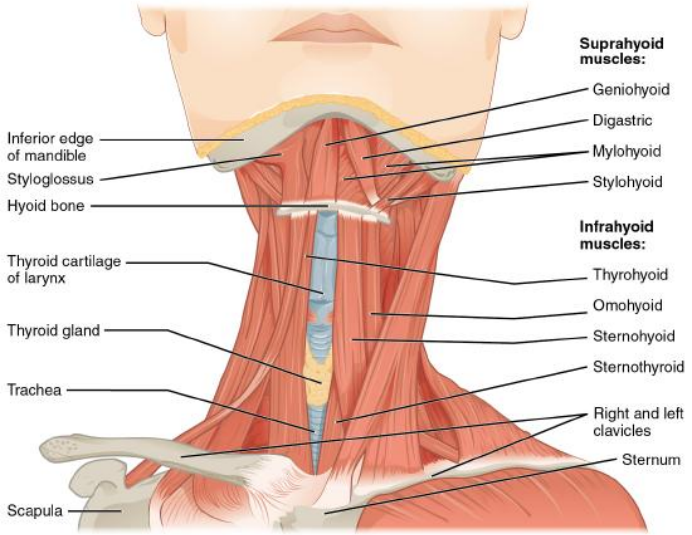

Figure 10.4.5: Muscles of the Anterior Neck. The anterior muscles of the neck facilitate swallowing and speech. The suprahyoid muscles originate from above the hyoid bone in the chin region. The infrahyoid muscles originate below the hyoid bone in the lower neck. (Image credit: "Muscles of the Anterior Neck" by Openstax is licensed under CC BY 4.0)

The suprahyoid muscles raise the hyoid bone, the floor of the mouth, and the larynx during deglutition. These include the **digastric** muscle, which has anterior and posterior bellies that work to elevate the hyoid bone and larynx when one swallows; it also depresses the mandible. The **stylohyoid** muscle moves the hyoid bone posteriorly, elevating the larynx, and the **mylohyoid** muscle lifts it and helps press the tongue to the top of the mouth. The **geniohyoid** depresses the mandible in addition to raising and pulling the hyoid bone anteriorly.

The strap-like infrahyoid muscles generally depress the hyoid bone and control the position of the larynx. The **omohyoid** muscle, which has superior and inferior bellies, depresses the hyoid bone in conjunction with the **sternohyoid** and **thyrohyoid** muscles. The thyrohyoid muscle also elevates the larynx's thyroid cartilage, whereas the **sternothyroid** depresses it to create different tones of voice.

Muscles That Move the Head

The head, attached to the top of the vertebral column, is balanced, moved, and rotated by the neck muscles (Table 10.4.5). When these muscles act unilaterally, the head rotates. When they contract bilaterally, the head flexes or extends. The major muscle that laterally flexes and rotates the head is the **sternocleidomastoid**. In addition, both muscles working together are the flexors of the head. Place your fingers on both sides of the neck and turn your head to the left and to the right. You will feel the movement

originate there. This muscle divides the neck into anterior and posterior triangles when viewed from the side (Figure 10.4.6).

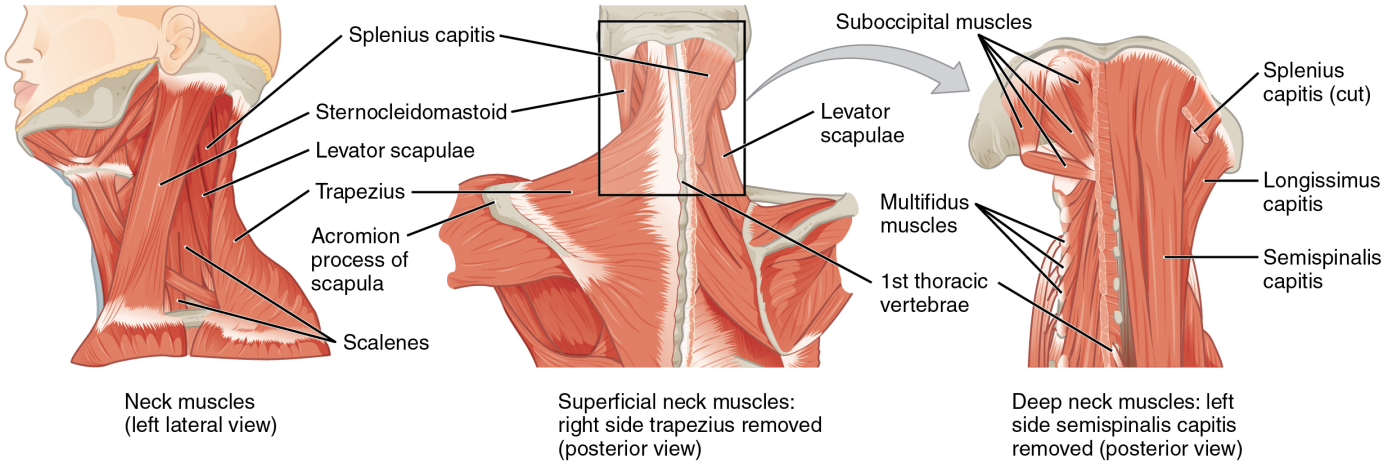

Figure 10.4.6: Posterior and Lateral Views of the Neck. The superficial and deep muscles of the neck are responsible for moving the head, cervical vertebrae, and scapulas. (Image credit: "Posterior and Side Views of the Neck" by Openstax is licensed under CC BY 4.0)

Table 10.4.5: Muscles That Move the Head

Prime Mover	Origin	Insertion	Movement	Target	Target motion direction
Longissimus capitis	Transverse and articular processes of cervical and thoracic vertebrae	Mastoid process of temporal bone	Rotates and tilts head to the side; tilts head backward	Skull; vertebrae	Individually: laterally flexes and rotates head to same side; bilaterally: extension
Semispinalis capitis	Transverse and articular processes of cervical and thoracic vertebrae	Occipital bone	Rotates and tilts head backward	Skull; vertebrae	Individually: laterally flexes and rotates head to same side; bilaterally: extension
Splenius capitis	Spinous process of cervical and thoracic vertebrae	Mastoid process of temporal bone; occipital bone	Rotates and tilts head to the side; tilts head backward	Skull; vertebrae	Individually: laterally flexes and rotates head to same side; bilaterally: extension
Sternocleidomastoid	Sternum; clavicle	Mastoid process of temporal bone; occipital bone	Rotates and tilts head to the side; tilts head forward	Skull; vertebrae	Individually: rotates head to opposite side; bilaterally: flexion

Muscles of the Posterior Neck and the Back

The posterior muscles of the neck are primarily concerned with head movements, like extension. The back muscles stabilize and move the vertebral column, and are grouped according to the lengths and direction of the fascicles.

The **splenius** muscles originate at the midline and run laterally and superiorly to their insertions. From the sides and the back of the neck, the **splenius capitis** inserts onto the head region, and the **splenius cervicis** extends onto the cervical region. These muscles can extend the head, laterally flex it, and rotate it (Figure 10.4.7).

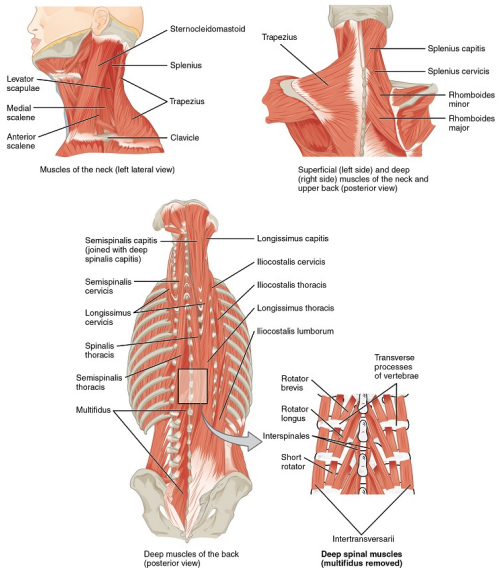

Figure 10.4.7: Muscles of the Neck and Back. The large, complex muscles of the neck and back move the head, shoulders, and vertebral column. (Image credit: "Muscles of the Neck and Back" by Openstax is licensed under CC BY 4.0)

The **erector spinae group** forms the majority of the muscle mass of the back and it is the primary extensor of the vertebral column. It controls flexion, lateral flexion, and rotation of the vertebral column, and maintains the lumbar curve. The erector spinae comprises the iliocostalis (laterally placed) group, the longissimus (intermediately placed) group, and the spinalis (medially placed) group.

The **iliocostalis group** includes the **iliocostalis cervicis**, associated with the cervical region; the **iliocostalis thoracis**, associated with the thoracic region; and the **iliocostalis lumborum**, associated with the lumbar region. The three muscles of the **longissimus group** are the **longissimus capitis**, associated with the head region; the **longissimus cervicis**, associated with the cervical region; and the **longissimus thoracis**, associated with the thoracic region. The third group, the **spinalis group**, comprises the **spinalis capitis** (head region), the **spinalis cervicis** (cervical region), and the **spinalis thoracis** (thoracic region).

The **transversospinales** muscles run from the transverse processes to the spinous processes of the vertebrae. Similar to the erector spinae muscles, the semispinalis muscles in this group are named for the areas of the body with which they are associated. The semispinalis muscles include the **semispinalis capitis**, the **semispinalis cervicis**, and the **semispinalis thoracis**. The **multifidus** muscle of the lumbar region helps extend and laterally flex the vertebral column.

Important in the stabilization of the vertebral column is the **segmental muscle group**, which includes the interspinales and intertransversarii muscles. These muscles bring together the spinous and transverse processes of each consecutive vertebra. Finally, the **scalene muscles** work together to flex, laterally flex, and rotate the head. They also contribute to deep inhalation. The scalene muscles include the **anterior scalene** muscle (anterior to the middle scalene), the **middle scalene** muscle (the longest, intermediate between the anterior and posterior scalenes), and the **posterior scalene** muscle (the smallest, posterior to the middle scalene).

Concept Review

Muscles are either axial muscles or appendicular. The axial muscles are grouped based on location, function, or both. Some axial muscles cross over to the appendicular skeleton. The muscles of the head and neck are all axial. The muscles in the face create facial expression by inserting into the skin rather than onto bone. Muscles that move the eyeballs are extrinsic, meaning they originate outside of the eye and insert onto it. Tongue muscles are both extrinsic and intrinsic. The genioglossus depresses the tongue and moves it anteriorly; the styloglossus lifts the tongue and retracts it; the palatoglossus elevates the back of the tongue; and the hyoglossus depresses and flattens it. The muscles of the anterior neck facilitate swallowing and speech, stabilize the hyoid bone and position the larynx. The muscles of the neck stabilize and move the head. The sternocleidomastoid divides the neck into anterior and posterior triangles.

The muscles of the back and neck that move the vertebral column are complex, overlapping, and can be divided into five groups. The splenius group includes the splenius capitis and the splenius cervicis. The erector spinae has three subgroups. The

iliocostalis group includes the iliocostalis cervicis, the iliocostalis thoracis, and the iliocostalis lumborum. The longissimus group includes the longissimus capitis, the longissimus cervicis, and the longissimus thoracis. The spinalis group includes the spinalis capitis, the spinalis cervicis, and the spinalis thoracis. The transversospinales include the semispinalis capitis, semispinalis cervicis, semispinalis thoracis, multifidus, and rotatores. The segmental muscles include the interspinales and intertransversarii. Finally, the scalenes include the anterior scalene, middle scalene, and posterior scalene.

Review Questions

Q. Which of the following is a prime mover in head flexion?

A. occipitofrontalis

B. corrugator supercilii

C. sternocleidomastoid

D. masseter

Answer

Answer: C

Q. Where is the inferior oblique muscle located?

A. in the abdomen

B. in the eye socket

C. in the anterior neck

D. in the face

Answer

Answer: B

Q. What is the action of the masseter?

A. swallowing

B. chewing

C. moving the lips

D. closing the eye

Answer

A. B

Q. The names of the extrinsic tongue muscles commonly end in _____.

A. -glottis

B. -glossus

C. -gluteus

D. -hyoid

Answer

Answer: B

Q. What is the function of the erector spinae?

A. movement of the arms

B. stabilization of the pelvic girdle

C. postural support

D. rotating of the vertebral column

Answer

Answer: C

Critical Thinking Questions

Q. Explain the difference between axial and appendicular muscles.

Answer

A. Axial muscles originate on the axial skeleton (the bones in the head, neck, and core of the body), whereas appendicular muscles originate on the bones that make up the body's limbs.

Q. Describe the muscles of the anterior neck.

Answer

A. The muscles of the anterior neck are arranged to facilitate swallowing and speech. They work on the hyoid bone, with the suprahyoid muscles pulling up and the infrahyoid muscles pulling down.

Q. Why are the muscles of the face different from typical skeletal muscle?

Answer

A. Most skeletal muscles create movement by actions on the skeleton. Facial muscles are different in that they create facial movements and expressions by pulling on the skin—no bone movements are involved.

Glossary

anterior scalene
a muscle anterior to the middle scalene

appendicular
of the arms and legs

axial
of the trunk and head

buccinator
muscle that compresses the cheek

corrugator supercilii
prime mover of the eyebrows

deglutition
swallowing

digastric
: muscle that has anterior and posterior bellies and elevates the hyoid bone and larynx when one swallows; it also depresses the mandible

epicranial aponeurosis
: (also, galea aponeurosis) flat broad tendon that connects the frontalis and occipitalis

erector spinae group
: large muscle mass of the back; primary extensor of the vertebral column

extrinsic eye muscles
: originate outside the eye and insert onto the outer surface of the white of the eye, and create eyeball movement

frontalis
: front part of the occipitofrontalis muscle

genioglossus
: muscle that originates on the mandible and allows the tongue to move downward and forward

geniohyoid
: muscle that depresses the mandible, and raises and pulls the hyoid bone anteriorly

hyoglossus
: muscle that originates on the hyoid bone to move the tongue downward and flatten it

iliocostalis cervicis
: muscle of the iliocostalis group associated with the cervical region

iliocostalis group
: laterally placed muscles of the erector spinae

iliocostalis lumborum
: muscle of the iliocostalis group associated with the lumbar region

iliocostalis thoracis
: muscle of the iliocostalis group associated with the thoracic region

infrahyoid muscles
: anterior neck muscles that are attached to, and inferior to the hyoid bone

lateral pterygoid
: muscle that moves the mandible from side to side

longissimus capitis
: muscle of the longissimus group associated with the head region

longissimus cervicis
: muscle of the longissimus group associated with the cervical region

longissimus group
: intermediately placed muscles of the erector spinae

longissimus thoracis
: muscle of the longissimus group associated with the thoracic region

masseter
: main muscle for chewing that elevates the mandible to close the mouth

mastication
: chewing

medial pterygoid
: muscle that moves the mandible from side to side

middle scalene
: longest scalene muscle, located between the anterior and posterior scalenes

multifidus
: muscle of the lumbar region that helps extend and laterally flex the vertebral column

mylohyoid
: muscle that lifts the hyoid bone and helps press the tongue to the top of the mouth

occipitalis
: posterior part of the occipitofrontalis muscle

occipitofrontalis
: muscle that makes up the scalp with a frontal belly and an occipital belly

omohyoid
: muscle that has superior and inferior bellies and depresses the hyoid bone

orbicularis oculi
: circular muscle that closes the eye

orbicularis oris
: circular muscle that moves the lips

palatoglossus
: muscle that originates on the soft palate to elevate the back of the tongue

posterior scalene
: smallest scalene muscle, located posterior to the middle scalene

scalene muscles
: flex, laterally flex, and rotate the head; contribute to deep inhalation

segmental muscle group
: interspinales and intertransversarii muscles that bring together the spinous and transverse processes of each consecutive vertebra

semispinalis capitis
: transversospinales muscle associated with the head region

semispinalis cervicis
: transversospinales muscle associated with the cervical region

semispinalis thoracis
: transversospinales muscle associated with the thoracic region

spinalis capitis
: muscle of the spinalis group associated with the head region

spinalis cervicis
: muscle of the spinalis group associated with the cervical region

spinalis group
: medially placed muscles of the erector spinae

spinalis thoracis
: muscle of the spinalis group associated with the thoracic region

splenius
: posterior neck muscles; includes the splenius capitis and splenius cervicis

splenius capitis
: neck muscle that inserts into the head region

splenius cervicis
: neck muscle that inserts into the cervical region

sternocleidomastoid
: major muscle that laterally flexes and rotates the head

sternohyoid
: muscle that depresses the hyoid bone

sternothyroid
: muscle that depresses the larynx's thyroid cartilage

styloglossus
: muscle that originates on the styloid bone, and allows upward and backward motion of the tongue

stylohyoid
: muscle that elevates the hyoid bone posteriorly

suprahyoid muscles
: neck muscles that are superior to the hyoid bone

temporalis
: muscle that retracts the mandible

thyrohyoid
: muscle that depresses the hyoid bone and elevates the larynx's thyroid cartilage

transversospinales
: muscles that originate at the transverse processes and insert at the spinous processes of the vertebrae

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10.5: Axial Muscles of the Abdominal Wall and Thorax

By the end of this section, you will be able to:

- Identify the intrinsic skeletal muscles of the back and neck, and the skeletal muscles of the abdominal wall and thorax
- Identify the movement and function of the intrinsic skeletal muscles of the back and neck, and the skeletal muscles of the abdominal wall and thorax

It is a complex job to balance the body on two feet and walk upright. The muscles of the vertebral column, thorax, and abdominal wall extend, flex, and stabilize different parts of the body's trunk. The deep muscles of the core of the body help maintain posture as well as carry out other functions. The brain sends out electrical impulses to these various muscle groups to control posture by alternate contraction and relaxation. This is necessary so that no single muscle group becomes fatigued too quickly. If any one group fails to function, body posture will be compromised.

Muscles of the Abdomen

There are four pairs of abdominal muscles that cover the anterior and lateral abdominal region and meet at the anterior midline. These muscles of the anterolateral abdominal wall can be divided into four groups: the external obliques, the internal obliques, the transversus abdominis, and the rectus abdominis (Figure 10.5.1 and Table 10.5.1).

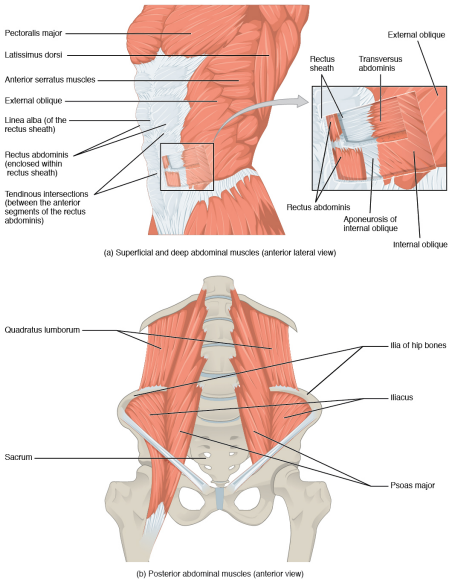

Figure 10.5.1: Muscles of the Abdomen. (a) The anterior abdominal muscles include the medially located rectus abdominis, which is covered by a sheet of connective tissue called the rectus sheath. On the flanks of the body, medial to the rectus abdominis, the abdominal wall is composed of three layers. The external oblique muscles form the superficial layer, while the internal oblique muscles form the middle layer, and the transverses abdominus forms the deepest layer. (b) The muscles of the lower back move the lumbar spine but also assist in femur movements. (Image credit: "Muscles of the Abdomen" by Openstax is licensed under CC BY 4.0)

Table 10.5.1: Muscles of the Abdomen

Prime Mover	Origin	Insertion	Movement	Target	Target motion direction
External obliques; Internal obliques	Ilium; ribs 5 - 12	Ilium; linea alba; ribs 7 - 10	Twisting at waist; also bending to the side	Vertebral column	Supination; lateral flexion

Prime Mover	Origin	Insertion	Movement	Target	Target motion direction
Quadratus lumborum	Ilium; ribs 5 - 10	Rib 12; vertebrae L1 - L4	Bending to the side	Vertebral column	Lateral flexion
Rectus abdominis	Pubis	Ribs 5 and 7; sternum	Sitting up	Vertebral column	Flexion
Transverse abdominus	Ilium; ribs 5 - 10	Linea alba; pubis; sternum	Squeezing abdomen during forceful exhalations, defecation, urination, and childbirth	Abdominal cavity	Compression

There are three flat skeletal muscles in the antero-lateral wall of the abdomen. The **external oblique**, closest to the surface, extend inferiorly and medially, in the direction of sliding one's four fingers into pants pockets. Perpendicular to it is the intermediate **internal oblique**, extending superiorly and medially, the direction the thumbs usually go when the other fingers are in the pants pocket. The deep muscle, the **transversus abdominis**, is arranged transversely around the abdomen, similar to the front of a belt on a pair of pants. This arrangement of three bands of muscles in different orientations allows various movements and rotations of the trunk. The three layers of muscle also help to protect the internal abdominal organs in an area where there is no bone.

The **linea alba** is a white, fibrous band that is made of the bilateral **rectus sheaths** that join at the anterior midline of the body. These enclose the **rectus abdominis** muscles (a pair of long, linear muscles, commonly called the "sit-up" muscles) that originate at the pubic crest and symphysis, and extend the length of the body's trunk. Each muscle is segmented by three transverse bands of collagen fibers called the **tendinous intersections**. This results in the look of "six-pack abs," as each segment hypertrophies on individuals at the gym who do many sit-ups.

The posterior abdominal wall is formed by the lumbar vertebrae, parts of the ilia of the hip bones, psoas major and iliacus muscles, and **quadratus lumborum** muscle. This part of the core plays a key role in stabilizing the rest of the body and maintaining posture.

CAREER CONNECTIONS

Physical Therapist

Those who have a muscle or joint injury will most likely be sent to a physical therapist (PT) after seeing their regular doctor. PTs have a master's degree or doctorate, and are highly trained experts in the mechanics of body movements. Many PTs also specialize in sports injuries.

If you injured your shoulder while you were kayaking, the first thing a physical therapist would do during your first visit is to assess the functionality of the joint. The range of motion of a particular joint refers to the normal movements the joint performs. The PT will ask you to abduct and adduct, circumduct, and flex and extend the arm. The PT will note the shoulder's degree of function, and based on the assessment of the injury, will create an appropriate physical therapy plan.

The first step in physical therapy will probably be applying a heat pack to the injured site, which acts much like a warm-up to draw blood to the area, to enhance healing. You will be instructed to do a series of exercises to continue the therapy at home, followed by icing, to decrease inflammation and swelling, which will continue for several weeks. When physical therapy is complete, the PT will do an exit exam and send a detailed report on the improved range of motion and return of normal limb function to your doctor. Gradually, as the injury heals, the shoulder will begin to function correctly. A PT works closely with patients to help them get back to their normal level of physical activity.

Muscles of the Thorax

The muscles of the chest serve to facilitate breathing by changing the size of the thoracic cavity (Table 10.5.2). When you inhale,

your chest rises because the cavity expands. Alternately, when you exhale, your chest falls because the thoracic cavity decreases in size.

Table 10.5.2: Muscles of the Thorax

Prime Mover	Origin	Insertion	Movement	Target	Target motion direction
Diaphragm	Lumbar vertebrae; ribs 6 - 12; sternum	Central tendon	Inhalation; exhalation	Thoracic cavity	Compression; expansion
External intercostals	Rib superior to each intercostal muscle	Rib inferior to each intercostal muscle	Inhalation; exhalation	Ribs	Elevation (expands thoracic cavity)
Internal intercostals	Rib inferior to each intercostal muscle	Rib superior to each intercostal muscle	Forced exhalation	Ribs	Movement along superior/inferior axis to bring ribs closer together

The Diaphragm

The change in volume of the thoracic cavity during breathing is due to the alternate contraction and relaxation of the **diaphragm** (Figure 10.5.2). It separates the thoracic and abdominal cavities, and is dome-shaped at rest. The superior surface of the diaphragm is convex, creating the elevated floor of the thoracic cavity. The inferior surface is concave, creating the curved roof of the abdominal cavity.

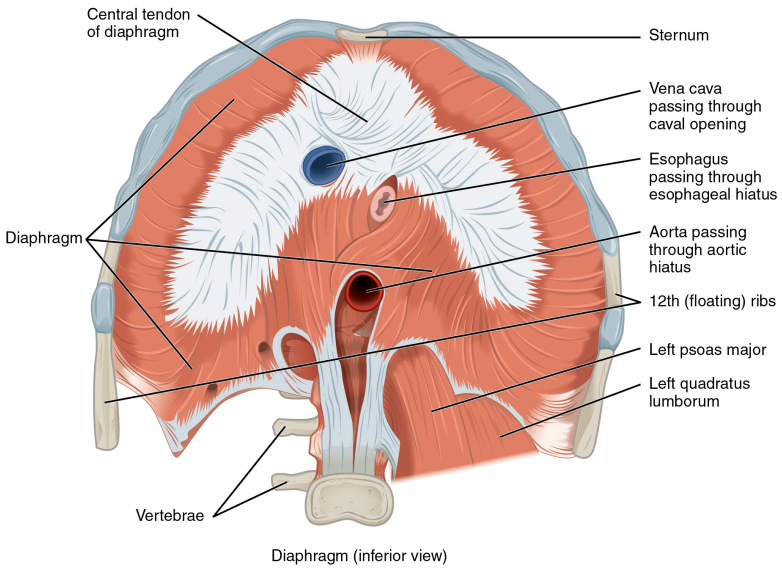

Figure 10.5.2: Muscles of the Diaphragm. The diaphragm separates the thoracic and abdominal cavities. (Image credit: "The Diaphragm" by Openstax is licensed under CC BY 4.0)

Defecating, urination, and even childbirth involve cooperation between the diaphragm and abdominal muscles (this cooperation is referred to as the “Valsalva maneuver”). You hold your breath by a steady contraction of the diaphragm; this stabilizes the volume and pressure of the peritoneal cavity. When the abdominal muscles contract, the pressure cannot push the diaphragm up, so it increases pressure on the intestinal tract (defecation), urinary tract (urination), or reproductive tract (childbirth).

The inferior surface of the pericardial sac and the inferior surfaces of the pleural membranes (parietal pleura) fuse onto the central tendon of the diaphragm. To the sides of the tendon are the skeletal muscle portions of the diaphragm, which insert into the tendon while having a number of origins including the xiphoid process of the sternum anteriorly, the inferior six ribs and their cartilages laterally, and the lumbar vertebrae and 12th ribs posteriorly.

The diaphragm also includes three openings for the passage of structures between the thorax and the abdomen. The inferior vena cava passes through the **caval opening**, and the esophagus and attached nerves pass through the esophageal hiatus. The aorta, thoracic duct, and azygous vein pass through the aortic hiatus of the posterior diaphragm.

The Intercostal Muscles

There are three sets of muscles, called **intercostal muscles**, which span each of the intercostal spaces. The principal role of the intercostal muscles is to assist in breathing by changing the dimensions of the rib cage (Figure 10.5.3).

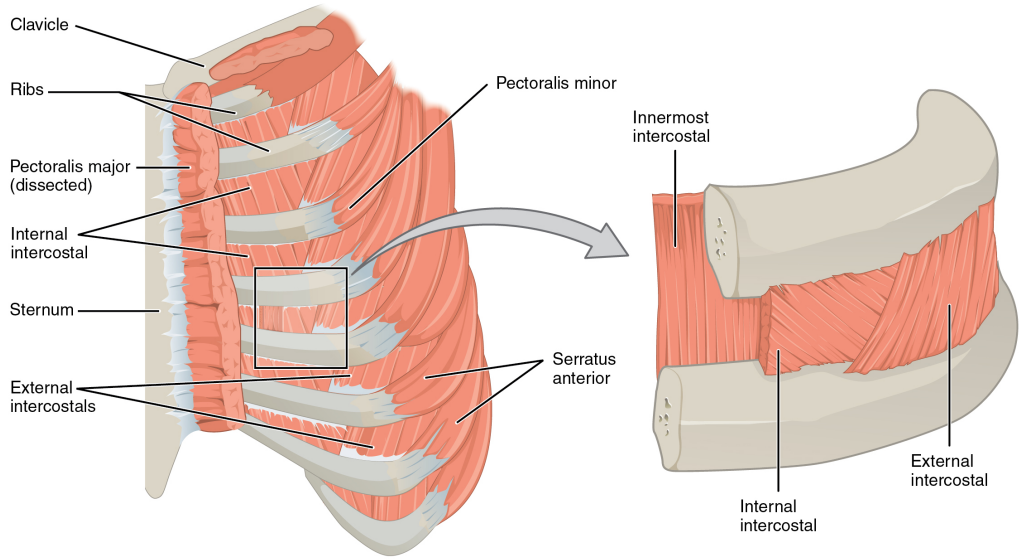

Figure 10.5.3: Intercostal Muscles. The external intercostals are located laterally on the sides of the body. The internal intercostals are located medially near the sternum. The innermost intercostals are located deep to both the internal and external intercostals. (Image credit: "The Thorax" by Openstax is licensed under CC BY 4.0)

The 11 pairs of superficial **external intercostal** muscles aid in inspiration of air during breathing because when they contract, they raise the rib cage, which expands it. The 11 pairs of **internal intercostal** muscles, just under the externals, are used for expiration because they draw the ribs together to constrict the rib cage. The **innermost intercostal** muscles are the deepest, and they act as synergists for the action of the internal intercostals.

Muscles of the Pelvic Floor and Perineum

The pelvic floor is a muscular sheet that defines the inferior portion of the pelvic cavity. The **pelvic diaphragm**, spanning anteriorly to posteriorly from the pubis to the coccyx, comprises the levator ani and the ischiococcygeus. Its openings include the anal canal and urethra, and the vagina in females.

The large **levator ani** consists of two skeletal muscles, the **pubococcygeus** and the **iliococcygeus** (Figure 10.5.4). The levator ani is considered the most important muscle of the pelvic floor because it supports the pelvic viscera. It resists the pressure produced by contraction of the abdominal muscles so that the pressure is applied to the colon to aid in defecation and to the uterus to aid in childbirth (assisted by the **ischiococcygeus**, which pulls the coccyx anteriorly). This muscle also creates skeletal muscle sphincters at the urethra and anus.

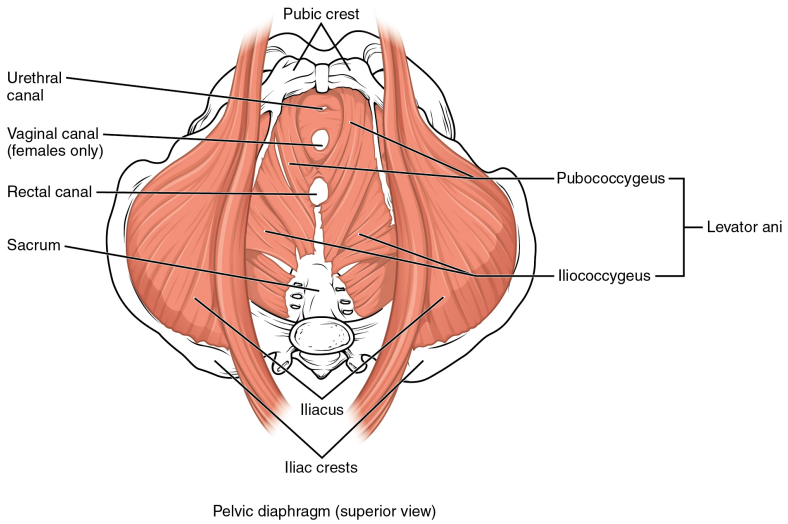

Figure 10.5.4: Muscles of the Pelvic Floor. The pelvic floor muscles support the pelvic organs, resist intra-abdominal pressure, and work as sphincters for the urethra, rectum, and vagina. (Image credit: "Muscles of the Pelvic Floor" by Openstax is licensed under CC BY 4.0)

The **perineum** is the diamond-shaped space between the pubic symphysis (anteriorly), the coccyx (posteriorly), and the ischial tuberosities (laterally), lying just inferior to the pelvic diaphragm (levator ani and coccygeus). Divided transversely into triangles, the anterior is the **urogenital triangle**, which includes the external genitals. The posterior is the **anal triangle**, which contains the anus (Figure 10.5.5). The perineum is also divided into superficial and deep layers with some of the muscles common to males and females (Table 10.5.3). Females also have the **compressor urethrae** and the **sphincter urethrovaginalis**, which function to close the vagina. In males, there is the **deep transverse perineal** muscle that plays a role in ejaculation.

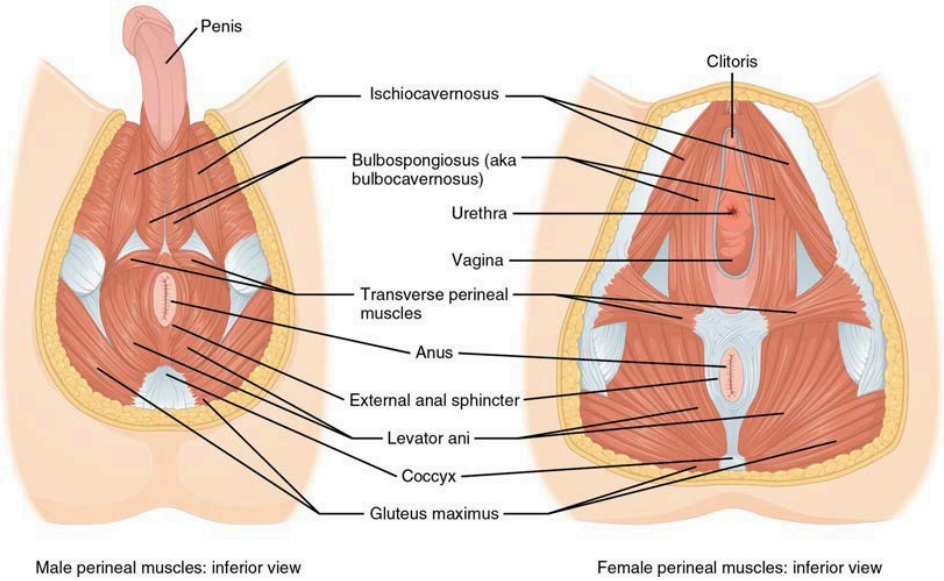

Figure 10.5.5: Muscles of the Perineum. The perineum muscles play roles in urination in both sexes, ejaculation in men, and vaginal contraction in women. (Image credit: "Muscles of the Perineum" by Openstax is licensed under CC BY 4.0)

Table 10.5.3: Muscles of the Perineum Common to Males and Females

Prime Mover	Origin	Insertion	Movement	Target	Target Motion Direction
Levator ani; pubococcygeus; levator ani iliococcygeus	Pubis; ischium	Urethra; anal canal; perineal body; coccyx	Defecation; urination; birth; coughing	Abdominal cavity	Superior (resists pressure during abdominal compression)
Superficial Muscles					
Bulbospongiosus	Perineal body	Perineal membrane; corpus spongiosum of penis; deep fascia of penis; clitoris in female	Involuntary response that compresses urethra when excreting urine in both sexes or while ejaculating in males; also aids in erection of penis in males	Urethra	Compression
Ischiocavernosus	Ischium; ischial rami; pubic rami	Pubic symphysis; corpus cavernosum of penis in male; clitoris of female	Compresses veins to maintain erection of penis in males; erection of clitoris in females	Veins in penis and clitoris	Compression
Superficial transverse perineal	Iscium	Perineal body	None - supports perineal body maintaining anus at center of perineum	Perineal body	none
Deep Muscles					
External anal sphincter	Anoccoccygeal ligament	Perineal body	Closes anus	Anus	Sphincter
External urethral sphincter	Ischial rami; pubic rami	Male: median raphe Female: vaginal wall	Voluntarily compresses urethra during urination	Urethra	Compression

Concept Review

Made of skin, fascia, and four pairs of muscle, the anterior abdominal wall protects the organs located in the abdomen and moves the vertebral column. These muscles include the rectus abdominis, which extends through the entire length of the trunk, the external oblique, the internal oblique, and the transversus abdominus. The quadratus lumborum forms the posterior abdominal wall.

The muscles of the thorax play a large role in breathing, especially the dome-shaped diaphragm. When it contracts and flattens, the volume inside the pleural cavities increases, which decreases the pressure within them. As a result, air will flow into the lungs. The external and internal intercostal muscles span the space between the ribs and help change the shape of the rib cage and the volume-pressure ratio inside the pleural cavities during inspiration and expiration.

The perineum muscles play roles in urination in both sexes, ejaculation in men, and vaginal contraction in women. The pelvic floor muscles support the pelvic organs, resist intra-abdominal pressure, and work as sphincters for the urethra, rectum, and vagina.

Review Questions

Q. Which of the following abdominal muscles is not a part of the anterior abdominal wall?

A. quadratus lumborum

B. rectus abdominis

C. interior oblique

D. exterior oblique

Answer

Answer: A

Q. Which muscle pair plays a role in respiration?

A. intertransversarii, interspinales

B. semispinalis cervicis, semispinalis thoracis

C. trapezius, rhomboids

D. diaphragm, scalene

Answer

Answer: D

Q. What is the linea alba?

A. a small muscle that helps with compression of the abdominal organs

B. a long tendon that runs down the middle of the rectus abdominis

C. a long band of collagen fibers that connects the hip to the knee

D. another name for the tendinous inscription

Answer

Answer: B

Critical Thinking Questions

Q. Describe the fascicle arrangement in the muscles of the abdominal wall. How do they relate to each other?

Answer

A. Arranged into layers, the muscles of the abdominal wall are the internal and external obliques, which run on diagonals, the rectus abdominis, which runs straight down the midline of the body, and the transversus abdominis, which wraps across the trunk of the body.

Q. What are some similarities and differences between the diaphragm and the pelvic diaphragm?

Answer

A. Both diaphragms are thin sheets of skeletal muscle that horizontally span areas of the trunk. The diaphragm separating the thoracic and abdominal cavities is the primary muscle of breathing. The pelvic diaphragm, consisting of two paired muscles, the coccygeus and the levator ani, forms the pelvic floor at the inferior end of the trunk.

Glossary

anal triangle
: posterior triangle of the perineum that includes the anus

caval opening
: opening in the diaphragm that allows the inferior vena cava to pass through; foramen for the vena cava

compressor urethrae
: deep perineal muscle in women

deep transverse perineal
: deep perineal muscle in men

diaphragm
: skeletal muscle that separates the thoracic and abdominal cavities and is dome-shaped at rest

external intercostal
: superficial intercostal muscles that raise the rib cage

external oblique
: superficial abdominal muscle with fascicles that extend inferiorly and medially

iliococcygeus
: muscle that makes up the levator ani along with the pubococcygeus

innermost intercostal
: the deepest intercostal muscles that draw the ribs together

intercostal muscles
: muscles that span the spaces between the ribs

internal intercostal
: muscles the intermediate intercostal muscles that draw the ribs together

internal oblique
: flat, intermediate abdominal muscle with fascicles that run perpendicular to those of the external oblique

ischiococcygeus
: muscle that assists the levator ani and pulls the coccyx anteriorly

levator ani
: pelvic muscle that resists intra-abdominal pressure and supports the pelvic viscera

linea alba
: white, fibrous band that runs along the midline of the trunk

pelvic diaphragm
: muscular sheet that comprises the levator ani and the ischiococcygeus

perineum
: diamond-shaped region between the pubic symphysis, coccyx, and ischial tuberosities

pubococcygeus
: muscle that makes up the levator ani along with the iliococcygeus

quadratus lumborum
: posterior part of the abdominal wall that helps with posture and stabilization of the body

rectus abdominis
: long, linear muscle that extends along the middle of the trunk

rectus sheaths
tissue that makes up the linea alba

sphincter urethrovaginalis
deep perineal muscle in women

tendinous intersections
three transverse bands of collagen fibers that divide the rectus abdominis into segments

transversus abdominis
deep layer of the abdomen that has fascicles arranged transversely around the abdomen

urogenital triangle
anterior triangle of the perineum that includes the external genitals

Contributors and Attributions

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10.6: Appendicular Muscles of the Pectoral Girdle and Upper Limbs

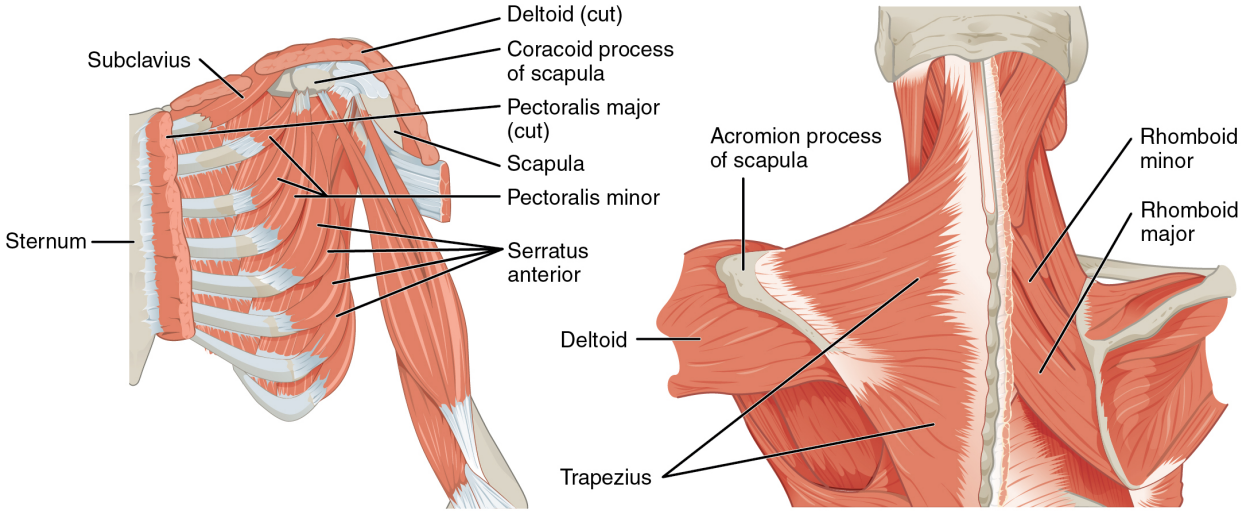
By the end of this section, you will be able to:

- Identify the muscles of the pectoral girdle and upper limbs
- Identify the movement and function of the pectoral girdle and upper limbs

Muscles of the shoulder and upper limb can be divided into four groups: muscles that stabilize and position the pectoral girdle, muscles that move the arm, muscles that move the forearm, and muscles that move the wrists, hands, and fingers. The **pectoral girdle**, or shoulder girdle, consists of the lateral ends of the clavicle and scapula, along with the proximal end of the humerus, and the muscles covering these three bones to stabilize the shoulder joint. The girdle creates a base from which the head of the humerus, in its ball-and-socket joint with the glenoid fossa of the scapula, can move the arm in multiple directions.

Muscles That Position the Pectoral Girdle

Muscles that position the pectoral girdle are located either on the anterior thorax or on the posterior thorax (Figure 10.6.1 and Table 10.6.1). The anterior muscles include the **subclavius**, **pectoralis minor**, and **serratus anterior**. The posterior muscles include the **trapezius**, **rhomboid major**, and **rhomboid minor**. When the rhomboids are contracted, your scapula moves medially, which can pull the shoulder and upper limb posteriorly.



Pectoral girdle muscle (left anterior lateral view)

Pectoral girdle muscles (posterior view)

Figure 10.6.1: Muscles That Position the Pectoral Girdle. The muscles that stabilize the pectoral girdle make it a steady base on which other muscles can move the arm. Note that the pectoralis major and deltoid, which move the humerus, are cut here to show the deeper positioning muscles. (Image credit: "Muscles that Position the Pectoral Girdle" by Openstax is licensed under CC BY 4.0)

Table 10.6.1: Muscles that Position the Pectoral Girdle

Prime Mover	Origin	Insertion	Movement	Target	Target motion direction	Position in the Thorax
Pectoralis Major	Anterior surfaces of certain ribs (2 - 4 or 3 - 5)	Corocoid process of scapula	Rotates shoulder anteriorly (throwing motion); assists with inhalation	Scapula; ribs	Scapula: depresses; ribs: elevates	Anterior thorax

Prime Mover	Origin	Insertion	Movement	Target	Target motion direction	Position in the Thorax
Rhomboid major	Thoracic vertebrae (T2 - T5)	Medial border of scapula	Stabilizes scapula during pectoral girdle movement	Scapula	Retracts; rotates inferiorly	Posterior thorax
Rhomboid minor	Cervical and thoracic vertebrae (C7 and T1)	Medial border of scapula	Stabilizes scapula during pectoral girdle movement	Scapula	Retracts; rotates inferiorly	Posterior thorax
Serratus anterior	Muscle slips from certain ribs (1 - 8 or 1 - 9)	Anterior surface of vertebral border of scapula	Moves arm from side of body to front of body; assists with inhalation	Scapula; ribs	Scapula: protracts; ribs: elevates	Anterior thorax
Subclavius	First rib	Inferior surface of clavicle	Stabilizes clavicle during movement by depressing it	Clavicle	Depression	Anterior thorax
Trapezius	Skull; vertebral column	Acromion and spin of scapula; clavicle	Elevates shoulders (shrugging); pulls shoulder blades together; tilts head backwards	Scapula; cervical spine	Scapula: rotests inferiorly, retracts, elevates, and depresses; spine: extends	Posterior thorax

Muscles That Move the Humerus

Similar to the muscles that position the pectoral girdle, muscles that cross the shoulder joint and move the humerus bone of the arm include both axial and scapular muscles (Figure 10.6.2 and Table 10.6.2). The two axial muscles are the **pectoralis major** and the latissimus dorsi. The pectoralis major is thick and fan-shaped, covering much of the superior portion of the anterior thorax. The broad, triangular **latissimus dorsi** is located on the inferior part of the back, where it inserts into a thick connective tissue shealth called an aponeurosis.

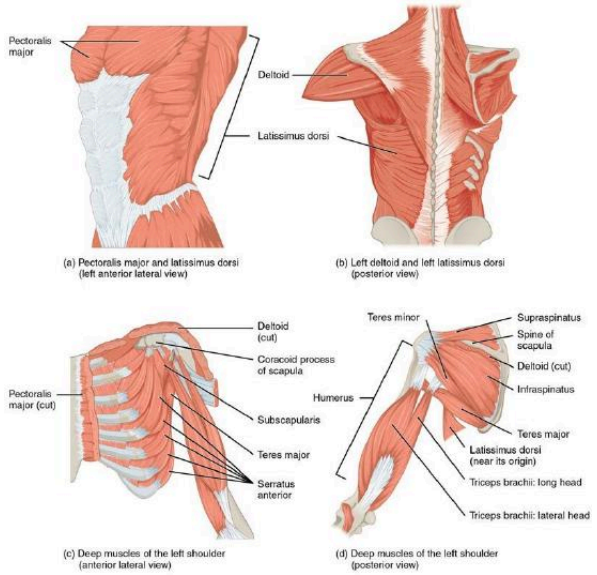


Figure 10.6.2: Muscles That Move the Humerus. (a, c) The muscles that move the humerus anteriorly are generally located on the anterior side of the body and originate from the sternum (e.g., pectoralis major) or the anterior side of the scapula (e.g., subscapularis). (b) The muscles that move the humerus superiorly generally originate from the superior surfaces of the scapula and/or the clavicle (e.g., deltoids). The muscles that move the humerus inferiorly generally originate from middle or lower back (e.g., latissiumus dorsi). (d) The muscles that move the humerus posteriorly are generally located on the posterior side of the body and insert into the scapula (e.g., infraspinatus). (Image credit: "Muscles that Move the Humerus" by Openstax is licensed under CC BY 4.0)

Table 10.6.2*: Muscles that Move the Humerus*

Prime Mover	Origin	Insertion	Movement	Target	Target Motion Direction
Axial muscles					
Latissimus dorsi	Thoracic vertebrae (t7 - T12); lumbar vertebrae; lower ribs (9 - 12); iliac crest	Intertubercular sulcus of humerus	Moves elbow back (as in elbowing someone standing behind you); spreads elbows apart	Humerus; scapula	Humerus: extension, adduction, and medial rotation Scapula: depression
Pectoralis major	Clavicle; sternum; cartilage of certain ribs (1 - 6 or 1 - 7); aponeurosis of external oblique muscle	Greater tubercle of humerus	Brings elbows together; moves elbow up (as during an uppercut punch)	Humerus	Flexion; adduction; medial rotation
Scapular Muscles					
Coracobra chialis	Coracoid process of scapula	Medial surface of humerus shaft	Moves elbow up and across body, as when putting hand on chest	Humerus	Flexion; adduction
Deltoid	Trapezius; clavicle; acromion and spine of scapula	Deltoid tuberosity of humerus	Lifts arms at shoulder	Humerus	Abduction; flexion; extension; medial and lateral rotation
Infraspinatus	Infraspinous fossa of scapula	Greater tubercle of humerus	Rotates elbow outwards, as during a tennis swing	Humerus	Extension; adduction
Subscapularis	Subscapular fossa of scapula	Lesser tubercle of humerus	Assists pectoralis major in bringing elbows together and stabilizes shoulder joint during movement of the pectoral girdle	Humerus	Medial rotation
Supraspinatus	Supraspinous fossa of scapula	Greater tubercle of humerus	Rotates elbow outwards, as during a tennis swing	Humerus	Abduction
Teres major	Posterior surface of scapula	Intertubercular sulcus of humerus	Assists infraspinatus in rotating elbow outwards	Humerus	Extension; adduction
Teres minor	Lateral border of dorsal scapular surface	Greater tubercle of humerus	Assists infraspinatus in rotating elbow outwards	Humerus	Extension; adduction

The rest of the shoulder muscles originate on the scapula. The anatomical and ligamental structure of the shoulder joint and the arrangements of the muscles covering it, allows the arm to carry out different types of movements. The **deltoid**, the thick muscle that creates the rounded lines of the shoulder is the major abductor of the arm, but it also facilitates flexing and medial rotation, as well as extension and lateral rotation. The **subscapularis** originates on the anterior scapula and medially rotates the arm. Named for their locations, the **supraspinatus** (superior to the spine of the scapula) and the **infraspinatus** (inferior to the spine of the scapula) abduct the arm, and laterally rotate the arm, respectively. The thick and flat **teres major** is inferior to the teres minor and extends the arm, and assists in adduction and medial rotation of it. The long **teres minor** laterally rotates and extends the arm. Finally, the **coracobrachialis** flexes and adducts the arm.

The tendons of the deep subscapularis, supraspinatus, infraspinatus, and teres minor connect the scapula to the humerus,

forming the **rotator cuff** (musculotendinous cuff), the circle of tendons around the shoulder joint. When baseball pitchers undergo shoulder surgery it is usually on the rotator cuff, which becomes pinched and inflamed, and may tear away from the bone due to the repetitive motion of bring the arm overhead to throw a fast pitch.

Muscles That Move the Forearm

The forearm, made of the radius and ulna bones, has four main types of action at the hinge of the elbow joint: flexion, extension, pronation, and supination. The forearm flexors include the biceps brachii, brachialis, and brachioradialis. The extensors are the **triceps brachii** and **anconeus**. The pronators are the **pronator teres** and the **pronator quadratus**, and the **supinator** is the only one that turns the forearm anteriorly. When the forearm faces anteriorly, it is supinated. When the forearm faces posteriorly, it is pronated.

The biceps brachii, brachialis, and brachioradialis flex the forearm. The two-headed **biceps brachii** crosses the shoulder and elbow joints to flex the forearm, also taking part in supinating the forearm at the radioulnar joints and flexing the arm at the shoulder joint. Deep to the biceps brachii, the **brachialis** provides additional power in flexing the forearm. Finally, the **brachioradialis** can flex the forearm quickly or help lift a load slowly. These muscles and their associated blood vessels and nerves form the **anterior compartment of the arm** (anterior flexor compartment of the arm) (Figure 10.6.3 and Table 10.6.3).

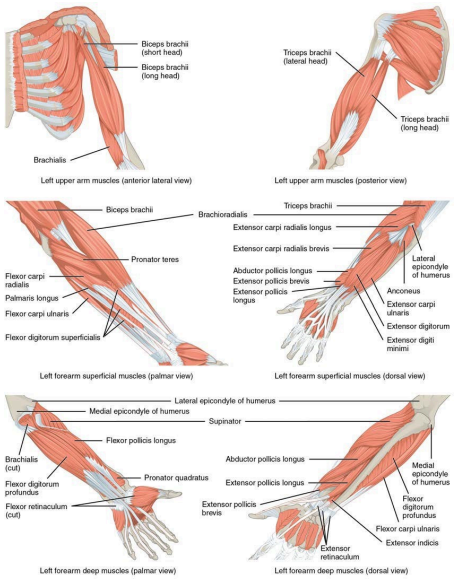


Figure 10.6.3: Muscles That Move the Forearm. The muscles originating in the upper arm flex, extend, pronate, and supinate the forearm. The muscles originating in the forearm move the wrists, hands, and fingers. (Image credit: "Muscles that Move the Forearm" by Openstax is licensed under CC BY 4.0)

Table 10.6.3: Muscles that Move the Forearm

Prime Mover	Origin	Insertion	Movement	Target	Target Motion Direction
Anterior Muscles (Flexion)					
Biceps brachii	Coracoid process; tubercle above glenoid cavity	Radial tuberosity	Performs a bicep curl; also allows palm of hand to point toward body while flexing	Forearm	Flexion; supination
Brachialis	Front of distal humerus	Coronoid process of ulna	Performs a bicep curl	Forearm	Flexion
Brachioradialis	Lateral supracondylar ridge at distal end of humerus	Base of styloid process of radius	Assists and stabilizes elbow during bicep curl motion	Forearm	Flexion

Prime Mover	Origin	Insertion	Movement	Target	Target Motion Direction
Posterior Muscles (Extension)					
Anconeus	Lateral epicondyle of humerus	Lateral aspect of olecranon process of ulna	Assists in extending forearm; also allows forearm to extend away from the body	Forearm	Extension; abduction
Triceps brachii	Infraglenoid tubercle of scapula; posterior shaft of humerus; posterior humeral shaft distal to the radial groove	Olecranon process of ulna	Extends forearm, as during a punch	Forearm	Extension
Anterior Muscles (Pronation)					
Pronator quadratus	Distal portion of anterior ulnar shaft	Distal surface of anterior radius	Assists in turning hand palm down	Forearm	Pronation
Pronator teres	Medial epicondyle of humerus; coronoid process of ulna	Lateral radius	Turns hand palm down	Forearm	Pronation
Posterior Muscles (Supination)					
Supinator	Lateral epicondyle of humerus; proximal ulna	Proximal end of radius	Turns hand palm up	Forearm	Supination

Muscles That Move the Wrist, Hand, and Fingers

Wrist, hand, and finger movements are facilitated by two groups of muscles. The forearm is the origin of the **extrinsic muscles of the hand**. The palm is the origin of the intrinsic muscles of the hand.

Muscles of the Arm That Move the Wrists, Hands, and Fingers

The muscles in the **anterior compartment of the forearm** (anterior flexor compartment of the forearm) originate on the humerus and insert onto different parts of the hand. These make up the bulk of the forearm. From lateral to medial, the **superficial anterior compartment of the forearm** includes the **flexor carpi radialis**, **palmaris longus**, **flexor carpi ulnaris**, and **flexor digitorum superficialis**. The flexor digitorum superficialis flexes the hand as well as the digits at the knuckles, which allows for rapid finger movements, as in typing or playing a musical instrument (Table 10.6.4 and Table 10.6.5). However, poor ergonomics can irritate the tendons of these muscles as they slide back and forth with the carpal tunnel of the anterior wrist and pinch the median nerve, which also travels through the tunnel, causing Carpal Tunnel Syndrome. The **deep anterior compartment** produces flexion and bends fingers to make a fist. These are the **flexor pollicis longus** and the **flexor digitorum profundus**.

The muscles in the **superficial posterior compartment of the forearm** (superficial posterior extensor compartment of the forearm) originate on the humerus. These are the **extensor radialis longus**, **extensor carpi radialis brevis**, **extensor digitorum**, **extensor digiti minimi**, and the **extensor carpi ulnaris**.

The muscles of the **deep posterior compartment of the forearm** (deep posterior extensor compartment of the forearm) originate on the radius and ulna. These include the **abductor pollicis longus**, **extensor pollicis brevis**, **extensor pollicis longus**, and **extensor indicis** (Table 10.6.4).

Table 10.6.4: Muscles that Move the Wrist, Hands, and Forearm

Prime Mover	Origin	Insertion	Movement	Target	Target Motion Direction
Superficial Anterior Compartment of Forearm					

Prime Mover	Origin	Insertion	Movement	Target	Target Motion Direction
Flexor carpi ulnaris	Medial epicondyle of humerus; olecranon process; posterior surface of ulna	Pisiform bone; hamate bone; base of fifth metacarpal	Assists in bending hand up toward shoulder; tilts hand to side away from body; stabilizes wrist	Wrist; hand	Flexion; abduction
Flexor carpi radialis	Medial epicondyle of humerus	Base of second and third metacarpals	Bends wrist toward body; tilts hand to side away from body	Wrist; hand	Flexion; abduction
Flexor digitorum superficialis	Medial epicondyle of humerus; coronoid process of ulna; shaft of radius	Middle phalages of fingers 2 - 5	Bends fingers to make fist	Wrist; fingers 2 - 5	Flexion
Palmaris longus	Medical epicondyle of humerus	Palmar aponeurosis; skin and fascia of palm	Assists in bending hand up toward shoulder	Wrist	Flexion
Deep Anterior Compartment of Forearm					
Flexor digitorum profundus	Coronoid process; anteromedial surface of ulna; interosseous membrane	Distal phalanges of fingers 2 - 5	Bends fingers to make a fist; also bends wrist toward body	Wrist; fingers	Flexion
Flexor pollicus longus	Anterior surface of radius; interosseous membrane	Distal phalanx of thumb	Bends tip of thumb	Thumb	Flexion
Superficial Posterior Compartment of Forearm					
Extensor carpi radialis brevis	Lateral epicondyle of humerus	Base of third metacarpal	Assists extensor radialis longus in extending and abducting wrist; also stabilizes hand during finger flexion	Wrist	Extension; abduction
Extensor carpi ulnaris	Lateral epicondyle of humerus; posterior border of ulna	Base of fifth metacarpal	Straightens wrist away from body; tilts hand to side toward body	Wrist	Extension; adduction
Extensor digiti minimi	Lateral epicondyle of humerus	Extensor expansion; distal phalanx of finger 5 (little finger)	Extends finger 5 (little finger)	Finger 5 (little finger)	Extension
Extensor digitorum	Lateral epicondyle of humerus	Extensor expansions; distal phalanges of fingers	Opens fingers and moves them sideways away from the body	Wrist; fingers	Extension; abduction
Extensor radialis longus	Lateral supracondylar ridge of humerus	Base of second metacarpal	Straightens wrist away from body	Wrist	Extension; abduction
Deep Posterior Compartment of Forearm					
Abductor pollicis longus	Posterior surface of radius and ulna; interosseous membrane	Base of first metacarpal; trapezium	Moves thumb sideways toward body; extends thumb; moves hand sideways toward body	Wrist; thumb	Thumb: abduction; extension Wrist: abduction

Prime Mover	Origin	Insertion	Movement	Target	Target Motion Direction
Extensor indicis	Posterior surface of distal ulna; interosseous membrane	Tendon of extensor digitorum of finger 2 (index finger)	Extends finger 2 (index finger); straightens wrist away from body	Wrist; finger 2 (index finger)	Extension
Extensor pollicis brevis	Dorsal shaft of radius and ulna; interosseous membrane	Base of proximal phalanx of thumb	Extends thumb	Thumb	Extension
Extensor pollicis longus	Dorsal shaft of radius and ulna; interosseous membrane	Base of distal phalanx of thumb	Extends thumb	Thumb	Extension

The tendons of the forearm muscles attach to the wrist and extend into the hand. Fibrous bands called **retinacula** sheath the tendons at the wrist. The **flexor retinaculum** extends over the palmar surface of the hand while the **extensor retinaculum** extends over the dorsal surface of the hand.

Intrinsic Muscles of the Hand

The **intrinsic muscles of the hand** both originate and insert within it (Figure 10.6.4). These muscles allow your fingers to also make precise movements for actions, such as typing or writing. These muscles are divided into three groups. The **thenar** muscles are on the radial aspect of the palm. The **hypothenar** muscles are on the medial aspect of the palm, and the **intermediate** muscles are midpalmar.

The thenar muscles include the **abductor pollicis brevis**, **opponens pollicis**, **flexor pollicis brevis**, and the **adductor pollicis**. These muscles form the **thenar eminence**, the rounded contour of the base of the thumb, and all act on the thumb. The movements of the thumb play an integral role in most precise movements of the hand.

The hypothenar muscles include the **abductor digiti minimi**, **flexor digiti minimi brevis**, and the **opponens digiti minimi**. These muscles form the **hypothenar eminence**, the rounded contour of the little finger, and as such, they all act on the little finger. Finally, the intermediate muscles act on all the fingers and include the **lumbrical**, the **palmar interossei**, and the **dorsal interossei**.

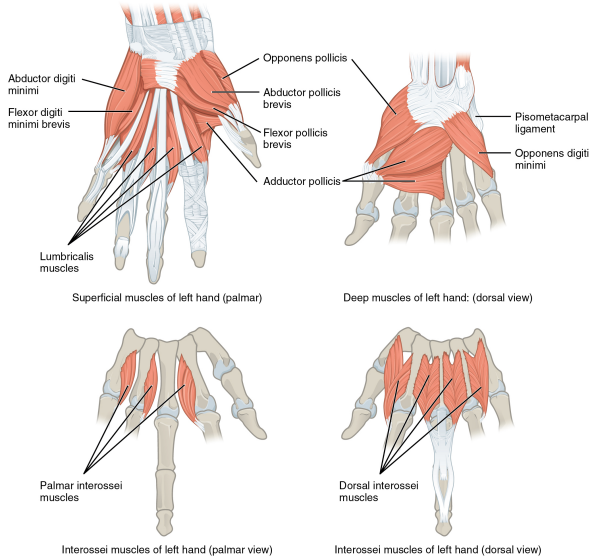


Figure 10.6.4: Intrinsic Muscles of the Hand. The intrinsic muscles of the hand both originate and insert within the hand. These muscles provide the fine motor control of the fingers by flexing, extending, abducting, and adducting the more distal finger and thumb segments. (Image credit: "Intrinsic Muscles of the Hand" by Openstax is licensed under CC BY 4.0)

Table 10.6.5: Intrinsic Muscles of the Hand

Prime mover	Origin	Insertion	Movement	Target	Target Motion Direction
Thenar Muscles					
Abductor pollicis brevis	Flexor retinaculum; and nearby carpals	Lateral base of proximal phalanx of thumb	Moves thumb toward body	Thumb	Abduction
Adductor pollicis	Capitate bone; bases of metacarpals 2 - 4; front of metacarpal 3	Medial base of proximal phalanx of thumb	Moves thumb away from body	Thumb	Adduction
Flexor pollicis brevis	Flexor retinaculum; trapezium	Lateral base of proximal phalanx of thumb	Flexes thumb	Thumb	Flexion
Opponens pollicis	Flexor retinaculum; trapezium	Anterior of first metacarpal	Moves thumb across palm to touch other fingers	Thumb	Opposition
Hypothenar Muscles					
Abductor digiti minimi	Pisiform bone	Medial side of proximal phalanx of finger 5 (little finger)	Moves finger 5 (little finger) toward body	Finger 5 (little finger)	Abduction
Flexor digiti minimi brevis	Hamate bone; flexor retinaculum	Medial side of proximal phalanx of finger 5 (little finger)	Flexes finger 5 (little finger)	Finger 5 (little finger)	Flexor
Opponens digiti minimi	Hamate bone; flexor retinaculum	Medial side of fifth metacarpal	Moves finger 5 (little finger) across palm to touch thumb	Finger 5 (little finger)	Opposition
Intermediate Muscles					
Dorsal interossei	Sides of metacarpals	Both sides of finger 3; for each other finger, extensor expansion over first phalanx on side opposite finger 3	Abducts and flexes the three middle fingers at metacarpo-phalangeal joints; extends the three middle fingers at interphalangeal joints	Fingers	Abduction; flexion; extension
Lumbricals	Palm (lateral sides of tendons in flexor digitorum profundus)	Fingers 2–5 (lateral edges of extensional expansions on first phalanges)	Flexes each finger at metacarpo-phalangeal joints; extends each finger at interphalangeal joints	Fingers	Flexion
Palmar interossei	Side of each metacarpal that faces metacarpal 3 (absent from metacarpal 3)	Extensor expansion on first phalanx of each finger (except finger 3) on side facing finger 3	Adducts and flexes each finger at metacarpo-phalangeal joints; extends each finger at interphalangeal joints	Fingers	Adduction; flexion; extension

Concept Review

The clavicle and scapula make up the pectoral girdle, which provides a stable origin for the muscles that move the humerus. The muscles that position and stabilize the pectoral girdle are located on the thorax. The anterior thoracic muscles are the subclavius, pectoralis minor, and the serratus anterior. The posterior thoracic muscles are the trapezius, levator scapulae, rhomboid major, and rhomboid minor. Nine muscles cross the shoulder joint to move the humerus. The ones that originate on the axial skeleton are the pectoralis major and the latissimus dorsi. The deltoid, subscapularis, supraspinatus, infraspinatus, teres major, teres minor, and coracobrachialis originate on the scapula.

The forearm flexors include the biceps brachii, brachialis, and brachioradialis. The extensors are the triceps brachii and anconeus. The pronators are the pronator teres and the pronator quadratus. The supinator is the only one that turns the forearm anteriorly.

The extrinsic muscles of the hands originate along the forearm and insert into the hand in order to facilitate crude movements of the wrists, hands, and fingers. The superficial anterior compartment of the forearm produces flexion. These muscles are the flexor carpi radialis, palmaris longus, flexor carpi ulnaris, and the flexor digitorum superficialis. The deep anterior compartment produces flexion as well. These are the flexor pollicis longus and the flexor digitorum profundus. The rest of the compartments produce extension. The extensor carpi radialis longus, extensor carpi radialis brevis, extensor digitorum, extensor digiti minimi, and extensor carpi ulnaris are the muscles found in the superficial posterior compartment. The deep posterior compartment includes the abductor longus, extensor pollicis brevis, extensor pollicis longus, and the extensor indicis.

Finally, the intrinsic muscles of the hands allow our fingers to make precise movements, such as typing and writing. They both originate and insert within the hand. The thenar muscles, which are located on the lateral part of the palm, are the abductor pollicis brevis, opponens pollicis, flexor pollicis brevis, and adductor pollicis. The hypothenar muscles, which are located on the medial part of the palm, are the abductor digiti minimi, flexor digiti minimi brevis, and opponens digiti minimi. The intermediate muscles, located in the middle of the palm, are the lumbricals, palmar interossei, and dorsal interossei.

Review Questions

Q. The rhomboid major and minor muscles are deep to the _____.

A. rectus abdominis

B. scalene muscles

C. trapezius

D. ligamentum nuchae

Answer

Answer: C

Q. Which muscle extends the forearm?

A. biceps brachii

B. triceps brachii

C. brachialis

D. deltoid

Answer

Answer: B

Q. What is the origin of the wrist flexors?

A. the lateral epicondyle of the humerus

B. the medial epicondyle of the humerus

C. the carpal bones of the wrist

D. the deltoid tuberosity of the humerus

Answer

Answer: B

Q. Which muscles stabilize the pectoral girdle?

A. axial and scapular

B. axial

C. appendicular

D. axial and appendicular

Answer

Answer: A

Critical Thinking Questions

Q. The tendons of which muscles form the rotator cuff? Why is the rotator cuff important?

Answer

A. Tendons of the infraspinatus, supraspinatus, teres minor, and the subscapularis form the rotator cuff, which forms a foundation on which the arms and shoulders can be stabilized and move.

Q. List the general muscle groups of the shoulders and upper limbs as well as their subgroups.

Answer

A. The muscles that make up the shoulders and upper limbs include the muscles that position the pelvic girdle, the muscles that move the humerus, the muscles that move the forearm, and the muscles that move the wrists, hands, and fingers.

Glossary

abductor digiti minimi
muscle that abducts the little finger

adductor pollicis
muscle that adducts the thumb

abductor pollicis brevis
muscle that abducts the thumb

abductor pollicis longus
muscle that inserts into the first metacarpal

anconeus
small muscle on the lateral posterior elbow that extends the forearm

anterior compartment of the arm
(anterior flexor compartment of the arm) the biceps brachii, brachialis, brachioradialis, and their associated blood vessels and nerves

anterior compartment of the forearm
(anterior flexor compartment of the forearm) deep and superficial muscles that originate on the humerus and insert into the hand

biceps brachii
two-headed muscle that crosses the shoulder and elbow joints to flex the forearm while assisting in supinating it and flexing the arm at the shoulder

brachialis
: muscle deep to the biceps brachii that provides power in flexing the forearm.

brachioradialis
: muscle that can flex the forearm quickly or help lift a load slowly

coracobrachialis
: muscle that flexes and adducts the arm

deep anterior compartment
: flexor pollicis longus, flexor digitorum profundus, and their associated blood vessels and nerves

deep posterior compartment of the forearm
: (deep posterior extensor compartment of the forearm) the abductor pollicis longus, extensor pollicis brevis, extensor pollicis longus, extensor indicis, and their associated blood vessels and nerves

deltoid
: shoulder muscle that abducts the arm as well as flexes and medially rotates it, and extends and laterally rotates it

dorsal interossei
: muscles that abduct and flex the three middle fingers at the metacarpophalangeal joints and extend them at the interphalangeal joints

extensor carpi radialis brevis
: muscle that extends and abducts the hand at the wrist

extensor carpi ulnaris
: muscle that extends and adducts the hand

extensor digiti minimi
: muscle that extends the little finger

extensor digitorum
: muscle that extends the hand at the wrist and the phalanges

extensor indicis
: muscle that inserts onto the tendon of the extensor digitorum of the index finger

extensor pollicis brevis
: muscle that inserts onto the base of the proximal phalanx of the thumb

extensor pollicis longus
: muscle that inserts onto the base of the distal phalanx of the thumb

extensor radialis longus
: muscle that extends and abducts the hand at the wrist

extensor retinaculum
: band of connective tissue that extends over the dorsal surface of the hand

extrinsic muscles of the hand
: muscles that move the wrists, hands, and fingers and originate on the arm

flexor carpi radialis
: muscle that flexes and abducts the hand at the wrist

flexor carpi ulnaris
: muscle that flexes and adducts the hand at the wrist

flexor digiti minimi brevis
: muscle that flexes the little finger

flexor digitorum profundus
: muscle that flexes the phalanges of the fingers and the hand at the wrist

flexor digitorum superficialis
: muscle that flexes the hand and the digits

flexor pollicis brevis
: muscle that flexes the thumb

flexor pollicis longus
: muscle that flexes the distal phalanx of the thumb

flexor retinaculum
: band of connective tissue that extends over the palmar surface of the hand

hypothenar
: group of muscles on the medial aspect of the palm

hypothenar eminence
: rounded contour of muscle at the base of the little finger

infraspinatus
: muscle that laterally rotates the arm

intermediate
: group of midpalmar muscles

intrinsic muscles of the hand
: muscles that move the wrists, hands, and fingers and originate in the palm

latissimus dorsi
: broad, triangular axial muscle located on the inferior part of the back

lumbrical
: muscle that flexes each finger at the metacarpophalangeal joints and extend each finger at the interphalangeal joints

opponens digiti minimi
: muscle that brings the little finger across the palm to meet the thumb

opponens pollicis
: muscle that moves the thumb across the palm to meet another finger

palmar interossei
: muscles that abduct and flex each finger at the metacarpophalangeal joints and extend each finger at the interphalangeal joints

palmaris longus
: muscle that provides weak flexion of the hand at the wrist

pectoral girdle
: shoulder girdle, made up of the clavicle and scapula

pectoralis major
: thick, fan-shaped axial muscle that covers much of the superior thorax

pectoralis minor
: muscle that moves the scapula and assists in inhalation

pronator quadratus
: pronator that originates on the ulna and inserts on the radius

pronator teres
: pronator that originates on the humerus and inserts on the radius

retinacula
: fibrous bands that sheath the tendons at the wrist

rhomboid major
: muscle that attaches the vertebral border of the scapula to the spinous process of the thoracic vertebrae

rhomboid minor
: muscle that attaches the vertebral border of the scapula to the spinous process of the thoracic vertebrae

rotator cuff
: (also, musculotendinous cuff) the circle of tendons around the shoulder joint

serratus anterior
: large and flat muscle that originates on the ribs and inserts onto the scapula

subclavius
: muscle that stabilizes the clavicle during movement

subscapularis
: muscle that originates on the anterior scapula and medially rotates the arm

superficial anterior compartment of the forearm
: flexor carpi radialis, palmaris longus, flexor carpi ulnaris, flexor digitorum superficialis, and their associated blood vessels and nerves

superficial posterior compartment of the forearm
: extensor radialis longus, extensor carpi radialis brevis, extensor digitorum, extensor digiti minimi, extensor carpi ulnaris, and their associated blood vessels and nerves

supinator
: muscle that moves the palm and forearm anteriorly

supraspinatus
: muscle that abducts the arm

teres major
: muscle that extends the arm and assists in adduction and medial rotation of it

teres minor
: muscle that laterally rotates and extends the arm

thenar
: group of muscles on the lateral aspect of the palm

thenar eminence
: rounded contour of muscle at the base of the thumb

trapezius
: muscle that stabilizes the upper part of the back

triceps brachii
: three-headed muscle that extends the forearm

Contributors and Attributions

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10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs

By the end of this section, you will be able to:

- Identify the appendicular muscles of the pelvic girdle and lower limb
- Identify the movement and function of the pelvic girdle and lower limb

The appendicular muscles of the lower body position and stabilize the **pelvic girdle**, which serves as a foundation for the lower limbs. Comparatively, there is much more movement at the pectoral girdle than at the pelvic girdle. There is very little movement of the pelvic girdle because of its connection with the sacrum at the base of the axial skeleton. The pelvic girdle is less range of motion because it was designed to stabilize and support the body.

Muscles of the Thigh

What would happen if the pelvic girdle, which attaches the lower limbs to the torso, were capable of the same range of motion as the pectoral girdle? For one thing, walking would expend more energy if the heads of the femurs were not secured in the acetabula of the pelvis. The body's center of gravity is in the area of the pelvis. If the center of gravity were not to remain fixed, standing up would be difficult as well. Therefore, what the leg muscles lack in range of motion and versatility, they make up for in size and power, facilitating the body's stabilization, posture, and movement.

Gluteal Region Muscles That Move the Femur

Most muscles that insert on the femur (the thigh bone) and move it, originate on the pelvic girdle. The **psoas major** and **iliacus** make up the **iliopsoas group**. Some of the largest and most powerful muscles in the body are the gluteal muscles or **gluteal group**. The **gluteus maximus** is the largest; deep to the gluteus maximus is the **gluteus medius**, and deep to the gluteus medius is the **gluteus minimus**, the smallest of the trio (Figure 10.7.1 and Table 10.7.1).

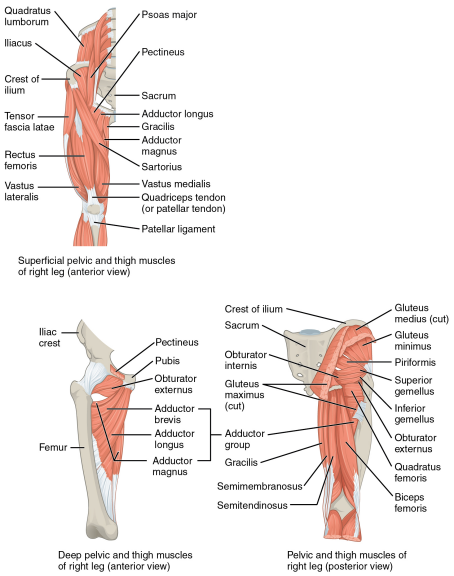

Figure 10.7.1: Hip and Thigh Muscles. The large and powerful muscles of the hip that move the femur generally originate on the pelvic girdle and insert into the femur. The muscles that move the lower leg typically originate on the femur and insert into the bones of the knee joint. The anterior muscles of the femur extend the lower leg but also aid in flexing the thigh. The posterior muscles of the femur flex the lower leg but also aid in extending the thigh. A combination of gluteal and thigh muscles also adduct, abduct, and rotate the thigh and lower leg. (Image credit: "Gluteal Muscles that Move the Femur" by Openstax is licensed under CC BY 4.0)

Table 10.7.1*: Gluteal Region Muscles That Move the Femur*

Prime Mover	Origin	Insertion	Movement	Target	Target Motion Direction
Iliopsoas group					
Iliacus	Iliac fossa; iliac crest; lateral sacrum	Lesser trochanter of femur	Raises knee at hip, as if performing knee attack; assists lateral rotators in twisting thigh (and lower leg) outward; assists with bending over, maintaining posture	Femur	Thigh: flexion; lateral rotation Torso: flexion
Psoas major	Lumbar vertebrae (L1 - L5); thoracic vertebrae (T12)	Lesser trochanter of femur	Raises knee at hip, as if performing knee attack; assists lateral rotators in twisting thigh (and lower leg) outward; assists with bending over, maintaining posture	Femur	Thigh: flexion; lateral rotation Torso: flexion
Gluteal Group					
Gluteus maximus	Dorsal ilium; sacrum; coccyx	Gluteal tuberosity of femur; iliotibial tract	Lower knee and moves thigh back, as when getting ready to kick a ball	Femur	Extension
Gluteus medius	Lateral surface of ilium	Greater trochanter of femur	Opens thighs, as when doing a split	Femur	Abduction
Gluteus minimus	External surface of ilium	Greater trochanter of femur	Brings thighs back together	Femur	Abduction
Tensor fascia lata	Anterior aspect of iliac crest; anterior superior iliac spine	Iliotibial tract	Assists with raising the knee at hip and opening thighs; maintains posture by stabilizing the iliotibial tract, which connects to the knee	Femur	Flexion; abduction
Lateral Rotators					
Inferior gemellus	Ischial tuberosity	Greater trochanter of femur	Twists thigh (and lower leg) outward; maintains posture by stabilizing hip joint	Femur	Lateral rotation
Obturator externus	Outer surfaces of obturator membrane, pubis, and ischium; margins of obturator foramen	Trochanteric fossa of posterior femur	Twists thigh (and lower leg) outward; maintains posture by stabilizing hip joint	Femur	Lateral rotation
Obturator internus	Inner surface of obturator membrane; greater sciatic notch; margins of obturator foramen	Greater trochanter in front of piriformis	Twists thigh (and lower leg) outward; maintains posture by stabilizing hip joint	Femur	Lateral rotation

Prime Mover	Origin	Insertion	Movement	Target	Target Motion Direction
Piriformis	Anterolateral surface of sacrum	Greater trochanter of femur	Twists thigh (and lower leg) outward; maintains posture by stabilizing hip joint	Femur	Lateral rotation
Quadratus femoris	Ischial tuberosity	Trochanteric crest of femur	Twists thigh (and lower leg) outward; maintains posture by stabilizing hip joint	Femur	Lateral rotation
Superior gemellus	Ischial spine	Greater trochanter of femur	Twists thigh (and lower leg) outward; maintains posture by stabilizing hip joint	Femur	Lateral rotation
Adductors					
Adductor brevis	Body of pubis; inferior ramus of pubis	Linea aspera above adductor longus	Brings thighs back together; assists with raising knee	Femur	Adduction; flexion
Adductor longus	Pubis near pubic symphysis	Linea aspera	Brings thighs back together; assists with raising knee	Femur	Adduction; flexion
Adductor magnus	Ischial rami; pubic rami; ischial tuberosity	Linea aspera; adductor tubercle of femur	Brings thighs back together; assists with raising knee and moving thigh back	Femur	Adduction; flexion; extension
Pectineus	Pectineal line of pubis	Lesser trochanter to linea aspera of posterior aspect of femur	Opens thighs; assists with raising the knee and turning the thigh (and lower leg) inward	Femur	Adduction; flexion; medial rotation

The **tensor fascia latae** is a thick, squarish muscle in the superior aspect of the lateral thigh. It acts as a synergist of the gluteus medius and iliopsoas in flexing and abducting the thigh. It also helps stabilize the lateral aspect of the knee by pulling on the iliotibial tract (band), making it taut. Deep to the gluteus maximus, the **piriformis**, **obturator internus**, **obturator externus**, **superior gemellus**, **inferior gemellus**, and **quadratus femoris** laterally rotate the femur at the hip.

The **adductor longus**, **adductor brevis**, and **adductor magnus** can both medially and laterally rotate the thigh depending on the placement of the foot. The adductor longus flexes the thigh, whereas the adductor magnus extends it. The **pectineus** adducts and flexes the femur at the hip as well. The pectineus is located in the **femoral triangle**, which is formed at the junction between the hip and the leg and also includes the femoral nerve, the femoral artery, the femoral vein, and the deep inguinal lymph nodes.

Thigh Muscles That Move the Femur, Tibia, and Fibula

Deep fascia in the thigh separates it into medial, anterior, and posterior compartments (Figure 10.7.1 and Table 10.7.2). The muscles in the **medial compartment of the thigh** are responsible for adducting the femur at the hip. Along with the adductor longus, adductor brevis, adductor magnus, and pectineus, the strap-like **gracilis** adducts the thigh in addition to flexing the leg at the knee.

Table 10.7.2: Thigh Muscles That Move the Femur, Tibia, and Fibula

Prime Mover	Origin	Insertion	Movement	Target	Target Motion Direction
Medial Compartment of Thigh					

Prime Mover	Origin	Insertion	Movement	Target	Target Motion Direction
Gracilis	Inferior ramus; body of pubis; ischial ramus	Medial surface of tibia	Moves back of lower legs up toward buttocks, as when kneeling; assists in opening thighs	Femur; tibia/ fibula	Thigh: adduction Lower leg: flexion
Anterior Compartment of Thigh: Quadricepts Femoris Group					
Rectus femoris	Anterior inferior iliac spine; superior margin of acetabulum	Patella; tibial tuberosity	Moves lower leg out in front of body, as when kicking; assists in raising knee	Femur; tibia/ fibula	Thigh: flexion Lower leg: extension
Sartorius	Anterior superior iliac spine	Medial aspect of proximal tibia	Moves back of lower legs up and back toward the buttocks, as when kneeling; assists in moving thigh diagonally upward and outward as when mounting a bike	Femur; tibia/ fibula	Thigh: flexion; abduction; lateral rotation Lower leg: flexion
Vastus intermedius	Proximal femur shaft	Patella; tibial tuberosity	Moves lower leg out in front of body, as when kicking	Tibia/ fibula	Extension
Vastus lateralis	Greater trochanter; intertrochanteric line; linea apera	Patella; tibial tuberosity	Moves lower leg out in front of body, as when kicking	Tibia/ fibula	Extension
Vastus medialis	Linea aspera; intertrochanteric line	Patella; tibial tuberosity	Moves lower leg out in front of body, as when kicking	Tibia/ fibula	Extension
Posterior Compartment of Thigh: Hamstring Group					
Biceps femoris	Ischial tuberosity; linea aspera; distal femur	Head of fibula; lateral condyle of tibia	Moves back of lower legs up and back toward the buttocks, as when kneeling; moves thigh down and back; twists the thigh (and lower leg) outward	Femur; tibia/ fibula	Thigh: extension; lateral rotation Lower leg: flexion

Prime Mover	Origin	Insertion	Movement	Target	Target Motion Direction
Semimembranosus	Ischial tuberosity	Medial condyle of tibia; lateral condyle of femur	Moves back of lower legs up and back toward the buttocks, as when kneeling; moves thigh down and back; twists the thigh (and lower leg) outward	Femur; tibia/ fibula	Thigh: extension; medial rotation Lower leg: flexion
Semitendinosus	Ischial tuberosity	Upper tibial shaft	Moves back of lower legs up and back toward the buttocks, as when kneeling; moves thigh down and back; twists the thigh (and lower leg) outward	Femur; tibia/ fibula	Thigh: extension; medial rotation Lower leg: flexion

The muscles of the **anterior compartment of the thigh** flex the thigh and extend the leg. This compartment contains the **quadriceps femoris group**, which actually comprises four muscles that extend and stabilize the knee. The **rectus femoris** is on the anterior aspect of the thigh, the **vastus lateralis** is on the lateral aspect of the thigh, the **vastus medialis** is on the medial aspect of the thigh, and the **vastus intermedius** is between the vastus lateralis and vastus medialis and deep to the rectus femoris. The tendon common to all four is the **quadriceps tendon** (patellar tendon), which inserts into the patella and continues below it as the **patellar ligament**. The patellar ligament attaches to the tibial tuberosity. In addition to the quadriceps femoris, the **sartorius** is a band-like muscle that extends from the anterior superior iliac spine to the medial side of the proximal tibia. This versatile muscle flexes the leg at the knee and flexes, abducts, and laterally rotates the leg at the hip. This muscle allows us to sit cross-legged.

The **posterior compartment of the thigh** includes muscles that flex the leg and extend the thigh. The three long muscles on the back of the knee are the **hamstring group**, which flexes the knee. These are the **biceps femoris**, **semitendinosus**, and **semimembranosus**. The tendons of these muscles form the **popliteal fossa**, the diamond-shaped space at the back of the knee.

Muscles That Move the Feet and Toes

Similar to the thigh muscles, the muscles of the leg are divided by deep fascia into compartments, although the leg has three: anterior, lateral, and posterior (Figure 10.7.2 and Table 10.7.3).

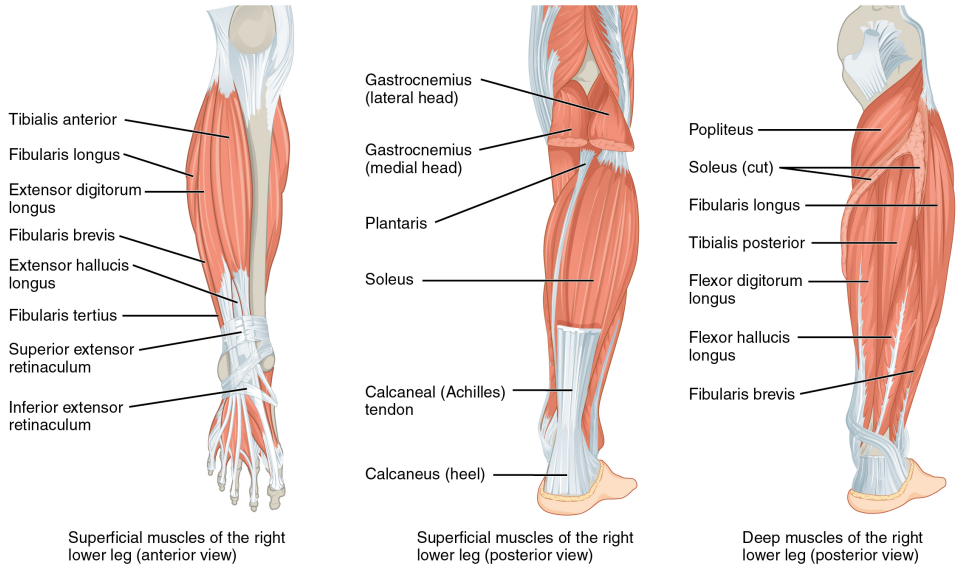

Figure 10.7.2: Muscles of the Lower Leg. The muscles of the anterior compartment of the lower leg are generally responsible for dorsiflexion, and the muscles of the posterior compartment of the lower leg are generally responsible for plantar flexion. The lateral and medial muscles in both compartments invert, evert, and rotate the foot. (Image credit: "Muscles of the Leg that Move the Foot and Toes" by Openstax is licensed under CC BY 4.0)

Table 10.7.3: Muscles That Move the Feet and Toes

Prime Mover	Origin	Insertion	Movement	Target	Target Motion Direction
Anterior Compartment of Leg					
Extensor digitorum longus	Lateral condyle of tibia; proximal portion of fibula; interosseous membrane	Middle and distal phalanges of toes 2 - 5	Raises the sole of the foot off the ground, as when preparing to foot-tap; extends toes	Foot; toes 2 - 5	Foot: dorsiflexion Toes: extension
Extensor hallucis longus	Anteromedial fibula shaft; interosseous membrane	Distal phalanx hallux (big toe)	Raises the sole of the foot off the ground, as when preparing to foot-tap; extends the big toe	Foot; big toe	Foot: dorsiflexion Big toe: extension
Tibialis anterior	Lateral condyle and upper tibial shaft; interosseous membrane	Interior surface of medial cuneiform; first metatarsal bone	Raises the sole of the foot off the ground as when preparing to foot-tap; bends the inside of the foot upwards, as when catching your balance while falling laterally toward the opposite side as the balancing foot	Foot	Dorsiflexion; inversion
Lateral Compartment of Leg					
Fibularis (peroneus) brevis	Distal fibula shaft	Proximal end of fifth metatarsal	Lowers the sole of the foot to the ground as when foot-tapping or jumping; bends the inside of the foot downward, as when catching your balance while falling laterally toward the same side as the balancing foot	Foot	Plantar flexion; eversion

Prime Mover	Origin	Insertion	Movement	Target	Target Motion Direction
Fibularis longus	Upper portion of lateral fibula	First metatarsal; medial cuneiform	Lowers the sole of the foot to the ground as when foot-tapping or jumping; bends the inside of the foot downward, as when catching your balance while falling laterally toward the same side as the balancing foot	Foot	Plantar flexion; eversion
Posterior Compartment of Leg: Superficial Muscles					
Gastrocnemius	Medial and lateral condyles of femur	Posterior calcaneus	Lowers the sole of the foot to the ground, as when foot-tapping or jumping; assists in moving the back of the lower legs up and back toward the buttocks	Foot; tibia/ fibula	Foot: plantar flexion Tibia/fibula: flexion
Plantaris	Posterior femur above lateral condyle	Calcaneus or calcaneus tendon	Lowers the sole of the foot to the ground, as when foot-tapping or jumping; assists in moving the back of the lower legs up and back toward the buttocks	Foot; tibia/ fibula	Foot: plantar flexion Tibia/fibula: flexion
Soleus	Superior tibia; fibula; interosseous membrane	Posterior calcaneus	Lowers the sole of the foot to the ground, as when foot-tapping or jumping; maintains posture while walking	Foot	Plantar flexion
Tibialis posterior	Superior tibia; fibula; interosseous membrane	Several tarsals and metatarsals 2 - 4	Lowers the sole of the foot to the ground, as when foot-tapping or jumping	Foot	Plantar flexion
Posterior Compartment of Leg: Deep Muscles					
Flexor digitorum longus	Posterior tibia	Distal phalanges of toes 2 - 5	Lowers the sole of the foot to the ground, as when foot-tapping or jumping; bends the inside of the foot upward and flexes toes	Foot; toes 2 - 5	Foot: plantar flexion; inversion Toes: flexion
Flexor hallucis longus	Midshaft of fibula; interosseous membrane	Distal phalanx of hallux (big toe)	Flexes big toe	Foot; big toe	Foot: plantar flexion Big toe: flexion

Prime Mover	Origin	Insertion	Movement	Target	Target Motion Direction
Popliteus	Lateral condyle of femur; lateral meniscus	Proximal tibia	Moves the back of the lower legs up and back toward buttocks; assists in rotation of the leg at the knee and thigh	Tibia/ fibula	Tibia/fibula: flexion Thigh and lower leg: medial and lateral rotation

The muscles in the **anterior compartment of the leg**: the **tibialis anterior**, a long and thick muscle on the lateral surface of the tibia, the **extensor hallucis longus**, deep under it, and the **extensor digitorum longus**, lateral to it, all contribute to raising the front of the foot when they contract. The **fibularis tertius**, a small muscle that originates on the anterior surface of the fibula, is associated with the extensor digitorum longus and sometimes fused to it, but is not present in all people. Thick bands of connective tissue called the **superior extensor retinaculum** (transverse ligament of the ankle) and the **inferior extensor retinaculum**, hold the tendons of these muscles in place during dorsiflexion.

The **lateral compartment of the leg** includes two muscles: the **fibularis longus** (peroneus longus) and the **fibularis brevis** (peroneus brevis). The superficial muscles in the **posterior compartment of the leg** all insert onto the **calcaneal tendon** (Achilles tendon), a strong tendon that inserts into the calcaneal bone of the ankle. The muscles in this compartment are large and strong and keep humans upright. The most superficial and visible muscle of the calf is the **gastrocnemius**. Deep to the gastrocnemius is the wide, flat **soleus**. The **plantaris** runs obliquely between the two; some people may have two of these muscles, whereas no plantaris is observed in about seven percent of other cadaver dissections. The plantaris tendon is a desirable substitute for the fascia lata in hernia repair, tendon transplants, and repair of ligaments. There are four deep muscles in the posterior compartment of the leg as well: the **popliteus**, **flexor digitorum longus**, **flexor hallucis longus**, and **tibialis posterior**.

The foot also has intrinsic muscles, which originate and insert within it (similar to the intrinsic muscles of the hand). These muscles primarily provide support for the foot and its arch, and contribute to movements of the toes (Figure 10.7.3 and Table 10.7.4). The principal support for the longitudinal arch of the foot is a deep fascia called **plantar aponeurosis**, which runs from the calcaneus bone to the toes (inflammation of this tissue is the cause of “plantar fasciitis,” which can affect runners. The intrinsic muscles of the foot consist of two groups. The **dorsal group** includes only one muscle, the **extensor digitorum brevis**. The second group is the **plantar group**, which consists of four layers, starting with the most superficial.

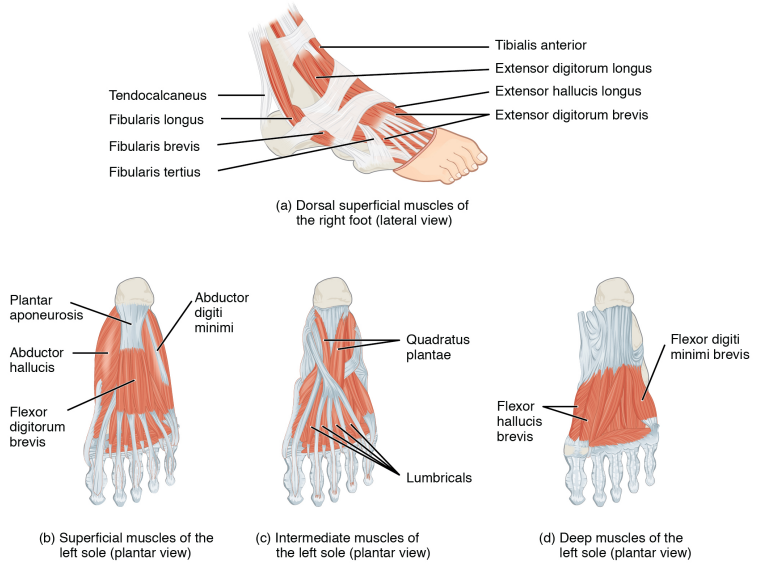

Figure 10.7.3: Intrinsic Muscles of the Foot. The muscles along the dorsal side of the foot (a) generally extend the toes while the muscles of the plantar side of the foot (b, c, d) generally flex the toes. The plantar muscles exist in three layers, providing the foot the strength to counterbalance the weight of the body. In this diagram, these three layers are shown from a plantar view beginning with the bottom-most layer just under the plantar skin of the foot (b) and ending with the top-most layer (d) located just inferior to the foot and toe bones. (Image credit: "Intrinsic Muscles of the Foot" by Openstax is licensed under CC BY 4.0)

Table 10.7.4: Intrinsic Muscles in the Foot

Prime Mover	Origin	Insertion	Movement	Target	Target Motion Direction
Dorsal Group					
Extensor digitorum brevis	Calcaneus; extensor retinaculum	Base of proximal phalanx of big toe; extensor expansions on toes 2 - 5	Extends toes 2 - 5	Toes 2 - 5	Extension
Plantar Group: Layer 1					
Abductor digiti minimi	Calcaneal tuberosity	Proximal phalanx of toe 5 (pinky toe)	Abducts and flexes toe 5	Toe 5	Abduction; flexion
Abductor hallucis	Calcaneal tuberosity; flexor retinaculum	Proximal phalanx of hallux (big toe)	Abducts and flexes big toe	Big toe	Abduction; flexion
Flexor digitorum brevis	Calcaneal tuberosity	Middle phalanx of toes 2 - 4	Flexes toes 2 - 4	Middle toes	Flexion
Plantar Group: Layer 2					
Lumbricals	tendons of flexor digitorum longus	Medial side of proximal phalanx of toes 2 - 5	Extends toes 2 - 5 at the interphalangeal joints; flexes the small toes at the metatarsophalangeal joints	Toes 2 - 5	Extension; flexion
Quadratus plantae	Medial and lateral sides of calcaneus	Tendon of flexor digitorum longus	Assists in flexing toes 2 - 5	Toes 2 - 5	Flexion
Plantar Group: Layer 3					

Prime Mover	Origin	Insertion	Movement	Target	Target Motion Direction
Adductor hallucis	Bases of metatarsals 2 - 4; fibularis longus tendon sheath; ligament across metatarsophalangeal joints	Base of proximal phalanx of hallux (big toe)	Adducts and flexes big toe	Big toe	Adduction; flexion
Flexor digiti minimi brevis	Base of metatarsal 5; tendon sheath of fibularis longus	Base of proximal phalanx of toe 5 (pinky toe)	Flexes pinky toe	Pinky toe	Flexion
Flexor hallicus brevis	Lateral cuneiform; cuboid bones	Base of proximal phalanx of hallux (big toe)	Flexes big toe	Big toe	Flexion
Plantar Group: Layer 4					
Dorsal interossei	Sides of metatarsals	Both sides of toe 2; for each other toe, extensor expansion over first phalanx on side opposite toe 2	Abducts and flexes middle toes at metatarsophalangeal joints; extends middle toes at interphalangeal joints	Middle toes	Abduction; flexion; extension
Plantar interossei	Side of each metatarsal that faces metatarsal 2 (absent from metatarsal 2)	Extensor expansion on first phalanx of each tow (except on 2) on side facing toe 2	Abducts toes 3 - 5; flexes proximal phalanges and extends distal phalanges	Small toes	Abduction; flexion; extension

Concept Review

The pelvic girdle attaches the legs to the axial skeleton. The hip joint is where the pelvic girdle and the leg come together. The hip is joined to the pelvic girdle by many muscles. In the gluteal region, the psoas major and iliacus form the iliopsoas. The large and strong gluteus maximus, gluteus medius, and gluteus minimus extend and abduct the femur. Along with the gluteus maximus, the tensor fascia lata muscle forms the iliotibial tract. The lateral rotators of the femur at the hip are the piriformis, obturator internus, obturator externus, superior gemellus, inferior gemellus, and quadratus femoris. On the medial part of the thigh, the adductor longus, adductor brevis, and adductor magnus adduct the thigh and medially rotate it. The pectineus muscle adducts and flexes the femur at the hip.

The thigh muscles that move the femur, tibia, and fibula are divided into medial, anterior, and posterior compartments. The medial compartment includes the adductors, pectineus, and the gracilis. The anterior compartment comprises the quadriceps femoris, quadriceps tendon, patellar ligament, and the sartorius. The quadriceps femoris is made of four muscles: the rectus femoris, the vastus lateralis, the vastus medius, and the vastus intermedius, which together extend the knee. The posterior compartment of the thigh includes the hamstrings: the biceps femoris, semitendinosus, and the semimembranosus, which all flex the knee.

The muscles of the leg that move the foot and toes are divided into anterior, lateral, superficial- and deep-posterior compartments. The anterior compartment includes the tibialis anterior, the extensor hallucis longus, the extensor digitorum longus, and the fibularis (peroneus) tertius. The lateral compartment houses the fibularis (peroneus) longus and the fibularis (peroneus) brevis. The superficial posterior compartment has the gastrocnemius, soleus, and plantaris; and the deep posterior compartment has the popliteus, tibialis posterior, flexor digitorum longus, and flexor hallucis longus.

Review Questions

Q. The large muscle group that attaches the leg to the pelvic girdle and produces extension of the hip joint is the _____ group.

A. gluteal

B. obturator

C. adductor

D. abductor

Answer

Answer: A

Q. Which muscle produces movement that allows you to cross your legs?

A. the gluteus maximus

B. the piriformis

C. the gracilis

D. the sartorius

Answer

Answer: D

Q. What is the largest muscle in the lower leg?

A. soleus

B. gastrocnemius

C. tibialis anterior

D. tibialis posterior

Answer

Answer: B

Q. The vastus intermedius muscle is deep to which of the following muscles?

A. biceps femoris

B. rectus femoris

C. vastus medialis

D. vastus lateralis

Answer

Answer: B

Critical Thinking Questions

Q. Which muscles form the hamstrings? How do they function together?

Answer

A. The biceps femoris, semimembranosus, and semitendinosus form the hamstrings. The hamstrings flex the leg at the knee joint.

Q. Which muscles form the quadriceps? How do they function together?

Answer

A. The rectus femoris, vastus medialis, vastus lateralis, and vastus intermedius form the quadriceps. The quadriceps muscles extend the leg at the knee joint.

Glossary

adductor brevis
muscle that adducts and medially rotates the thigh

adductor longus
muscle that adducts, medially rotates, and flexes the thigh

adductor magnus
muscle with an anterior fascicle that adducts, medially rotates and flexes the thigh, and a posterior fascicle that assists in thigh extension

anterior compartment of the leg
region that includes muscles that dorsiflex the foot

anterior compartment of the thigh
region that includes muscles that flex the thigh and extend the leg

biceps femoris
hamstring muscle

calcaneal tendon
(also, Achilles tendon) strong tendon that inserts into the calcaneal bone of the ankle

dorsal group
region that includes the extensor digitorum brevis

extensor digitorum brevis
muscle that extends the toes

extensor digitorum longus
muscle that is lateral to the tibialis anterior

extensor hallucis longus
muscle that is partly deep to the tibialis anterior and extensor digitorum longus

femoral triangle
region formed at the junction between the hip and the leg and includes the pectineus, femoral nerve, femoral artery, femoral vein, and deep inguinal lymph nodes

fibularis brevis
(also, peroneus brevis) muscle that plantar flexes the foot at the ankle and everts it at the intertarsal joints

fibularis longus
(also, peroneus longus) muscle that plantar flexes the foot at the ankle and everts it at the intertarsal joints

fibularis tertius
small muscle that is associated with the extensor digitorum longus

flexor digitorum longus
muscle that flexes the four small toes

flexor hallucis longus
muscle that flexes the big toe

gastrocnemius
most superficial muscle of the calf

gluteal group
muscle group that extends, flexes, rotates, adducts, and abducts the femur

gluteus maximus
largest of the gluteus muscles that extends the femur

gluteus medius
muscle deep to the gluteus maximus that abducts the femur at the hip

gluteus minimus
smallest of the gluteal muscles and deep to the gluteus medius

gracilis
muscle that adducts the thigh and flexes the leg at the knee

hamstring group
three long muscles on the back of the leg

iliacus
muscle that, along with the psoas major, makes up the iliopsoas

iliopsoas group
muscle group consisting of iliacus and psoas major muscles, that flexes the thigh at the hip, rotates it laterally, and flexes the trunk of the body onto the hip

iliotibial tract
muscle that inserts onto the tibia; made up of the gluteus maximus and connective tissues of the tensor fasciae latae

inferior extensor retinaculum
cruciate ligament of the ankle

inferior gemellus
muscle deep to the gluteus maximus on the lateral surface of the thigh that laterally rotates the femur at the hip

lateral compartment of the leg
region that includes the fibularis (peroneus) longus and the fibularis (peroneus) brevis and their associated blood vessels and nerves

medial compartment of the thigh
a region that includes the adductor longus, adductor brevis, adductor magnus, pectineus, gracilis, and their associated blood vessels and nerves

obturator externus
muscle deep to the gluteus maximus on the lateral surface of the thigh that laterally rotates the femur at the hip

obturator internus
muscle deep to the gluteus maximus on the lateral surface of the thigh that laterally rotates the femur at the hip

patellar ligament
extension of the quadriceps tendon below the patella

pectineus
muscle that abducts and flexes the femur at the hip

pelvic girdle
hips, a foundation for the lower limb

piriformis
muscle deep to the gluteus maximus on the lateral surface of the thigh that laterally rotates the femur at the hip

plantar aponeurosis
: muscle that supports the longitudinal arch of the foot

plantar group
: four-layered group of intrinsic foot muscles

plantaris
: muscle that runs obliquely between the gastrocnemius and the soleus

popliteal fossa
: diamond-shaped space at the back of the knee

popliteus
: muscle that flexes the leg at the knee and creates the floor of the popliteal fossa

posterior compartment of the leg
: region that includes the superficial gastrocnemius, soleus, and plantaris, and the deep popliteus, flexor digitorum longus, flexor hallucis longus, and tibialis posterior

posterior compartment of the thigh
: region that includes muscles that flex the leg and extend the thigh

psoas major
: muscle that, along with the iliacus, makes up the iliopsoas

quadratus femoris
: muscle deep to the gluteus maximus on the lateral surface of the thigh that laterally rotates the femur at the hip

quadriceps femoris group
: four muscles, that extend and stabilize the knee

quadriceps tendon
: (also, patellar tendon) tendon common to all four quadriceps muscles, inserts into the patella

rectus femoris
: quadricep muscle on the anterior aspect of the thigh

sartorius
: band-like muscle that flexes, abducts, and laterally rotates the leg at the hip

semimembranosus
: hamstring muscle

semitendinosus
: hamstring muscle

soleus
: wide, flat muscle deep to the gastrocnemius

superior extensor retinaculum
: transverse ligament of the ankle

superior gemellus
: muscle deep to the gluteus maximus on the lateral surface of the thigh that laterally rotates the femur at the hip

tensor fascia lata
: muscle that flexes and abducts the thigh

tibialis anterior
: muscle located on the lateral surface of the tibia

tibialis posterior
: muscle that plantar flexes and inverts the foot

vastus intermedius
: quadricep muscle that is between the vastus lateralis and vastus medialis and is deep to the rectus femoris

vastus lateralis
: quadricep muscle on the lateral aspect of the thigh

vastus medialis
: quadricep muscle on the medial aspect of the thigh

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11: NERVOUS SYSTEM AND NERVOUS TISSUE

The nervous system is responsible for controlling much of the body, both through voluntary and involuntary functions. The focus of this chapter is on nervous (neural) tissue composed of neurons and glial cells. Within this chapter, you will look at the functions of the nervous system, its divisions, the characteristics of the cells found in it and how they communicate. Lastly, you will learn how the nervous system develops.

11.1: Introduction to the Nervous System

11.2: Organization and Functions of the Nervous System

11.3: Anatomy of Nervous Tissue

11.4: Neuronal Communication

11.5: Development of the Nervous System

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11.1: Introduction to the Nervous System

Chapter Learning Objectives

After studying this chapter, you will be able to:

- Name the major divisions of the nervous system, both anatomical and functional
- Describe the functional and structural differences between gray matter and white matter structures
- Recognize the structural and functional differences of the types of neurons present in the body
- List the types of glial cells and assign each to the proper division of the nervous system, along with their function(s)
- Distinguish the major functions of the nervous system: sensation, integration, and response
- Describe how neurons communicate with each other and other targets
- Understand the development of the nervous system

The study of the anatomy of the nervous system (called neuroanatomy) started very early on. The first known written record of a study of the anatomy of the human brain is an Egyptian medical document written around 3000 BC. The next major discoveries in neuroanatomy came from the Greek Alcmaeon, who determined that the brain and not the heart controlled the body, and that the senses were dependent on the brain. After Alcmaeon, many scientists, philosophers, and physicians from around the world continued to contribute to the understanding of neuroanatomy. Herophilus and Erasistratus of Alexandria were perhaps the most influential Greek neuroscientists with their studies involving dissecting brains. For several hundred years afterward, with the cultural taboo of dissection, no major progress occurred in neuroscience. However, in the Renaissance human dissections were allowed again, revitalizing the study of neuroanatomy (Figure 11.1.1). The subsequent centuries have produced a great deal of documentation and study of the neural system. However, our current level of understanding is nowhere close to its limit.

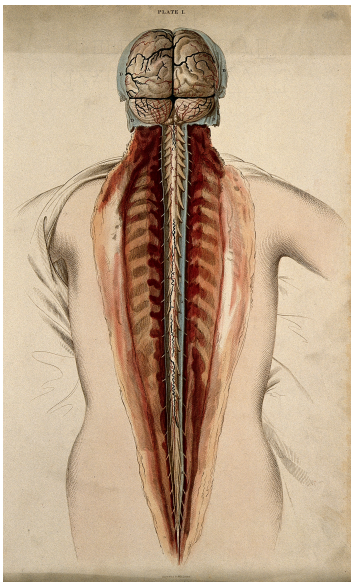

Figure 11.1.1: Dissection of Brain and Spinal Cord. Engraving with colored lines of a dissection of the human brain and spinal cord of the 19th century (Image credit: "Brain and spinal cord: dissection, back view." by W.H. Lizars, Wellcome Library is licensed under CC BY 4.0)

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11.2: Organization and Functions of the Nervous System

By the end of this section, you will be able to:

- Understand the basic structure of a neuron
- Distinguish between gray and white matter and relate their differences to the structure of neurons
- Identify the structural and functional divisions of the nervous system
- Identify the organs of the central and peripheral divisions of the nervous system
- Understand the basic functions and control of the nervous system

The picture you have in your mind of the nervous system probably includes the **brain**, the nervous tissue contained within the cranium in the cranial cavity, and the **spinal cord**, the extension of nervous tissue within the vertebral column. That suggests it is made of two organs—and you may not even think of the spinal cord as an organ—but the nervous system is a very complex structure. Within the brain, many different and separate regions are responsible for many different and separate functions. It is as if the nervous system is composed of many organs that all look similar and can only be differentiated using tools such as the microscope or an electrophysiology apparatus. In comparison, it is easy to see that the stomach is different than the esophagus or the liver, so you can imagine the digestive system as a collection of specific organs. For this reason, you will look at the organization of the nervous tissue first and the structures within it. Then you will look at the structural divisions of the nervous system by regions where the organs are located, and then the functional divisions by the specific functions achieved by the organs within it.

Organization of the Nervous Tissue

Nervous tissue contains two basic types of cells: neurons and glial cells. A **glial cell** is one of a variety of cells that provide a framework of tissue that supports the neurons and their activities. The **neuron** is the more functionally important of the two, in terms of the communicative function of the nervous system. To describe the functional divisions of the nervous system, it is important to understand the basic structure of a neuron (Figure 11.2.1). Neurons are cells and therefore have a **soma**, or **cell body**, but they also have extensions of the cell; each extension is generally referred to as a **process**. There is one important process that every neuron has called an **axon**, which is the fiber that connects a neuron with its target. Axons are partially insulated by a lipid-rich substance called **myelin**. Another type of process that branches off from the soma is the **dendrite**. Dendrites are responsible for receiving most of the input from other neurons.

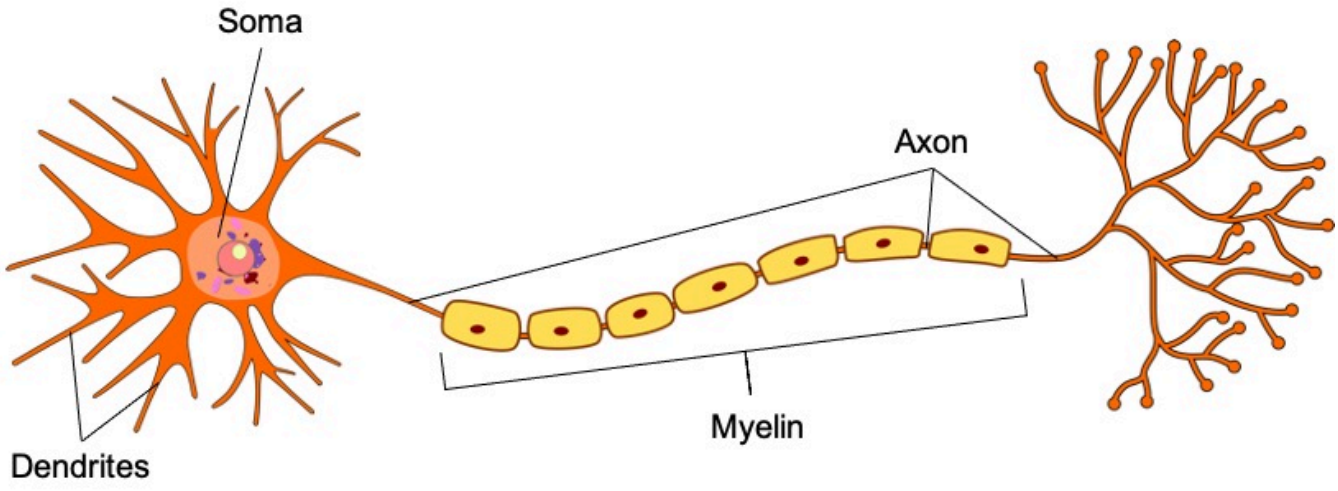

Figure 11.2.1: Basic Structure of a Neuron. Neurons have a soma (or cell body) and processes, which are extensions from the soma that receive or carry information. Processes can be diversified as dendrites which receive information or axon which carries information. The axon shown here is covered by insulating sheaths of myelin. (Image credit: "Labeled structure of a neuron" by Chiara Mazzasette is licensed under CC BY-SA 4.0 / A derivative from the original work)

Looking at nervous tissue, there are regions that predominantly contain cell bodies and regions that are largely composed of just axons. These two regions within nervous system structures are often referred to as **gray matter** (the regions with many cell bodies and dendrites) or **white matter** (the regions with many axons). Figure 11.2.2 demonstrates the appearance of these regions in the brain and spinal cord. The colors ascribed to these regions are what would be seen in "fresh," or unstained, nervous tissue. Gray matter is not necessarily gray. It can be pinkish because of blood content, or even slightly tan, depending on how long the tissue has been preserved. But white matter is white because axons are insulated by the lipids of the myelin. Lipids can appear as white ("fatty") material, much like the fat on a raw piece of chicken or beef. Actually, gray matter may have that color ascribed to it because next to the white matter, it is just darker—hence, gray. Cell bodies of neurons cluster in regions called nuclei or ganglia, depending on their location. Axons of neurons also tend to bundle up in structures called tracts (columns) or nerves (fibers), depending on their location.

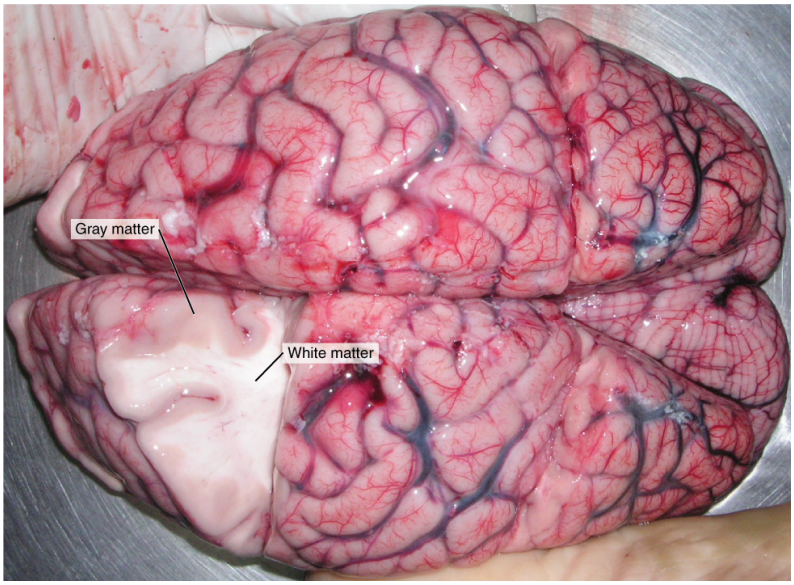

Figure 11.2.2: Gray Matter and White Matter. A brain removed during an autopsy, with a partial section dissected out to show white matter surrounded by gray matter. The gray matter makes up the outer cortex of the brain. (Image credit: "Human Brain" by Suseno is in the Public Domain / A derivative from the original work)

Structural Divisions of the Nervous System

The nervous system can be divided into two major regions: the central and peripheral nervous systems. The **central nervous system (CNS)** is composed of the brain and spinal cord, and the **peripheral nervous system (PNS)** is composed of ganglia (structures containing neurons outside of the CNS) and nerves (bundles of axons from CNS and PNS neurons) (Figure 11.2.3). The brain is contained within the cranial cavity of the skull, and the spinal cord is contained within the vertebral cavity of the vertebral column. It is a bit of an oversimplification to say that the CNS is what is inside these two cavities and the peripheral nervous system is outside of them, but that is one way to start to think about it. In actuality, there are some elements of the peripheral nervous system that are within the cranial or vertebral cavities. The peripheral nervous system is so named because it is on the periphery—meaning beyond the brain and spinal cord. Depending on different aspects of the nervous system, the dividing line between central and peripheral is not necessarily universal.

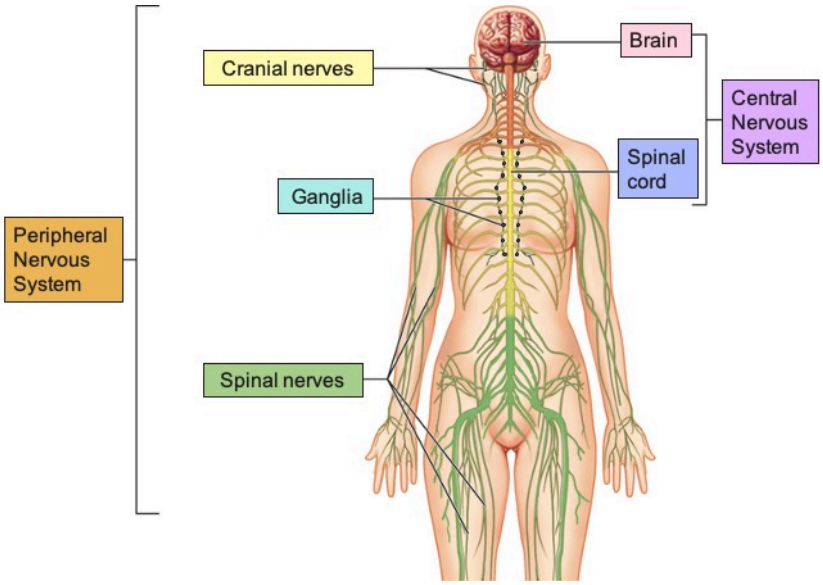

Figure 11.2.3: Structural Divisions of the Nervous System. The structures of the Central Nervous System (CNS) are the brain and spinal cord, located medially within the body. The brain is superior to the spinal cord. The structures of the Peripheral Nervous System (PNS) are ganglia and nerves. Nerves can be divided into cranial if they originate from the brain and spinal if they originate from the spinal cord. Spinal nerves originate laterally from the spinal cord. Ganglia are enlarged regions of the nerves that house neurons and glial cells within the PNS. (Image credit: "Structural divisions of the nervous system" by Chiara Mazzasette is licensed under CC BY 4.0 / A derivative from the original work)

The cell bodies or axons of neurons can be located in discrete anatomical structures that are specific to whether the structure is central or peripheral. A localized collection of neuron cell bodies in the CNS is referred to as a **nucleus**. In the PNS, a cluster of neuron cell bodies is referred to as a **ganglion**. Terminology applied to bundles of axons also differs depending on location. A bundle of axons, or fibers, found in the CNS is called a **tract** (or column) whereas the same thing in the PNS would be called a **nerve** (or nerve fiber). There is an important point to make about these terms, which is that they can both be used to refer to the same bundle of axons. The most obvious example of this is the axons that project from the retina of the eye into the brain. Those axons are called the optic nerve as they leave the eye, but when they are inside the cranium, they are referred to as the optic tract. Table 11.2.1 helps to clarify which of these terms apply to the central or peripheral nervous systems. There is a further classification of nerves depending on the location where they leave the central nervous system: **cranial nerves** emerge directly from the brain, while **spinal nerves** exit from different segments of the spinal cord.

	CNS	PNS
Group of Neuron Cell Bodies (i.e., gray matter)	*Nucleus*	*Ganglion*
Bundle of Axons (i.e., white matter)	*Tract or Column*	*Nerve or Nerve Fiber*

Table 11.2.1: Name of structures depend on the location. A group of neuron cell bodies within the gray matter is called a nucleus in the CNS and a ganglion in the PNS. A bundle of axon within the white matter is called a tract or column in the CNS, and a nerve or nerve fiber in the PNS.

Functional Divisions of the Nervous System

The nervous system can also be divided on the basis of its functions, but anatomical divisions and functional divisions are different. The CNS and the PNS both contribute to the same functions, but those functions can be attributed to different regions of the brain (such as the cerebral cortex or the hypothalamus) or to different ganglia in the periphery. The problem with trying to fit functional differences into anatomical divisions is that sometimes the same structure can be part of several functions. For example, the optic nerve carries signals from the retina that are either used for the conscious perception of visual stimuli, which takes place in the cerebral cortex, or for the reflexive responses of smooth muscle tissue that are processed through the hypothalamus.

There are two ways to consider how the nervous system is divided functionally. First, the basic functions of the nervous system are sensation, integration, and response. Secondly, control of the body can be somatic or autonomic—divisions that are largely defined by the structures that are involved in the response. There is also a region of the peripheral nervous system that is called the enteric nervous system that is responsible for a specific set of the functions within the realm of autonomic control related to gastrointestinal functions.

Basic Functions

The nervous system is involved in receiving information about the environment around us (sensation) and generating responses to that information (motor responses). The nervous system can be divided into regions that are responsible for **sensation** (sensory functions) and for the **response** (motor functions). But there is a third function that needs to be included. Sensory input needs to be integrated with other sensations, as well as with memories, emotional state, or learning (cognition). Some regions of the nervous system are termed **integration** or association areas. The process of integration combines sensory perceptions and higher cognitive functions such as memories, learning, and emotion to produce a response.

Sensation. The first major function of the nervous system is sensation—receiving information about the environment to gain input about what is happening outside the body (or, sometimes, within the body). The sensory functions of the nervous system register the presence of a change from homeostasis or a particular event in the environment, known as a **stimulus** (pl. stimuli). The senses we think of most are: taste, smell, vision, hearing and balance. The stimuli for taste and smell are chemical substances (molecules, compounds, ions, etc.), vision is light stimuli, hearing is the perception of sound and balance is the perception of where your head is in space. The last two rely on physical stimuli. The above senses are called **special senses** because they have specialized organs to sense the environment. There are actually more senses than just those, for example touch, pain and temperature sensation are perceived by the skin. These are called **general senses**. Special and general senses receive stimuli from the outside world and are perceived consciously, meaning that you are aware of them. This conscious sensation coming from special and general senses is called somatic sensation or **somatosensation**. Additional sensory stimuli might be from the internal environment (inside the body), such as the stretch of an organ wall or the concentration of certain ions in the blood or pain related to compression of nerves. These are called **visceral senses** and are not perceived consciously, meaning that you are not aware of them. Somatic and visceral sensory information is perceived by structures within the Peripheral Nervous System and travels towards the Central Nervous System. This inward direction is called **afferent**.

Integration. Stimuli that are received by sensory structures are communicated to the nervous system where that information is processed. Stimuli are compared with, or integrated with, other stimuli, memories of previous stimuli, or the state of a person at a particular time. This leads to the specific response that will be generated. Seeing a baseball pitched to a batter will not automatically cause the batter to swing. The trajectory of the ball and its speed will need to be considered. Maybe the count is three balls and one strike, and the batter wants to let this pitch go by in the hope of getting a walk to first base. Or maybe the batter's team is so far ahead, it would be fun to just swing away.

Response. The nervous system produces a response on the basis of the sensory stimuli. An obvious response would be the movement of muscles, such as withdrawing a hand from a hot stove, but there are broader uses of the term. The nervous system can cause the contraction of all three types of muscle tissue. For example, skeletal muscle contracts to move the skeleton, cardiac muscle is influenced as heart rate increases during exercise, and smooth muscle contracts as the digestive system moves food along the digestive tract. Responses also include the neural control of glands in the body as well, such as the production and secretion of sweat by the eccrine and merocrine sweat glands found in the skin to lower body temperature. Thus, muscles and glands are the targets of the motor response, become active when stimulated to carry out the response. For this reason, they are called **effectors**. Responses can be divided into those that are voluntary or conscious (contraction of skeletal muscle) and those that are involuntary or unconscious (contraction of smooth muscles, regulation of cardiac muscle, activation of glands). Voluntary responses are governed by the somatic nervous system and involuntary responses are governed by the autonomic and enteric nervous system, which are discussed in the next section. Motor information is generated by the Central Nervous System and travels to the Peripheral Nervous System. This outward direction is also **efferent**. Afferent and efferent sound the same but are different. One way to remember their differences is using the acronym SAME that stands for Sensory Afferent Motor Efferent.

Controlling the Body

The nervous system can be divided into two parts mostly on the basis of a functional difference in responses. The **somatic nervous system (SNS)** is responsible for conscious perception (somatosensation) and voluntary motor responses (also called somatic responses). Voluntary motor response means the contraction of skeletal muscle, but those contractions are not always voluntary in the sense that you have to want to perform them. Some somatic motor responses are reflexes, and often happen without a conscious decision to perform them. If your friend jumps out from behind a corner and yells "Boo!" you will be startled and you might scream or leap back. You didn't decide to do that, and you may not have wanted to give your friend a reason to laugh at your expense, but it is a reflex involving skeletal muscle contractions. Other motor responses become automatic (in other words, unconscious) as a person learns motor skills (referred to as "habit learning" or "procedural memory").

The **autonomic nervous system (ANS)** is responsible for involuntary control of the body, usually for the sake of homeostasis (regulation of the internal environment). Sensory input for autonomic functions can be from sensory structures tuned to external or internal environmental stimuli. The motor output extends to smooth and cardiac muscle as well as glandular tissue. The role of the autonomic system is to regulate the organ systems of the body, which usually means to control homeostasis. Sweat glands, for example, are controlled by the autonomic system. When you are hot, sweating helps cool your body down. That is a homeostatic mechanism. But when you are nervous, you might start sweating also. That is not homeostatic, it is the physiological response to an emotional state.

There is another division of the nervous system that describes functional responses. The **enteric nervous system (ENS)** is responsible for controlling the smooth muscle and glandular tissue in your digestive system. It is a large part of the PNS, and is not dependent on the CNS. It is sometimes valid, however, to consider the enteric system to be a part of the autonomic system

because the neural structures that make up the enteric system are a component of the autonomic output that regulates digestion. There are some differences between the two, but for our purposes here there will be a good bit of overlap. See Table 11.2.2 for a schematic representation of the different divisions based on their basic functions and control mechanisms.

	Sensation	Integration	Motor Response
Somatic	Conscious perception of environmental changes (light, sounds, molecules in food, movement, temperature, touch, etc) through somatic sensory neurons of PNS	Information processed in brain and spinal cord (CNS)	Voluntary and reflex response via skeletal muscles
Autonomic	Unconscious perception of external or internal changes (light, molecules, organ stretch, etc) through visceral sensory neurons in both CNS and PNS	Information processed in brain (particularly hypothalamus and brainstem) and spinal cord (CNS)	Involuntary movement of cardiac muscle, smooth muscle, glands
Enteric	Unconscious perception of internal changes (molecules, movement, stretch) within the gastrointestinal tract through visceral sensory neurons in gastrointestinal tract	Information processed within the gastrointestinal tract (PNS)	Involuntary movement of smooth muscle and glands of digestive system

Table 11.2.2: Basic functions of Somatic, Autonomic and Enteric Divisions of the Nervous System. The basic functions of the nervous system are sensation, integration and motor response (top row). These functions are carried out by all divisions of the nervous system (left column) through different neurons, anatomical regions and targets. What differentiates the somatic nervous system from the other two divisions is the ability to perceive and respond to stimuli at the conscious level, while the autonomic and enteric divisions are unconscious. (Table credit: Chiara Mazzasette)

Interactive Link

Creeping Weakness

Read the article Creeping Weakness about a woman that notices that her daughter is having trouble walking up the stairs. This leads to the discovery of a hereditary condition that affects the brain and spinal cord. The electromyography and MRI tests indicated deficiencies in the spinal cord and cerebellum (a region of the brain), both of which are responsible for controlling coordinated movements. To what functional division of the nervous system would these structures belong?

Answer available at the end of this section.

EVERYDAY CONNECTION: How Much of Your Brain Do You Use?

Have you ever heard the claim that humans only use 10 percent of their brains? Maybe you have seen an advertisement on a website saying that there is a secret to unlocking the full potential of your mind—as if there were 90 percent of your brain sitting idle, just waiting for you to use it. If you see an ad like that, don't click. It isn't true.

An easy way to see how much of the brain a person uses is to take measurements of brain activity while performing a task. An example of this kind of measurement is functional magnetic resonance imaging (fMRI), which generates a map of the most active areas and can be generated and presented in three dimensions (Figure 11.2.4). This procedure is different from the standard MRI technique because it is measuring changes in the tissue in time with an experimental condition or event.

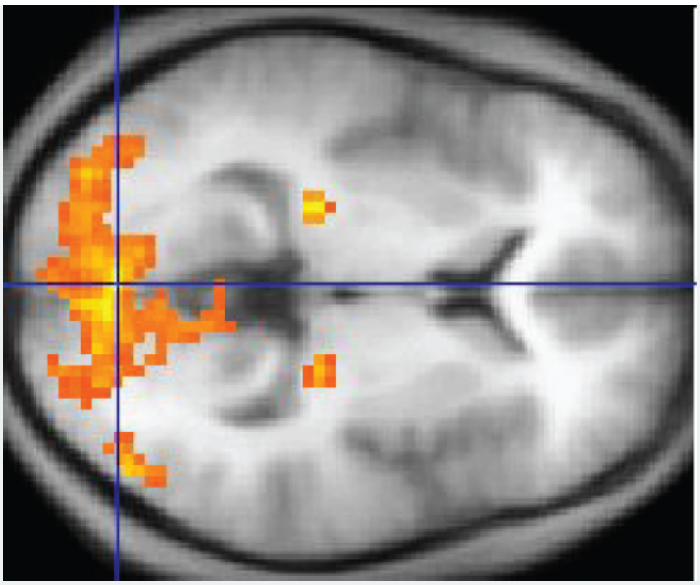

Figure 11.2.4: Functional Magnetic Resonance Imaging (fMRI) map. This imaging represents a transverse plane of the brain with the posterior side on the left and anterior side on the right. The orange areas represent highly active regions. In this particular example, the fMRI map shows activation of the visual cortex in response to visual stimuli. (Image credit: "1206 FMRI" by OpenStax is licensed under CC BY 4.0)

The underlying assumption is that active nervous tissue will have greater blood flow. By having the subject perform a visual task, activity all over the brain can be measured. Consider this possible experiment: the subject is told to look at a screen with a black dot in the middle (a fixation point). A photograph of a face is projected on the screen away from the center. The subject has to look at the photograph and decipher what it is. The subject has been instructed to push a button if the photograph is of someone they recognize. The photograph might be of a celebrity, so the subject would press the button, or it might be of a random person unknown to the subject, so the subject would not press the button.

In this task, visual sensory areas would be active, integrating areas would be active, motor areas responsible for moving the eyes would be active, and motor areas for pressing the button with a finger would be active. Those areas are distributed all around the brain and the fMRI images would show activity in more than just 10 percent of the brain (some evidence suggests that about 80 percent of the brain is using energy—based on blood flow to the tissue—during well-defined tasks similar to the one suggested above). This task does not even include all of the functions the brain performs. There is no language response, the body is mostly lying still in the MRI machine, and it does not consider the autonomic functions that would be ongoing in the background.

Concept Review

Nervous tissue is composed of neurons and glial cells. The basic structure of a neuron is composed of a soma (cell body) and processes. Processes can be classified in dendrites, which receive information, and axons, which carry information. The axons are partially covered by a lipid-rich sheath called myelin. Due to the high fat content of myelin, axons covered in myelin look white. Thus, the nervous tissue can also be described as gray matter and white matter on the basis of its appearance in unstained tissue. Cell bodies of neurons cluster in regions called nuclei or ganglia, depending on their location. Axons of neurons also tend to bundle up in structures called tracts (columns) or nerves (fibers), depending on their location.

The nervous system can be separated into divisions on the basis of anatomy and physiology. The anatomical divisions are the central nervous system (CNS) and peripheral nervous system (PNS). The CNS is composed of the brain and spinal cord. In the CNS, there are localized collection of neuron cell bodies called nuclei within the gray matter and bundles of axons called tracts within the white matter. The PNS is made of collections of neuron cell bodies called ganglia, and bundle of axons called nerves. A single axon can be part of a nerve when in the PNS, and then become a tract when crossing the CNS.

Functionally, the nervous system can be divided into those regions that are responsible for sensation, those that are responsible for integration, and those that are responsible for generating responses. All of these functional areas are found in both the central

and peripheral anatomy. The nervous system can also be divided on the basis of how it controls the body. The somatic nervous system (SNS) is responsible for functions that result in moving skeletal muscles. Any sensory or integrative functions that result in the movement of skeletal muscle would be considered somatic. The autonomic nervous system (ANS) is responsible for functions that affect cardiac or smooth muscle tissue, or that cause glands to produce their secretions. Autonomic functions are distributed between central and peripheral regions of the nervous system. The sensations that lead to autonomic functions can be the same sensations that are part of initiating somatic responses. Somatic and autonomic integrative functions may overlap as well. A special division of the nervous system is the enteric nervous system, which is responsible for controlling the digestive organs. Parts of the autonomic nervous system overlap with the enteric nervous system. The enteric nervous system is exclusively found in the periphery because it is the nervous tissue in the organs of the digestive system.

Review Questions

Q. Which of the following cavities contains a component of the central nervous system?

A. abdominal

B. pelvic

C. cranial

D. thoracic

Answer

Answer: C

Q. Which structure predominates in the white matter of the brain?

A. myelinated axons

B. neuronal cell bodies

C. autonomic ganglia

D. bundles of dendrites from the enteric nervous system

Answer

Answer: A

Q. Which part of a neuron transmits an electrical signal to a target cell?

A. dendrites

B. soma

C. cell body

D. axon

Answer

Answer: D

Q. Which term describes a bundle of axons in the peripheral nervous system?

A. nucleus

B. ganglion

C. tract

D. nerve

Answer

Answer: D

Q. Which functional division of the nervous system would be responsible for the physiological changes seen during exercise (e.g., increased heart rate and sweating)?

A. somatic

B. autonomic

C. enteric

D. central

Answer

Answer: B

Critical Thinking Questions

Q. What responses are generated by the nervous system when you run on a treadmill? Include an example of each type of tissue that is under nervous system control.

Answer

A. Running on a treadmill involves contraction of the skeletal muscles in the legs through the somatic nervous system, increase in contraction of the cardiac muscle of the heart, and the production and secretion of sweat in the skin to stay cool through the autonomic nervous system.

Q. When eating food, what anatomical and functional divisions of the nervous system are involved in the perceptual experience?

Answer

A. The sensation of taste associated with eating is sensed by nerves in the periphery that are involved in sensory and somatic functions. The process of chewing is somatic motor and uses skeletal muscles, while swallowing is both somatic motor (upper first phase) and autonomic motor (lower second phase).

Glossary

afferent
conducting or conducted inward or toward something

autonomic nervous system (ANS)
functional division of the nervous system that is responsible for homeostatic reflexes that coordinate control of cardiac and smooth muscle, as well as glandular tissue

axon
single process of the neuron that carries an electrical signal (action potential) away from the cell body toward a target cell

brain
the large organ of the central nervous system composed of white and gray matter, contained within the cranium and continuous with the spinal cord

cell body
in neurons, that portion of the cell that contains the nucleus, as opposed to the cell processes (axons and dendrites). Also known as soma

central nervous system (CNS)
anatomical division of the nervous system located within the cranial and vertebral cavities, namely the brain and spinal cord

cranial nerve
one of twelve nerves connected to the brain that are responsible for sensory or motor functions of the head and neck

dendrite
one of many branch-like processes that extends from the neuron cell body and functions as a contact for incoming signals (synapses) from other neurons or sensory cells

effector
a bodily tissue, structure, or organ (such as a gland or muscle) that becomes active in response to stimulation

efferent
conducted or conducting outward or away from something

enteric nervous system (ENS)
neural tissue associated with the digestive system that is responsible for nervous control through autonomic connections

ganglion
localized collection of neuron cell bodies in the peripheral nervous system

general sense
any sensory system that is distributed throughout the body and incorporated into organs of multiple other systems, such as the walls of the digestive organs or the skin

glial cell
one of the various types of neural tissue cells responsible for maintenance of the tissue, and largely responsible for supporting neurons

gray matter
regions of the nervous system containing cell bodies of neurons with few or no myelinated axons; actually may be more pink or tan in color, but called gray in contrast to white matter

integration
nervous system function that combines sensory perceptions and higher cognitive functions (memories, learning, emotion, etc.) to produce a response

myelin
lipid-rich insulating substance surrounding the axons of many neurons, allowing for faster transmission of electrical signals

nerve
cord-like bundle of axons located in the peripheral nervous system that transmits sensory input and response output to and from the central nervous system

neuron
neural tissue cell that is primarily responsible for generating and propagating electrical signals into, within, and out of the nervous system

nucleus
in the nervous system, a localized collection of neuron cell bodies that are functionally related; a “center” of neural function

peripheral nervous system (PNS)
anatomical division of the nervous system that is largely outside the cranial and vertebral cavities, namely all parts except the brain and spinal cord

process
in cells, an extension of a cell body; in the case of neurons, this includes the axon and dendrites

response
nervous system function that causes a target tissue (muscle or gland) to produce an event as a consequence to stimuli

sensation
nervous system function that receives information from the environment and translates it into the electrical signals of nervous tissue

soma
in neurons, that portion of the cell that contains the nucleus, as opposed to the cell processes (axons and dendrites). Also known as cell body

somatic nervous system (SNS)
functional division of the nervous system that is concerned with conscious perception, voluntary movement, and skeletal muscle reflexes

somatosensation
general senses related to the body, usually thought of as the senses of touch, which would include pain, temperature, and proprioception

spinal cord
organ of the central nervous system found within the vertebral cavity and connected with the periphery through spinal nerves; mediates reflex behaviors

special sense
any sensory system associated with a specific organ structure, namely smell, taste, sight, hearing, and balance

spinal nerve
one of 31 nerves connected to the spinal cord

stimulus
an event in the external or internal environment that registers as activity in a sensory neuron

tract
bundle of axons in the central nervous system having the same function and point of origin

visceral sense
sense associated with the internal organs

white matter
regions of the nervous system containing mostly myelinated axons, making the tissue appear white because of the high lipid content of myelin

Contributors and Attributions

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Answers

Interactive Link

Answer: They are part of the somatic nervous system, which is responsible for generating voluntary movements such as walking or climbing the stairs.

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11.3: Anatomy of Nervous Tissue

By the end of this section, you will be able to:

- Describe the basic structure of a neuron
- Identify the different types of neurons based on their structure and function
- List the glial cells of the CNS and describe their function
- List the glial cells of the PNS and describe their function
- Describe the process of myelination and axon regeneration

Nervous tissue is composed of two types of cells: neurons and glia, as shown in Figure 11.3.1. Neurons are the primary type of cell that most anyone associates with the nervous system. They are responsible for the computation and communication that the nervous system provides. They are electrically active and release chemical signals to target cells. Glial cells, or glia, or neuroglia, are known to play a supporting role for nervous tissue. Ongoing research pursues an expanded role that glial cells might play in signaling, but neurons are still considered the basis of this function. Neurons are important, but without glial support they would not be able to perform their function.

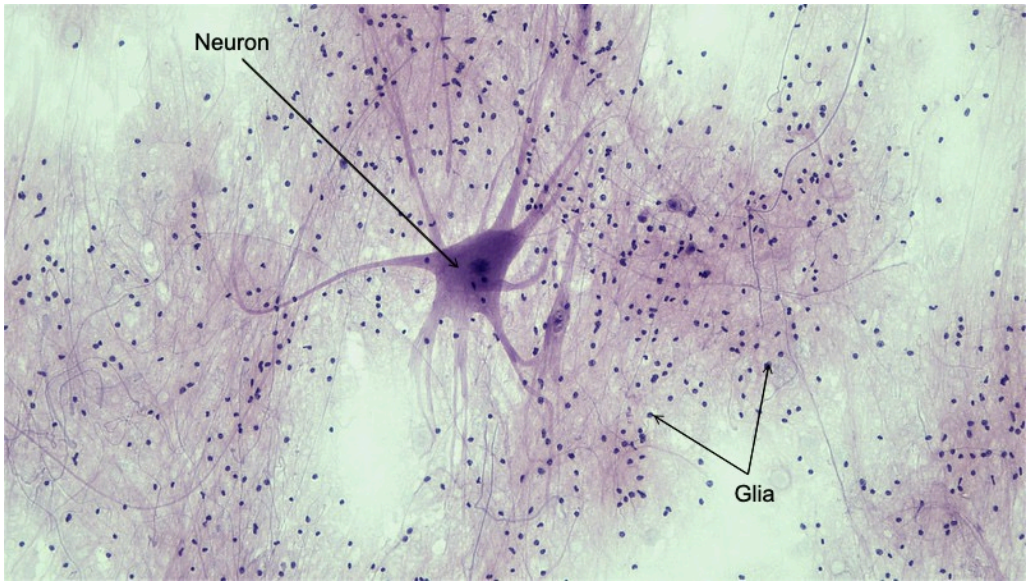


Figure 11.3.1: Nervous Tissue. A small chunk of nervous tissue of spinal cord was spread on a microscope slide to show neurons and glial cells. Glial cells are smaller and in larger quantities than neurons. The neuron shown is large and has multiple processes coming out of the soma. The magnification of the picture is 100X. (Image credit: "Labeled Nervous Tissue Smear" by Chiara Mazzasette is licensed under CC BY 4.0 / A derivative from the original work)

Neurons

Neurons are the cells that are characteristic of nervous tissue. They are large cells with a high metabolic rate. They depend on a continuous and abundant supply of oxygen and glucose. Some neurons live an entire lifespan while others are replaced within days. Neurons do not typically undergo mitosis, thus they are not able to divide and produce new neurons. Only certain areas of the brain and the sense organ of smell house mitotic neurons. They are responsible for the electrical signals that communicate information about sensations, and that produce movements in response to those stimuli, along with inducing thought processes within the brain. An important part of the function of neurons is in their structure, or shape. The three-dimensional shape of these cells makes the immense numbers of connections within the nervous system possible.

Parts of a Neuron

As you learned in the first section, the main part of a neuron is the **cell body**, which is also known as the **soma** (soma = "body"). The cell body contains the nucleus and most of the major organelles. What makes neurons special is that they have many extensions of their cell membranes, which are generally referred to as processes. Neurons are usually described as having one, and only one, **axon**—a fiber that emerges from the cell body and projects to target cells. That single axon can branch repeatedly to communicate with many target cells. It is the axon that propagates the nerve impulse, which is communicated to one or more cells. The other processes of the neuron are **dendrites**, which receive information from other neurons at specialized areas of contact called **synapses**. The dendrites are usually highly branched processes, providing locations for other neurons to communicate with the cell body. Information flows through a neuron from the dendrites, across the cell body, and down the axon.This asymmetrical distribution of cellular components within a neuron is called **neuronal polarity** and research is trying to understand how it is established and maintained. Figure 11.3.2 shows the relationship of these parts to one another.

Where the axon emerges from the cell body, there is a special region referred to as the **axon hillock**. This is a tapering of the cell body toward the axon fiber. Within the axon hillock, the cytoplasm changes to a solution of limited components called **axoplasm**. Many axons are wrapped by an insulating substance called myelin, which is actually made from glial cells. Myelin acts as insulation much like the plastic or rubber that is used to insulate electrical wires. A key difference between myelin and the insulation on a wire is that there are gaps in the myelin covering of an axon. Each gap is called a **node of Ranvier** and is important to the way that electrical signals travel down the axon. The length of the axon between each gap, which is wrapped in myelin, is referred to as an **axon segment**. At the end of the axon is the **axon terminal**, where there are usually several branches extending toward the target cell, each of which ends in an enlargement called a **synaptic end bulb**. These bulbs are what make the connection with the target cell at the synapse.

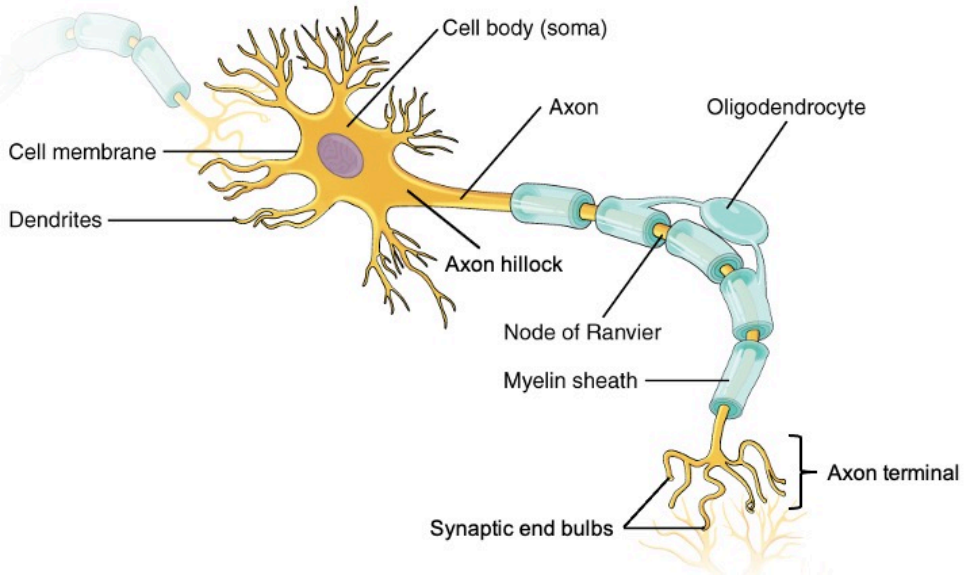


Figure 11.3.2: Parts of a Neuron in the CNS. A neuron has a soma (cell body) from which processes emerge. The processes that receive information from synapses are called dendrites, while the process that carry the information from the soma is called the axon. Neurons have only one axon. The axon emerges from the axon hillock and is covered by glial cells, in this case an oligodendrocyte of the CNS, that form the myelin. If the neuron was in the PNS, its axon would be covered by other glial cells called Schwann cells. Gaps between the myelin are called nodes of Ranvier. The axon ends in branches at the axon terminal and the branches enlarge at their ends to form synaptic end bulbs. (Image credit: "Labeled parts of a neuron" by Chiara Mazzasette is licensed under CC BY 4.0 / A derivative from the original work)

Types of Neurons

There are many neurons in the nervous system—a number in the trillions. And there are many different types of neurons. They can be classified depending on their structure or function. One type of structural classification depends on the number of processes attached to the cell body: one, two or multiple (Figure 11.3.3). The functional classification depends on which function the neuron is carrying out: sensation, integration or motor.

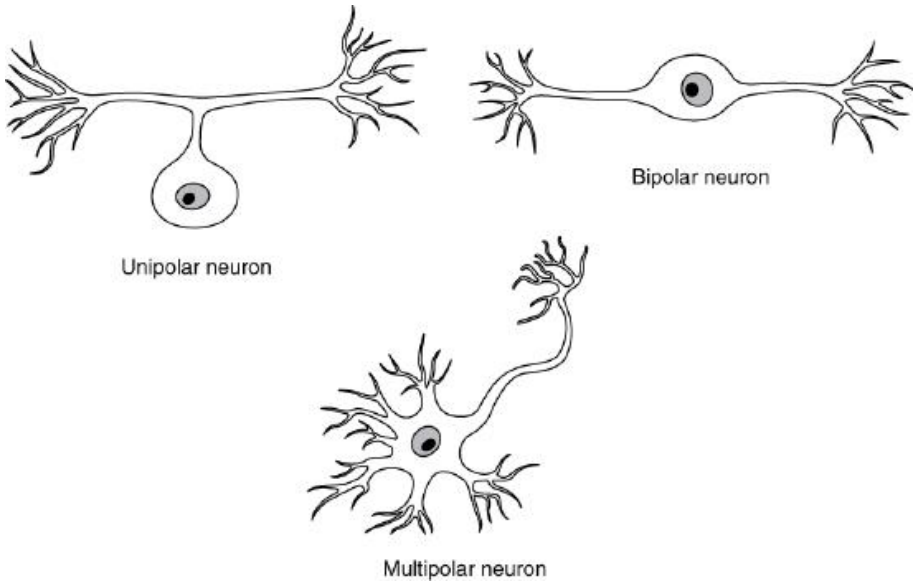


Figure 11.3.3: Neuron Classification by Structure. Unipolar neurons have one process emerging from the soma which contains both the axon and dendrites. Bipolar neurons have two processes emerging from the soma: one is an axon and the other is a dendrite. Multipolar neurons have more than two processes emerging from the soma: one is an axon and two or more other are dendrites. (Image credit: "Neuron Shape Classification" by OpenStax is licensed under CC BY 4.0)

Unipolar cells have only one process emerging from the cell. True unipolar cells are only found in invertebrate animals, so the unipolar cells in humans are more appropriately called “pseudo-unipolar” cells. Invertebrate unipolar cells do not have dendrites. Human unipolar cells have an axon that emerges from the cell body, but it splits so that the axon can extend along a very long distance. At one end of the axon are dendrites, and at the other end, the axon forms synaptic connections with a target. Unipolar cells are exclusively **sensory neurons** and have two unique characteristics. First, their dendrites are receiving sensory information, sometimes directly from the stimulus itself, as is the case for sensory neurons perceiving pressure, temperature change, touch, or pain from the skin. Secondly, the cell bodies of unipolar neurons are always found in ganglia. Sensory reception is a peripheral function (those dendrites are in the periphery, perhaps in the skin) so the cell body is in the periphery, though closer to the CNS in a ganglion. The axon projects from the dendrite endings, past the cell body in a ganglion, and into the central nervous system.

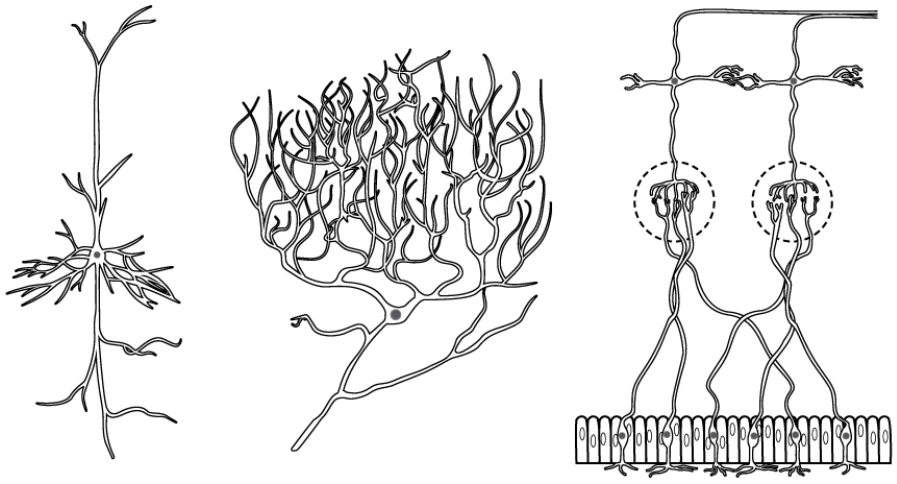
Bipolar cells have two processes, which extend from each end of the cell body, opposite to each other. One is the axon and one the dendrite. Bipolar cells are not very common. They are found mainly in the olfactory epithelium (where smell stimuli are sensed), and as part of the retina, and thus are sensory neurons.

Multipolar neurons are all of the neurons that are not unipolar or bipolar. They have one axon and two or more dendrites (usually many more). With the exception of the unipolar sensory ganglion cells, and the two specific bipolar cells mentioned above, all other neurons are multipolar. Multipolar neurons can have multiple functions. Multipolar neurons can be **motor neurons** which carry commands from the brain and spinal cord to muscles and glands. Motor neurons are located in the brain, spinal cord or autonomic ganglia. Multipolar neurons can also be classified as **interneurons** which constitute the majority of neurons. These neurons carry out integrative functions (such as retrieve, process and store information) and facilitate communication between sensory and motor neurons. Interneurons are found in the brain and spinal cord.

Some cutting edge research suggests that certain neurons in the CNS do not conform to the standard model of “one, and only one” axon. Some sources describe a fourth type of neuron, called an anaxonic neuron. The name suggests that it has no axon (an- = “without”), but this is not accurate. Anaxonic neurons are very small, and if you look through a microscope at the standard resolution used in histology (approximately 400X to 1000X total magnification), you will not be able to distinguish any process specifically as an axon or a dendrite. Any of those processes can function as an axon depending on the conditions at any given time. Nevertheless, even if they cannot be easily seen, and one specific process is definitively the axon, these neurons have multiple processes and are therefore multipolar.

Neurons can also be classified on the basis of where they are found, who found them, what they do, or even what chemicals they use to communicate with each other. Some neurons referred to in this section on the nervous system are named on the basis of those sorts of classifications (Figure 11.3.4). For example, a multipolar neuron that has a very important role to play in a part of the brain called the cerebellum is known as a Purkinje (commonly pronounced per-KIN-gee) cell. It is named after the anatomist

who discovered it (Jan Evangilista Purkinje, 1787–1869).



(a) Pyramidal cell of the cerebral cortex

(b) Purkinje cell of the cerebellar cortex

(c) Olfactory cells in the olfactory epithelium and olfactory bulbs

Figure 11.3.4: Other Neuron Classifications. Three examples of neurons that are classified on the basis of other criteria. (a) The pyramidal cell is a multipolar cell with a cell body that is shaped something like a pyramid. (b) The Purkinje cell in the cerebellum was named after the scientist who originally described it. (c) Olfactory neurons are named for the functional group with which they belong. (Image credit: "Other Types of Neurons" by OpenStax is licensed under CC BY 4.0)

Glial Cells

Glial cells, or neuroglia or simply glia, are the other type of cell found in nervous tissue. They are considered to be supporting cells, and many functions are directed at helping neurons complete their function for communication. The name glia comes from the Greek word that means “glue,” and was coined by the German pathologist Rudolph Virchow, who wrote in 1856: “This connective substance, which is in the brain, the spinal cord, and the special sense nerves, is a kind of glue (neuroglia) in which the nervous elements are planted.” Today, research into nervous tissue has shown that there are many deeper roles that these cells play. And research may find much more about them in the future.

There are six types of glial cells. Four of them are found in the CNS and two are found in the PNS. Table 11.3.1 outlines some common characteristics and functions.

Table 11.3.1: Glial Cell Types by Location and Basic Function.

CNS glia	PNS glia	Basic function
Astrocyte	Satellite cell	Support of the nervous tissue, form the blood-brain barrier (BBB)
Oligodendrocyte	Schwann cell	Insulation, myelination
Microglia	-	Immune surveillance and phagocytosis
Ependymal cell	-	Creating CSF

Glial Cells of the CNS

One cell providing support to neurons of the CNS is the **astrocyte**, so named because it appears to be star-shaped under the microscope (astro- = “star”). Astrocytes have many processes extending from their main cell body (not axons or dendrites like neurons, just cell extensions). Those processes extend to interact with neurons, blood vessels, or the connective tissue covering the CNS that is called the pia mater (Figure 11.3.5). Generally, they are supporting cells for the neurons in the central nervous system. Some ways in which they support neurons in the central nervous system are: 1) forming a structural network that strengthens the nervous tissue; 2) maintaining the homeostasis of signaling molecules, water and ions in the extracellular space; 3) providing an energy storage; 4) defending the nervous tissue from oxidative stress; 5) reacting to tissue damage and replacing

dead neurons; and 6) assisting neuronal development in the fetal brain. Another important role of astrocytes in the CNS is the contribution to the **blood-brain barrier (BBB)**. The blood-brain barrier is a physiological barrier that keeps many substances that circulate in the rest of the body from getting into the central nervous system, restricting what can cross from circulating blood into the CNS. Nutrient molecules, such as glucose or amino acids, can pass through the BBB, but other molecules cannot. This actually causes problems with drug delivery to the CNS. Pharmaceutical companies are challenged to design drugs that can cross the BBB as well as have an effect on the nervous system. Like a few other parts of the body, the brain has a privileged blood supply. Very little can pass through by diffusion. Most substances that cross the wall of a blood vessel into the CNS must do so through an active transport process. Because of this, only specific types of molecules can enter the CNS. Glucose—the primary energy source—is allowed, as are amino acids. Water and some other small particles, like gases and ions, can enter. But most everything else cannot, including white blood cells, which are one of the body's main lines of defense. While this barrier protects the CNS from exposure to toxic or pathogenic substances, it also keeps out the cells that could protect the brain and spinal cord from disease and damage. The BBB also makes it harder for pharmaceuticals to be developed that can affect the nervous system. Aside from finding efficacious substances, the means of delivery is also crucial.

Also found in CNS tissue is the **oligodendrocyte**, sometimes called just "oligo," which is the glial cell type that insulates axons in the CNS. The name means "cell of a few branches" (oligo- = "few"; dendro- = "branches"; -cyte = "cell"). There are a few processes that extend from the cell body. Each one reaches out and surrounds an axon to insulate it in myelin. One oligodendrocyte will provide the myelin for multiple axon segments, either for the same axon or for separate axons. The function of myelin will be discussed below.

Microglia are, as the name implies, smaller than most of the other glial cells. Ongoing research into these cells, although not entirely conclusive, suggests that they may originate as white blood cells, called macrophages, that become part of the CNS during early development. While their origin is not conclusively determined, their function is related to what macrophages do in the rest of the body. When macrophages encounter diseased or damaged cells in the rest of the body, they ingest and digest those cells or the pathogens that cause disease. Microglia are the cells in the CNS that can do this in normal, healthy tissue, and they are therefore also referred to as CNS-resident macrophages.

The **ependymal cell** is a glial cell that filters blood to make **cerebrospinal fluid (CSF)**, the fluid that circulates through the CNS. Because of the privileged blood supply inherent in the BBB, the extracellular space in nervous tissue does not easily exchange components with the blood. Ependymal cells line each **ventricle**, one of four central cavities that are remnants of the hollow center of the neural tube formed during the embryonic development of the brain. The **choroid plexus** is a specialized structure in the ventricles where ependymal cells come in contact with blood vessels and filter and absorb components of the blood to produce cerebrospinal fluid. Because of this, ependymal cells can be considered a component of the BBB, or a place where the CSF is actively secreted. These glial cells appear similar to epithelial cells, making a single layer of cells with little intracellular space and tight connections between adjacent cells. They also have cilia on their apical surface to help move the CSF through the ventricular space. The relationship of these glial cells to the structure of the CNS is seen in Figure 11.3.5.

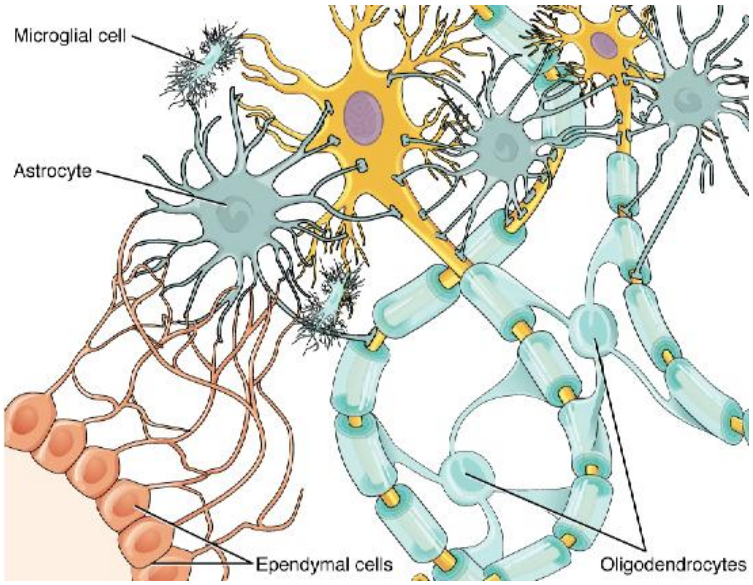


Figure 11.3.5: Glial Cells of the CNS. Ependymal cell line cavities within the brain and produce cerebrospinal fluid (CSF). Astrocytes form a barrier (blood-brain barrier) between the capillaries and the nervous tissue to protect it. Microglial cells act as defenders of the nervous tissue. Finally, oligodendrocytes wrap around multiple axons to insulate them. (Image credit: "Glial Cells of the CNS" by OpenStax is licensed under CC BY 4.0)

Glial Cells of the PNS

One of the two types of glial cells found in the PNS is the **satellite cell**. Satellite cells are found in sensory and autonomic ganglia, where they surround the cell bodies of neurons. This accounts for the name, based on their appearance under the microscope. They provide support, performing similar functions in the periphery as astrocytes do in the CNS—except, of course, for establishing the BBB.

The second type of glial cell is the **Schwann cell**, which insulate axons with myelin in the periphery. Schwann cells are different than oligodendrocytes, in that a Schwann cell wraps around a portion of only one axon segment and no others. Oligodendrocytes have processes that reach out to multiple axon segments, whereas the entire Schwann cell surrounds just one axon segment. The nucleus and cytoplasm of the Schwann cell are on the edge of the myelin sheath. The relationship of these two types of glial cells to ganglia and nerves in the PNS is seen in Figure 11.3.6.

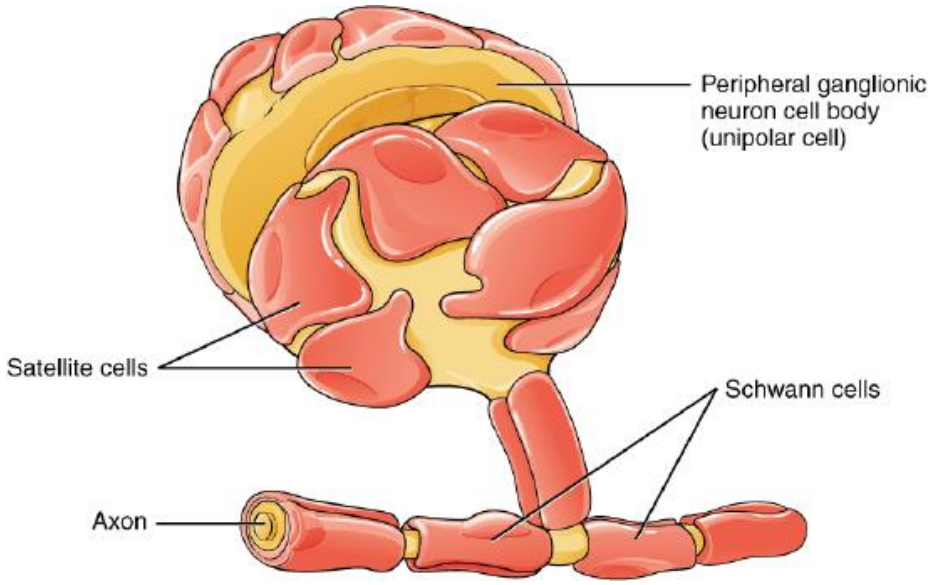


Figure 11.3.6: Glial Cells of the PNS. Satellite cells are wrapped around a unipolar neuron of a peripheral ganglion to support and protect it. Schwann cells are wrapped onto the neuron's axon to insulate it with their myelin sheath. (Image credit: "Glial Cells of the PNS" by OpenStax is licensed under CC BY 4.0)

DISORDERS OF THE...

Glial cells: Gliomas

Glioma is a type of tumor that occurs in the glial cells of the brain or spinal cord. Remember that tumor begins when the cell loses control over the checkpoints of mitosis and start proliferating excessively. Since neurons do not go under mitosis and can't produce new neurons, the only cells undergoing mitosis in the nervous system are the glial cells. Three types of glial cells can produce tumors. Gliomas are classified according to the type of glial cell involved in the tumor, as well as the tumor's genetic features, which can help predict how the tumor will behave over time and the treatments most likely to work. Types of glioma include:

- Astrocytomas, involving astrocytes
- Ependymomas, involving ependymal cells
- Oligodendrogliomas, involving oligodendrocytes

A glioma can affect the brain function and be life-threatening depending on its location and rate of growth. Gliomas are one of the most common types of primary brain tumors.

Myelin

The insulation for axons in the nervous system is provided by oligodendrocytes in the CNS and Schwann cells in the PNS. These cells use the same mechanism to insulate axon segments. Myelin is a lipid-rich sheath that surrounds the axon and by doing so creates a **myelin sheath** that facilitates the transmission of electrical signals along the axon. The lipids are essentially the phospholipids of the glial cell membrane. Myelin, however, is more than just the membrane of the glial cell. It also includes important proteins that are integral to that membrane. Some of the proteins help to hold the layers of the glial cell membrane closely together. The axon has parts that are not covered by myelin called nodes of Ranvier which ensure the propagation of the electrical signal. Axons can be completely enclosed by myelin (**myelinated**) or not fully enclosed by it (**unmyelinated**).

In myelinated nerves, the appearance of the myelin sheath can be thought of as similar to the pastry wrapped around a hot dog for “pigs in a blanket” or a similar food. The glial cell is wrapped around the axon several times with little to no cytoplasm between the glial cell layers. For oligodendrocytes in the CNS, the rest of the cell is separate from the myelin sheath as a cell process extends back toward the cell body. A few other processes provide the same insulation for other axon segments in the area. For Schwann cells in the PNS, the outermost layer of the cell membrane contains cytoplasm and the nucleus of the cell as a bulge on one side of the myelin sheath. During development, the glial cell is loosely or incompletely wrapped around the axon (Figure 11.3.7

.a). During myelination, the edges of this loose enclosure extend toward each other, and one end tucks under the other. The inner edge wraps around the axon, creating several layers, and the other edge closes around the outside so that the axon is completely enclosed. At the end of myelination, the myelin sheath is a thick layer that covers the axolemma (cell membrane of the neuronal axon) and results dark in an electron micrograph due to the staining technique (Figure 11.3.7.b).

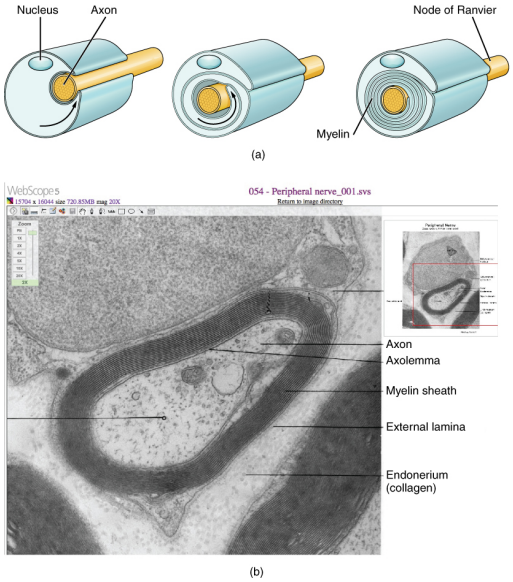


Figure 11.3.7: The Process of Myelination. In part (a), a drawing shows a myelinating glial cell wrapping several layers of cell membrane around the cell membrane of an axon segment and leaving its nucleus in the outer layer. In part (b), a histological slide shows a peripheral nerve in cross section covered by myelin sheath. The myelin looks dark grey under electron microscopy due to the staining technique used. Electron micrograph with magnification of 1,460,000X. (Image credit: "Myelinated Neuron" by OpenStax is licensed under CC BY 4.0/ Micrograph provided by the Regents of University of Michigan Medical School © 2012)

In unmyelinated nerves, the myelin sheath of oligodendrocytes or Schwann cells extends towards multiple axons. Since axons need to share the myelin sheath, they are not covered completely and one side of the axon remains unmyelinated (Figure 11.3.8). Since these nerves are not completely covered by myelin, their speed of electrical transmission is slower than myelinated nerves. Unmyelinated axons represent the majority of peripheral sensory (mainly related to pain caused by mechanical or temperature stimuli on the skin) and autonomic fibers.

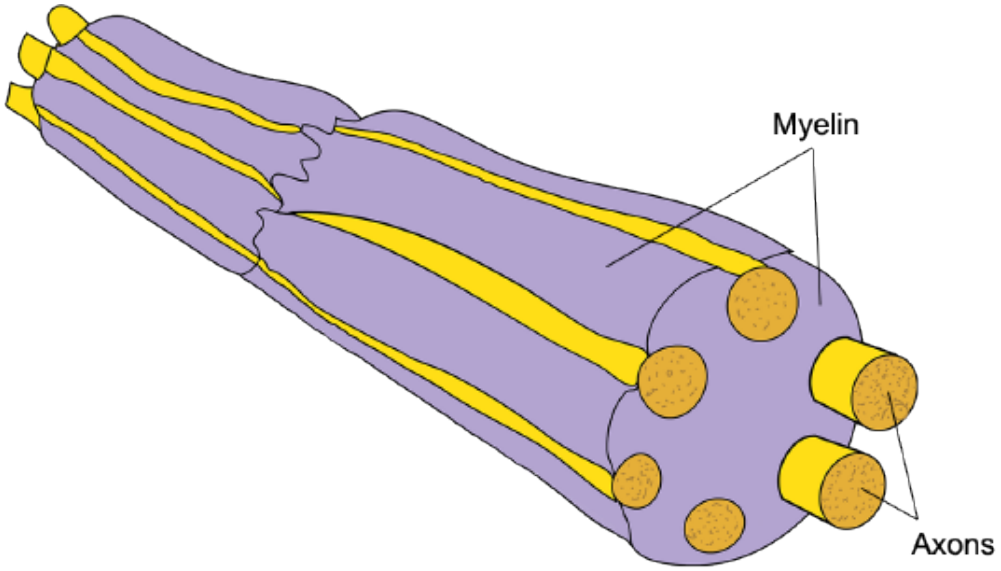


Figure 11.3.8: Unmyelinated Nerve. A myelinating cell embeds the axon into its cytoplasm, without covering them completely. Regions of the axons are not covered by myelin, making this type of axons slower than myelinated axons (Image credit: "Unmyelinated Nerve" by Chiara Mazzasette is a derivative from the original work of Daniel Donnelly and is licensed by CC BY 4.0)

Myelin sheaths can extend for one or two millimeters, depending on the diameter of the axon. Axon diameters can be as small as 1 to 20 micrometers. Because a micrometer is 1/1000 of a millimeter, this means that the length of a myelin sheath can be 100–1000 times the diameter of the axon. Figure 11.3.2, Figure 11.3.5, and Figure 11.3.6 show the myelin sheath surrounding an axon segment, but are not to scale. If the myelin sheath were drawn to scale, the neuron would have to be immense—possibly covering an entire wall of the room in which you are sitting.

Regeneration of Axons

Traumatic injuries can cause damage to nerves. When nerves are damaged within the PNS as in the case of a laceration, the axons distal to the injury degenerate. The Schwann cells that were wrapping the injured axons proliferate to form a new tube of myelin that guides the growing axons through physical and chemical support (Figure 11.3.9). Most of the times, axons can cross the injury site and can successfully grow back to the original targets. Sometimes the injury can affect also the surrounding tissues and form a scar that axons cannot cross. In that case, the axons are not able to grow back, unless surgery is performed to eliminate the scar tissue. The situation is different when injuries affect the CNS as in the case of spinal cord injuries. The oligodendrocytes respond to injury by undergoing apoptosis or becoming inactive. This contributes to the formation of scar tissue. Moreover, injury-activated astrocytes release molecules that inhibit axonal growth. Consequently, injured axons in the CNS are not able to grow back to their original target and nerve injuries in the CNS are permanent.

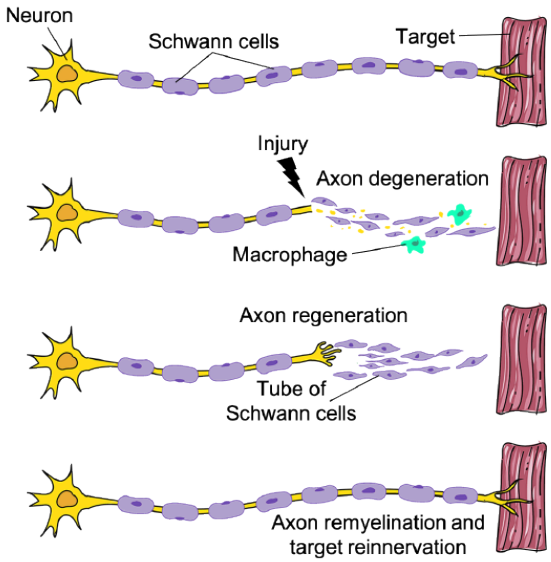


Figure 11.3.9: Axon Regeneration in the PNS. A neuron of the PNS innervates its target with its myelinated axon covered by Schwann cells. Following an injury, the part of the axon distal to the injury degenerates, leaving an axonal stump. The Schwann cells proliferate and produce new Schwann cells that form a tube to guide the axon back to its original target. Macrophages help clear up the debris from the axonal degeneration. The axonal stump grows following the tube of Schwann cells, which wrap it with myelin. The axon reaches the original target and the axon regeneration is complete. (Image credit: "Axon Regeneration in the PNS" by Chiara Mazzasette is a derivative from the original work of Daniel Donnelly and is licensed by CC BY 4.0)

DISORDERS OF THE...

Nervous Tissue: Demyelinating Diseases

Several diseases can result from the demyelination of axons. The causes of these diseases are not the same; some have genetic causes, some are caused by pathogens, and others are the result of autoimmune disorders. Though the causes are varied, the results are largely similar. The myelin insulation of axons is compromised, making electrical signaling slower.

Multiple sclerosis (MS) is one such disease. It is an example of an autoimmune disease. The antibodies produced by lymphocytes (a type of white blood cell) mark myelin as something that should not be in the body. This causes inflammation and the destruction of the myelin in the central nervous system. As the insulation around the axons is destroyed by the disease, scarring becomes obvious. This is where the name of the disease comes from; sclerosis

means hardening of tissue, which is what a scar is. Multiple scars are found in the white matter of the brain and spinal cord. The symptoms of MS include both somatic and autonomic deficits. Control of the musculature is compromised, as is control of organs such as the bladder.

Guillain-Barré (pronounced gee-YAN bah-RAY) syndrome is an example of a demyelinating disease of the peripheral nervous system. It is also the result of an autoimmune reaction, but the inflammation is in peripheral nerves. Sensory symptoms or motor deficits are common, and autonomic failures can lead to changes in the heart rhythm or a drop in blood pressure, especially when standing, which causes dizziness.

Concept Review

Nervous tissue contains two major cell types, neurons and glial cells. Neurons are the cells responsible for communication through electrical signals. Glial cells are supporting cells, maintaining the environment around the neurons.

Neurons are polarized cells, based on the flow of electrical signals along their membrane. Signals are received at the dendrites, are passed along the cell body, and propagate along the axon towards the target, which may be another neuron, muscle tissue, or a gland. Many axons are insulated by a lipid-rich substance called myelin. Specific types of glial cells provide this insulation.

Several types of glial cells are found in the nervous system, and they can be categorized by the anatomical division in which they are found. In the CNS, astrocytes, oligodendrocytes, microglia, and ependymal cells are found. Astrocytes are important for maintaining the chemical environment around the neuron and are crucial for regulating the blood-brain barrier. Oligodendrocytes are the myelinating glia in the CNS. Microglia act as phagocytes and play a role in immune surveillance. Ependymal cells are responsible for filtering the blood to produce cerebrospinal fluid, which is a circulatory fluid that performs some of the functions of blood in the brain and spinal cord because of the BBB. In the PNS, satellite cells are supporting cells for the neurons, and Schwann cells insulate peripheral axons. Thanks to the Schwann cells, injured axons in the PNS can often regenerate and re-innervate their targets, while injured axons in the CNS are not able to.

Review Questions

Q. What type of glial cell provides myelin for the axons in a tract?

A. oligodendrocyte

B. astrocyte

C. Schwann cell

D. satellite cell

Answer

Answer: A

Q. Which part of a neuron contains the nucleus?

A. dendrite

B. soma

C. axon

D. synaptic end bulb

Answer

Answer: B

Q. Which of the following substances is least able to cross the blood-brain barrier?

A. water

B. sodium ions

C. glucose

D. white blood cells

Answer

Answer: D

Q. What type of glial cell is the resident macrophage behind the blood-brain barrier?

A. microglia

B. astrocyte

C. Schwann cell

D. satellite cell

Answer

Answer: A

Q. What two types of macromolecules are the main components of myelin?

A. carbohydrates and lipids

B. proteins and nucleic acids

C. lipids and proteins

D. carbohydrates and nucleic acids

Answer

Answer: C

Critical Thinking Questions

Q. Multiple sclerosis is a demyelinating disease affecting the central nervous system. What type of cell would be the most likely target of this disease? Why?

Answer

A. The disease would target oligodendrocytes. In the CNS, oligodendrocytes provide the myelin for axons.

Q. Which type of neuron, based on its shape, is best suited for relaying information directly from one neuron to another? Explain why.

Answer

A. Bipolar cells, because they have one dendrite that receives input and one axon that provides output, would be a direct relay between two other cells.

Glossary

astrocyte
glial cell type of the CNS that provides support for neurons and maintains the blood-brain barrier

axon
single process of the neuron that carries an electrical signal (action potential) away from the cell body toward a target cell

axon hillock
tapering of the neuron cell body that gives rise to the axon

axon segment
single stretch of the axon insulated by myelin and bounded by nodes of Ranvier at either end (except for the first, which is after the axon hillock, and the last, which is followed by the axon terminal)

axon terminal
end of the axon, where there are usually several branches extending toward the target cell

axoplasm
cytoplasm of an axon, which is different in composition than the cytoplasm of the neuronal cell body

bipolar
shape of a neuron with two processes extending from the neuron cell body—the axon and one dendrite

blood-brain barrier (BBB)
physiological barrier between the circulatory system and the central nervous system that establishes a privileged blood supply, restricting the flow of substances into the CNS

cell body
in neurons, that portion of the cell that contains the nucleus, as opposed to the cell processes (axons and dendrites). Also known as soma

cerebrospinal fluid (CSF)
circulatory medium within the CNS that is produced by ependymal cells in the choroid plexus filtering the blood

choroid plexus
specialized structure containing ependymal cells that line blood capillaries and filter blood to produce CSF in the four ventricles of the brain

dendrite
one of many branch-like processes that extends from the neuron cell body and functions as a contact for incoming signals (synapses) from other neurons or sensory cells

ependymal cell
glial cell type in the CNS responsible for producing cerebrospinal fluid

interneuron
functional classification of a neuron that integrates information between sensory and motor neurons

microglia
glial cell type in the CNS that serves as the resident component of the immune system

motor neuron
functional classification of a neuron that carries commands from the brain and spinal cord to muscles and glands

multipolar
shape of a neuron that has multiple processes—the axon and two or more dendrites

myelin sheath
lipid-rich layer of insulation that surrounds an axon, formed by oligodendrocytes in the CNS and Schwann cells in the PNS; facilitates the transmission of electrical signals

myelinated
(of a nerve fiber) fully enclosed in a myelin sheath

neuronal polarity
asymmetrical distribution of cellular components (dendrites and axon) within a neuron

node of Ranvier
gap between two myelinated regions of an axon, allowing for strengthening of the electrical signal as it propagates down the axon

oligodendrocyte
glial cell type in the CNS that provides the myelin insulation for axons in tracts

satellite cell
glial cell type in the PNS that provides support for neurons in the ganglia

Schwann cell
glial cell type in the PNS that provides the myelin insulation for axons in nerves

sensory neuron
functional classification of a neuron that carries sensory information from the body's periphery into the nervous system

soma
in neurons, that portion of the cell that contains the nucleus, as opposed to the cell processes (axons and dendrites). Also known as cell body

synapse
narrow junction across which a chemical signal passes from neuron to the next, initiating a new electrical signal in the target cell

synaptic end bulb
swelling at the end of an axon where neurotransmitter molecules are released onto a target cell across a synapse

unipolar
shape of a neuron which has only one process that includes both the axon and dendrite

unmyelinated
(of a nerve fiber) not fully enclosed in myelin sheath

ventricle
central cavity within the brain where CSF is produced and circulates

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11.4: Neuronal Communication

By the end of this section, you will be able to:

- Explain the events that occur during the conduction of nerve impulses
- Differentiate the nerve impulse propagation in saltatory and continuous conduction
- Describe the components of synapses and compare electrical and chemical synapses

Having looked at the components of nervous tissue, and the basic anatomy of the nervous system, next comes an understanding of how nervous tissue is capable of communicating within the nervous system. Neurons communicate with other neurons, muscles or glands through the generation and conduction of nerve impulses. These nerve impulses represent changes in the electrical properties of the neuronal cell membrane. All cells have an electrical charge associated with their membrane. However, neurons and other cells are able to change their electrical charge by moving ions across the membrane. In this section, you will look at the basics of neuronal communication, mainly focusing on the conduction of the nerve impulse.

Conduction of Nerve Impulses

Neurons possess electrical excitability, which is the ability to respond to a stimulus by generating a nerve impulse. In the majority of cases, the dendrites of a neuron are the place where local changes in the membrane electrical properties happen through synapses. Dendrites receive stimuli from the external environment (e.g. somatic sensory neurons) or internal environment (e.g. visceral sensory neurons, motor neurons or interneurons). The amount of change in the membrane electrical charge is determined by the strength of the stimulus that causes it. For example, a needle pricking a fingertip will result in a bigger stimulus compared to a blunt object touching the same fingertip. Once a stimulus (or multiple stimuli) produces a significant change in the membrane electrical properties of a dendrite and reaches a predetermined **threshold**, then a nerve impulse (also called action potential) occurs. An **action potential** is generated at the axon hillock of a neuron and progresses rapidly along the axon's plasma membrane to reach the targets (a second neuron, a muscle or a gland). This movement of an action potential along the axon is called **propagation**. While the stimuli can be weak or strong, the action potential follows a **All-or-None Law** by which it always has the same strength (referred to as amplitude) independently of the stimulus. This minimizes the possibility that information will be lost along the way. The only way to modulate the response is through the frequency of action potentials - how many action potentials reach the target in a set amount of time. A bigger stimulus will produce a series (or train) of action potentials that are close together, while a weak stimulus will produce sparse action potentials.

The speed of an action potential is influenced by the diameter of the axon and by its myelination. The larger the diameter of the axon, the faster the action potential will be conducted. Myelinated axons are able to carry action potentials faster than unmyelinated axons. As discussed in the previous section, myelinating cells (oligodendrocytes in the CNS and Schwann cells in the PNS) wrap around axons forming the myelin. Nodes of Ranvier are gaps between segments of myelin. The electrical charges of the action potential can "jump" from one gap to another one, thus allowing a faster speed of the action potential. This progression of a nerve impulse is called **saltatory conduction**. However, in unmyelinated axons, one side of the axon is not covered by myelin and the electrical charges move along the entire axonal membrane, thus taking longer to reach their target. This progression of a nerve impulse is called **continuous conduction**. Once the action potential reaches the axon terminal, it is either transported as electrical charge into the next cell or transformed into a chemical signal, depending on the type of synapse that the synaptic end bulb is forming with its target.

Neurons and their targets form synapses. The neuron that generates and conducts the action potential to the target is called a **presynaptic cell**. The target cell receiving the action potential is called a **postsynaptic cell**. While the presynaptic cell is always a neuron (because only neurons have axons and can form a synapse), the postsynaptic cell can be a neuron or another type of cell such as skeletal, cardiac or smooth muscle cells, or glands. In Figure 11.4.1, a presynaptic neuron forms synapses with two postsynaptic neurons. The nerve impulse (or signal) travels from a presynaptic neuron to a postsynaptic cell. If the postsynaptic cell is a neuron, a new action potential might be generated in the postsynaptic neuron and reach its postsynaptic targets.

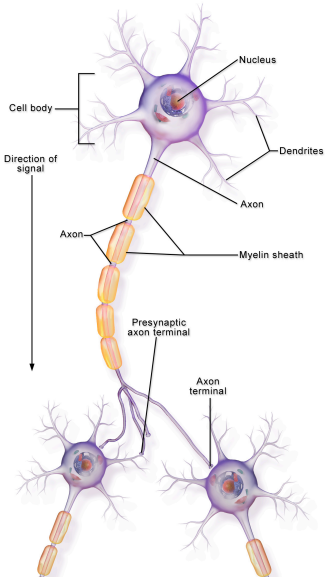

Figure 11.4.1: Presynaptic and postsynaptic neurons. A presynaptic neuron on top forms synapses with two postsynaptic neurons at the bottom. The parts of the presynaptic neuron are labeled as cell body, nucleus, dendrites and axon covered in a myelin sheath. The direction of signal shows that the electrical signal (action potential) travels from the axon of the presynaptic neuron to the axon terminals of the presynaptic neuron that are in contact with the dendrites and cell body of the postsynaptic neurons. (Image credit: "Neuron Part 1" by BruceBlaus is licensed under CC BY-SA 4.0)

Synapses

There are two types of connections between electrically active cells: electrical synapses and chemical synapses. In an **electrical synapse**, there is a direct connection between the presynaptic and postsynaptic cells and the connection is formed by gap junctions. Thus, the electrical charges of an action potential can pass directly from one cell to the next. If one cell delivers an action potential in an electrical synapse, the joined cell will also generate an action potential because the electrical charges will pass between the cells (Figure 11.4.2). Although representing the minority of synapses, electrical synapses are found throughout the nervous system. These synapses also occur between excitable cells other than neurons, for example between smooth muscle cells in the intestines and cardiac muscle cells in the heart.

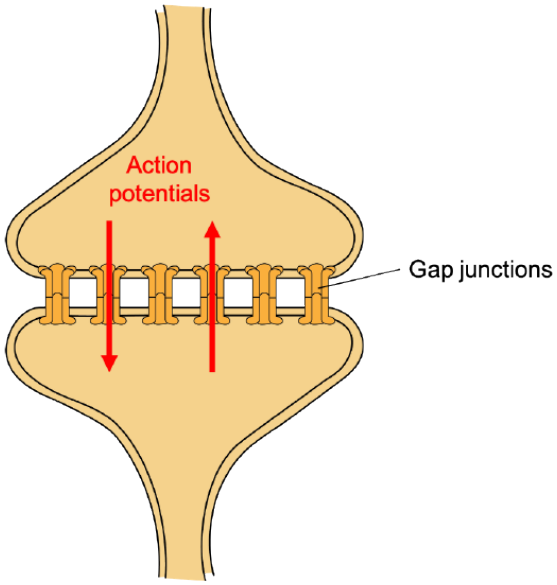

Figure 11.4.2: Electrical Synapse. Two synaptic end bulbs form an electrical synapse where gap junctions allow the passage of action potentials from one cytoplasm to the other, and viceversa. (Image credit: "Electrical Synapse" by Chiara Mazzasette is a derivative from the original work of Daniel Donnelly and is licensed by CC BY 4.0)

Chemical synapses involve the transmission of chemical information from one cell to the next and they represent the majority of the synapses found within the nervous system. In a **chemical synapse**, a chemical signal called a **neurotransmitter**, is released from the presynaptic cell and it affects the postsynaptic cell. There are many different types of neurotransmitters, for example acetylcholine, serotonin, dopamine, adrenaline, glutamate, etc. Each neurotransmitter has its own specific receptor on the postsynaptic membrane. Chemical synapses can then be classified based on the neurotransmitter that the cells use to communicate (for example glutamatergic synapses use glutamate). Different neurotransmitters and different receptors will determine the overall response to the stimulus. All chemical synapses have common characteristics, which can be summarized in this list and are shown in Figure 11.4.3:

- synaptic end bulb of presynaptic neuron
- neurotransmitter (packaged in vesicles)
- synaptic cleft
- receptors for neurotransmitter
- postsynaptic membrane of postsynaptic neuron

The synaptic end bulbs of chemical synapses are filled with vesicles containing one type of neurotransmitter. When an action potential reaches the axon terminals, the vesicles merge with the cell membrane at the synaptic end bulb, releasing the neurotransmitter through exocytosis into the small gap between the cells, known as the **synaptic cleft**. Once in the synaptic cleft, the neurotransmitter diffuses the short distance to the postsynaptic membrane and can interact with neurotransmitter receptors. Receptors are specific for the neurotransmitter, and the two fit together like a key and lock. One neurotransmitter binds to its receptor and will not bind to receptors for other neurotransmitters, making the binding a specific chemical event. The binding of the neurotransmitter to its receptor causes a brief electrical change across the postsynaptic membrane. The change depends on the type of neurotransmitter receptor. Changes in the postsynaptic cell membrane can cause a nerve impulse to begin in the postsynaptic cell or inhibit the generation of an action potential. The flow of information is unidirectional: from the presynaptic cell to the postsynaptic cell. After its release in a chemical synapse, neurotransmitters need to be removed from the synaptic cleft to ensure the propagation of new synaptic signals.

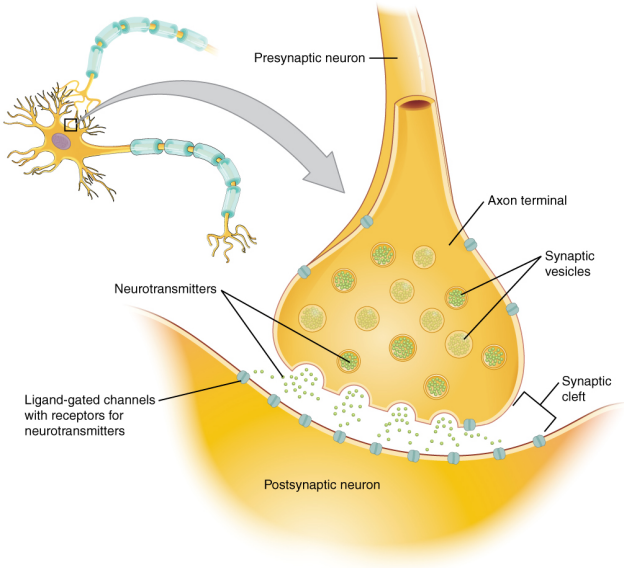

Figure 11.4.3: Chemical Synapse. The axon of the presynaptic neuron terminates at the axon terminal in a synaptic end bulb where the action potential arrives. The arrival of action potential causes the synaptic vesicles containing neurotransmitters to fuse with the membrane and release the neurotransmitters. The neurotransmitters diffuse across the synaptic cleft to bind to its receptor, in this case ligand-gated channels. Neurotransmitters will eventually be cleared from the synapse. (Image credit: "Chemical Synapse" by Young, KA., Wise, JA., DeSaix, P., Kruse, DH., Poe, B., Johnson, E., Johnson, JE., Korol, O., Betts, JG., & Womble, M. is licensed under CC BY 4.0)

DISORDERS OF THE...

Nervous System: Alzheimer's and Parkinson's Disease

The underlying cause of some neurodegenerative diseases, such as Alzheimer's and Parkinson's, appears to be related to proteins—specifically, to proteins behaving badly. One of the strongest theories of what causes Alzheimer's disease is based on the accumulation of beta-amyloid plaques, dense conglomerations of a protein that is not functioning correctly. Parkinson's disease is linked to an increase in a protein known as alpha-synuclein that is toxic to the cells of the substantia nigra nucleus in the midbrain.

For proteins to function correctly, they are dependent on their three-dimensional shape. The linear sequence of amino acids folds into a three-dimensional shape that is based on the interactions between and among those amino acids. When the folding is disturbed, and proteins take on a different shape, they stop functioning correctly. But the disease is not necessarily the result of functional loss of these proteins; rather, these altered proteins start to accumulate and may become toxic. For example, in Alzheimer's, the hallmark of the disease is the accumulation of these amyloid plaques in the cerebral cortex. The term coined to describe this sort of disease is "proteopathy" and it includes other diseases. Creutzfeld-Jacob disease, the human variant of the prion disease known as mad cow disease in the bovine, also involves the accumulation of amyloid plaques, similar to Alzheimer's. Diseases of other organ systems can fall into this group as well, such as cystic fibrosis or type 2 diabetes. Recognizing the relationship between these diseases has suggested new therapeutic possibilities. Interfering with the accumulation of the proteins, and possibly as early as their original production within the cell, may unlock new ways to alleviate these devastating diseases.

CAREER CONNECTIONS

Neurophysiologist

Understanding how the nervous system works could be a driving force in your career. Studying neurophysiology is a very rewarding path to follow. It means that there is a lot of work to do, but the rewards are worth the effort.

The career path of a research scientist can be straightforward: college, graduate school, postdoctoral research, academic research position at a university. A Bachelor's degree in science will get you started, and for neurophysiology that might be in biology, psychology, computer science, engineering, or neuroscience. But the real specialization comes in graduate school. There are many different programs out there to study the nervous system, not just neuroscience itself. Most graduate programs are doctoral, meaning that a Master's degree is not part of the work. These are usually considered five-year programs, with the first two years dedicated to course work and finding a research mentor, and the last three years dedicated to finding a research topic and pursuing that with a near single-mindedness. The research will usually result in a few publications in scientific journals, which will make up the bulk of a doctoral dissertation. After graduating with a Ph.D., researchers will go on to find specialized work called a postdoctoral fellowship within established labs. In this position, a researcher starts to establish their own research career with the hopes of finding an academic position at a research university.

Other options are available if you are interested in how the nervous system works. Especially for neurophysiology, a medical degree might be more suitable so you can learn about the clinical applications of neurophysiology and possibly work with human subjects. An academic career is not a necessity. Biotechnology firms are eager to find motivated scientists ready to tackle the tough questions about how the nervous system works so that therapeutic chemicals can be tested on some of the most challenging disorders such as Alzheimer's disease or Parkinson's disease, or spinal cord injury.

Others with a medical degree and a specialization in neuroscience go on to work directly with patients, diagnosing and treating mental disorders. You can do this as a psychiatrist, a neuropsychologist, a neuroscience nurse, or a neurodiagnostic technician, among other possible career paths.

Concept Review

The basis of the electrical signal within a neuron is the action potential that propagates down the axon. For a neuron to generate an action potential, it needs to receive input from another source, either another neuron or a sensory stimulus. That input will result in a change in the electrical properties of the cell membrane, based on the strength of the stimulus. Once the stimulus is strong enough, it will generate an action potential that travels along the axon to the synaptic end bulb.

The diameter of the axon and the presence or absence of myelin determines how fast the action potential is conducted down the axon. A larger diameter and the presence of a myelin sheath will ensure a fast propagation of the action potential.

Synapses are the contacts between neurons, which can either be chemical or electrical in nature. Chemical synapses are far more common. At a chemical synapse, neurotransmitter is released from the presynaptic element and diffuses across the synaptic cleft. The neurotransmitter binds to a receptor protein and causes a change in the postsynaptic membrane (the PSP). The neurotransmitter must diffuse, be inactivated or removed from the synaptic cleft so that the stimulus is limited in time.

Review Questions

Q. At an electrical synapse, what do the presynaptic and postsynaptic cells communicate through?

A. neurotransmitters

B. neurotransmitter receptors

C. nodes of Ranvier

D. gap junctions

Answer

Answer: D

Q. Which of the following axons would propagate an action potential faster than the others?

A. myelinated, large diameter, axons

B. myelinated, small diameter, axons

C. unmyelinated, large diameter, axons

D. unmyelinated, small diameter, axons

Answer

Answer: A

Glossary

action potential
change in the electrical properties of a cell membrane in response to a stimulus that results in transmission of an electrical signal; unique to neurons and muscle fibers

All-or-None Law
the principle that the strength by which a neuron responds to a stimulus is not dependent on the strength of the stimulus;

chemical synapse
connection between two neurons, or between a neuron and its target, where a neurotransmitter diffuses across a very short distance

continuous conduction
slower propagation of the action potential along an unmyelinated axon

electrical synapse
connection between two neurons, or any two electrically active cells, where an action potential can flow across gap junctions into the adjacent cell

neurotransmitter
chemical signal that is released from the synaptic end bulb of a neuron to cause a change in the target cell

postsynaptic cell
cell receiving a synapse from another cell

presynaptic cell
cell forming a synapse with another cell

propagation
movement of an action potential along the length of an axon

saltatory conduction
faster propagation of the action potential in a myelinated axon, from one node of Ranvier to the following node

synaptic cleft
small gap between cells in a chemical synapse where neurotransmitter diffuses from the presynaptic element to the postsynaptic element

threshold
membrane voltage at which an action potential is initiated

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11.5: Development of the Nervous System

By the end of this section, you will be able to:

- Describe the growth and differentiation of the anterior neural tube into primary and secondary vesicles
- Relate the different stages of development of the anterior neural tube to the adult brain regions
- Describe the development of the posterior neural tube into the adult spinal cord
- Explain the expansion of the ventricular system of the adult brain from the central canal of the neural tube

The brain is a complex organ composed of gray parts and white matter, which can be hard to distinguish. Starting from an embryologic perspective allows you to understand more easily how the parts relate to each other. The embryonic nervous system begins as a very simple structure—essentially just a straight line, which then gets increasingly complex. Looking at the development of the nervous system with a couple of early snapshots makes it easier to understand the whole complex system.

Many structures that appear to be adjacent in the adult brain are not connected, and the connections that exist may seem arbitrary. But there is an underlying order to the system that comes from how different parts develop. By following the developmental pattern, it is possible to learn what the major regions of the nervous system are.

Neural Tube

To begin, a sperm cell and an egg cell fuse to become a fertilized egg. The fertilized egg cell, or zygote, starts dividing to generate the cells that make up an entire organism. Sixteen days after fertilization, the developing embryo's cells belong to one of three germ layers that give rise to the different tissues in the body. The endoderm, or inner tissue, is responsible for generating the lining tissues of various spaces within the body, such as the mucosae of the digestive and respiratory systems. The mesoderm, or middle tissue, gives rise to most of the muscle and connective tissues. Finally the ectoderm, or outer tissue, develops into the integumentary system (the skin) and the nervous system. It is probably not difficult to see that the outer tissue of the embryo becomes the outer covering of the body. But how is it responsible for the nervous system?

As the embryo develops, a portion of the ectoderm differentiates into a specialized region of neuroectoderm, which is the precursor for the tissue of the nervous system. Molecular signals induce cells in this region to differentiate into the neuroepithelium, forming a **neural plate**. The cells then begin to change shape, causing the tissue to buckle and fold inward (Figure 11.5.1). A **neural groove** forms, visible as a line along the dorsal surface of the embryo. The ridge-like edge on either side of the neural groove is referred as the **neural fold**. As the neural folds come together and converge, the underlying structure forms into a tube just beneath the ectoderm called the **neural tube**. Cells from the neural folds then separate from the ectoderm to form a cluster of cells referred to as the **neural crest**, which runs lateral to the neural tube. The neural crest migrates away from the nascent, or embryonic, central nervous system (CNS) that will form along the neural groove and develops into several parts of the peripheral nervous system (PNS), including the enteric nervous tissue. Many tissues that are not part of the nervous system also arise from the neural crest, such as craniofacial cartilage and bone, and melanocytes.

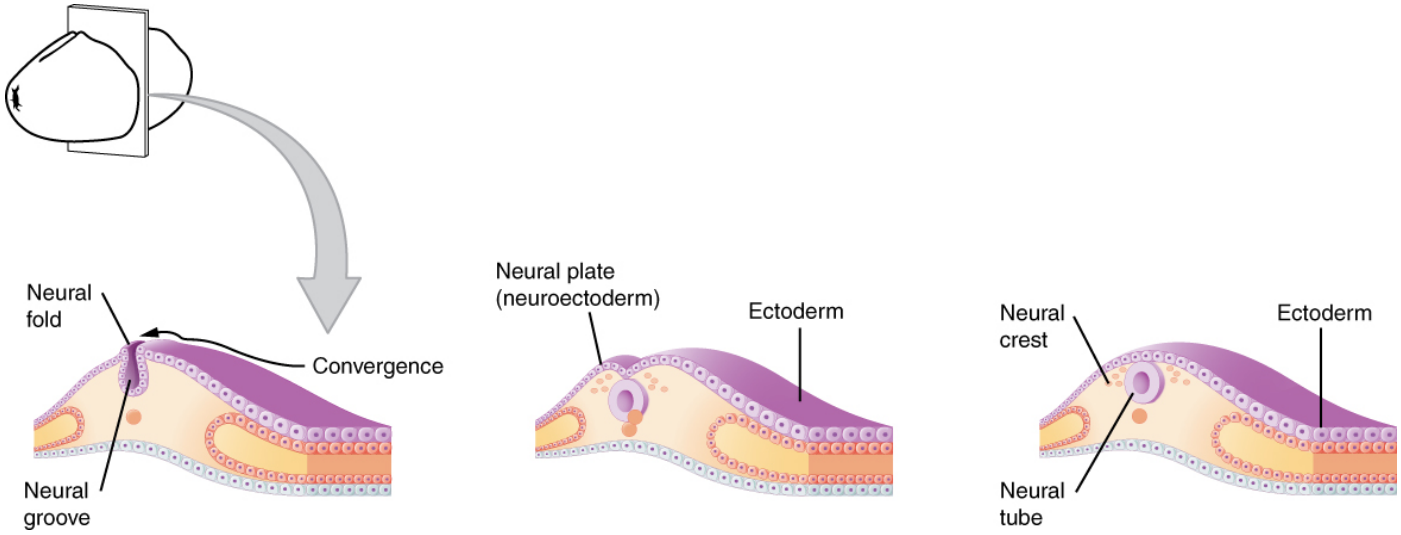

Figure 11.5.1: Early Embryonic Development of Nervous System. The neuroectoderm that forms the neural plate begins to fold inward to form the neural groove. As the two sides of the neural groove converge, they fuse together and form the neural tube, which lies beneath the ectoderm. The anterior end of the neural tube will develop into the brain, and the posterior portion will become the spinal cord. The neural crest which sits laterally to the neural tube develops into peripheral structures. (Image credit: "Neural Tube Development" by OpenStax is licensed under CC BY 4.0)

At this point, the early nervous system is a simple, hollow tube. It runs from the anterior end of the embryo to the posterior end. Beginning at 25 days, the anterior end develops into the brain, and the posterior portion becomes the spinal cord. This is the most basic arrangement of tissue in the nervous system, and it gives rise to the more complex structures by the fourth week of development.

Primary Vesicles

As the anterior end of the neural tube starts to develop into the brain, it undergoes a couple of enlargements; the result is the production of sac-like vesicles. Similar to a child's balloon animal, the long, straight neural tube begins to take on a new shape. Three vesicles form at the first stage, which are called **primary vesicles**. These vesicles are given names that are based on Greek words, the main root word being *enkephalon*, which means "brain" (en- = "inside"; kephalon = "head"). The prefix to each generally corresponds to its position along the length of the developing nervous system.

The **prosencephalon** (pros- = "in front") is the forward-most vesicle, and the term can be loosely translated to mean **forebrain**. The **mesencephalon** (mes- = "middle") is the next vesicle, which can be called the **midbrain**. The third vesicle at this stage is the **rhombencephalon**. The first part of this word is also the root of the word rhombus, which is a geometrical figure with four sides of equal length (a square is a rhombus with 90° angles). Whereas prosencephalon and mesencephalon translate into the English words forebrain and midbrain, there is not a word for "four-sided-figure-brain." However, the third vesicle can be called the **hindbrain**. One way of thinking about how the brain is arranged is to use these three regions—forebrain, midbrain, and hindbrain—which are based on the primary vesicle stage of development (Figure 11.5.2a).

Secondary Vesicles

The brain continues to develop, and the vesicles differentiate further (Figure 11.5.2b). The three primary vesicles become five **secondary vesicles**. The prosencephalon enlarges into two new vesicles called the **telencephalon** and the **diencephalon**. The telecephalon will become the cerebrum. The diencephalon gives rise to several adult structures; two that will be important are the thalamus and the hypothalamus. In the embryonic diencephalon, a structure known as the eye cup develops, which will eventually become the retina, the nervous tissue of the eye called the retina. This is a rare example of nervous tissue developing as part of the CNS structures in the embryo, but becoming a peripheral structure in the fully formed nervous system.

The mesencephalon does not differentiate into any finer divisions. The midbrain is an established region of the brain at the primary vesicle stage of development and remains that way. The rest of the brain develops around it and constitutes a large percentage of the mass of the brain. Dividing the brain into forebrain, midbrain, and hindbrain is useful in considering its developmental pattern, but the midbrain is a small proportion of the entire brain, relatively speaking.

The rhombencephalon develops into the **metencephalon** and **myelencephalon**. The metencephalon corresponds to the adult structure known as the pons and also gives rise to the cerebellum. The cerebellum (from the Latin meaning “little brain”) accounts for about 10 percent of the mass of the brain and is an important structure in itself. The most significant connection between the cerebellum and the rest of the brain is at the pons, because the pons and cerebellum develop out of the same vesicle. The myelencephalon corresponds to the adult structure known as the medulla oblongata. The structures that come from the mesencephalon and rhombencephalon, except for the cerebellum, are collectively considered the **brainstem**, which specifically includes the midbrain, pons, and medulla.

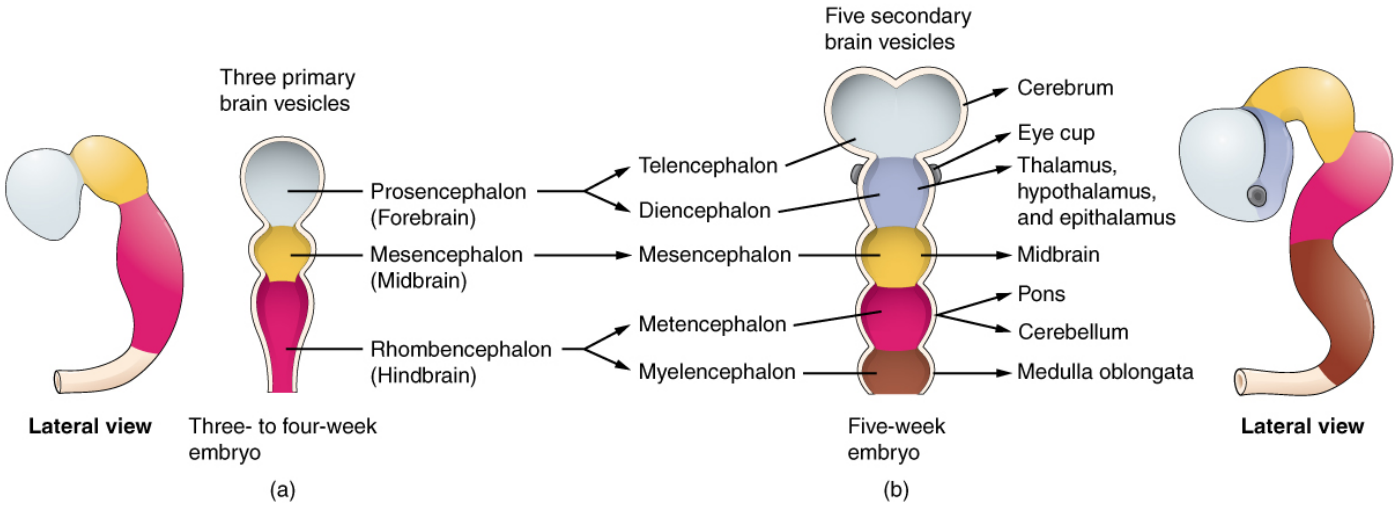

Figure 11.5.2: Primary and Secondary Vesicle Stages of Development. The embryonic brain develops complexity through enlargements of the neural tube called vesicles. In part a, the primary vesicle stage which happens around 3 to 4 weeks of embryonic development shows three vesicles: the prosencephalon is superior and anterior; the mesencephalon is inferior to the prosencephalon; and rhombencephalon is the most inferior vesicle. In part b, the secondary vesicle stage which happens at 5 weeks of embryonic development shows five regions. From anterior and superior to posterior and inferior, these regions are: telencephalon, diencephalon, mesencephalon, metencephalon and myelencephalon. (Image credit: "Brain Vesicle Development" by OpenStax is licensed under CC BY 4.0)

Spinal Cord Development

While the brain is developing from the anterior neural tube, the spinal cord is developing from the posterior neural tube. However, its structure does not differ from the basic layout of the neural tube. It is a long, straight cord with a small, hollow space down the center. The neural tube is defined in terms of its anterior versus posterior portions, but it also has a dorsal–ventral dimension. As the neural tube separates from the rest of the ectoderm, the side closest to the surface is dorsal, and the deeper side is ventral.

As the spinal cord develops, the cells making up the wall of the neural tube proliferate and differentiate into the neurons and glia of the spinal cord. The dorsal tissues will be associated with sensory functions, and the ventral tissues will be associated with motor functions.

Relating Embryonic Development to the Adult Brain

Embryonic development can help in understanding the structure of the adult brain because it establishes a framework on which more complex structures can be built. First, the neural tube establishes the anterior–posterior dimension of the nervous system, which is called the **neuraxis**. The embryonic nervous system in mammals can be said to have a standard arrangement. Humans (and other primates, to some degree) make this complicated by standing up and walking on two legs. The anterior–posterior dimension of the neuraxis overlays the superior–inferior dimension of the body. However, there is a major curve between the brainstem and forebrain, which is called the **cephalic flexure**. Because of this, the neuraxis starts in an inferior position—the end of the spinal cord—and ends in an anterior position, the front of the cerebrum. If this is confusing, just imagine a four-legged animal standing up on two legs. Without the flexure in the brainstem, and at the top of the neck, that animal would be looking straight up instead of straight in front (Figure 11.5.3).

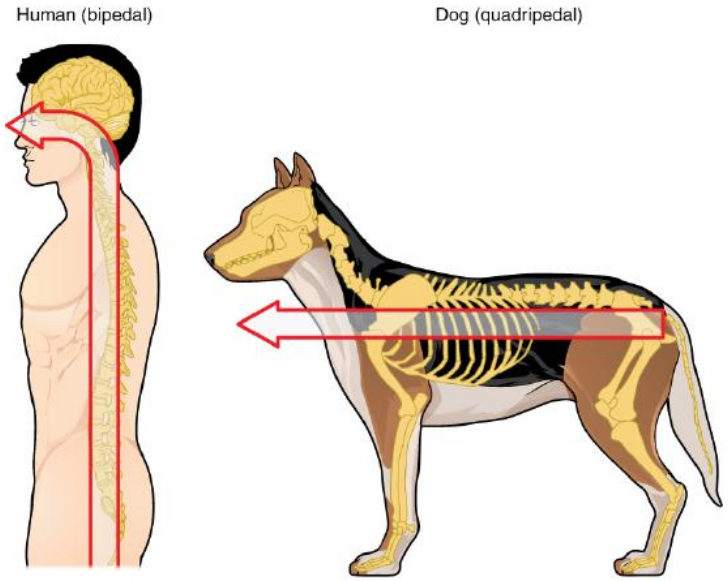

Figure 11.5.3: Human Neuraxis. The mammalian nervous system is arranged with the neural tube running along an anterior to posterior axis, from nose to tail for a four-legged animal like a dog. Humans, as two-legged animals, have a bend in the neuraxis between the brainstem and the diencephalon, along with a bend in the neck, so that the eyes and the face are oriented forward. (Image credit: "Human Neuraxis" by OpenStax is licensed under CC BY 4.0)

In summary, the primary vesicles help to establish the basic regions of the nervous system: forebrain, midbrain, and hindbrain. These divisions are useful in certain situations, but they are not equivalent regions. The midbrain is small compared with the hindbrain and particularly the forebrain. The secondary vesicles go on to establish the major regions of the adult nervous system that will be followed in this text. The telencephalon is the cerebrum, which is the major portion of the human brain. The diencephalon continues to be referred to by this Greek name, because there is no better term for it (dia- = “through”). The diencephalon is between the cerebrum and the rest of the nervous system and can be described as the region through which all projections have to pass between the cerebrum and everything else. The brainstem includes the midbrain, pons, and medulla, which correspond to the mesencephalon, metencephalon, and myelencephalon. The cerebellum, being a large portion of the brain, is considered a separate region. Table connects the different stages of development to the adult structures of the CNS.

One other benefit of considering embryonic development is that certain connections are more obvious because of how these adult structures are related. The retina, which began as part of the diencephalon, is primarily connected to the diencephalon. The eyes are just inferior to the anterior-most part of the cerebrum, but the optic nerve extends back to the thalamus as the optic tract, with branches into a region of the hypothalamus. There is also a connection of the optic tract to the midbrain, but the mesencephalon is adjacent to the diencephalon, so that is not difficult to imagine. The cerebellum originates out of the metencephalon, and its largest white matter connection is to the pons, also from the metencephalon. There are connections between the cerebellum and both the medulla and midbrain, which are adjacent structures in the secondary vesicle stage of development. In the adult brain, the cerebellum seems close to the cerebrum, but there is no direct connection between them.

Another aspect of the adult CNS structures that relates to embryonic development is the ventricles—open spaces within the CNS where cerebrospinal fluid circulates. They are the remnant of the hollow center of the neural tube. The four ventricles and the tubular spaces associated with them can be linked back to the hollow center of the embryonic brain (see Table 11.5.1).

Stages of Embryonic Development				
Neural tube	**Primary vesicle stage**	**Secondary vesicle stage**	**Adult structures**	**Ventricles**
Anterior neural tube	Prosencephalon	Telencephalon	Cerebrum	Lateral ventricles
Anterior neural tube	Prosencephalon	Diencephalon	Diencephalon	Third ventricle
Anterior neural tube	Mesencephalon	Mesencephalon	Midbrain	Cerebral aqueduct
Anterior neural tube	Rhombencephalon	Metencephalon	Pons cerebellum	Fourth ventricle
Anterior neural tube	Rhombencephalon	Myelencephalon	Medulla	Fourth ventricle
Posterior neural tube			Spinal cord	Central canal

Table 11.5.1 Stages of Embryonic Development

DISORDERS OF THE...

Development of the Nervous System: Spina Bifida

Early formation of the nervous system depends on the formation of the neural tube. A groove forms along the dorsal surface of the embryo, which becomes deeper until its edges meet and close off to form the tube. If this fails to happen, especially in the posterior region where the spinal cord forms, a developmental defect called spina bifida occurs. The closing of the neural tube is important for more than just the proper formation of the nervous system. The surrounding tissues are dependent on the correct development of the tube. The connective tissues surrounding the CNS can be involved as well.

There are three classes of this disorder: occulta, meningocele, and myelomeningocele (Figure 11.5.4). The first type, spina bifida occulta, is the mildest because the vertebral bones do not fully surround the spinal cord, but the spinal cord itself is not affected. No functional differences may be noticed, which is what the word occulta means; it is hidden spina bifida. The other two types both involve the formation of a cyst—a fluid-filled sac of the connective tissues that cover the spinal cord called the meninges. “Meningocele” means that the meninges protrude through the spinal column but nerves may not be involved and few symptoms are present, though complications may arise later in life. “Myelomeningocele” means that the meninges protrude and spinal nerves are involved, and therefore severe neurological symptoms can be present.

Often surgery to close the opening or to remove the cyst is necessary. The earlier that surgery can be performed, the better the chances of controlling or limiting further damage or infection at the opening. For many children with meningocele, surgery will alleviate the pain, although they may experience some functional loss. Because the myelomeningocele form of spina bifida involves more extensive damage to the nervous tissue, neurological damage may persist, but symptoms can often be handled. Complications of the spinal cord may present later in life, but overall life expectancy is not reduced.

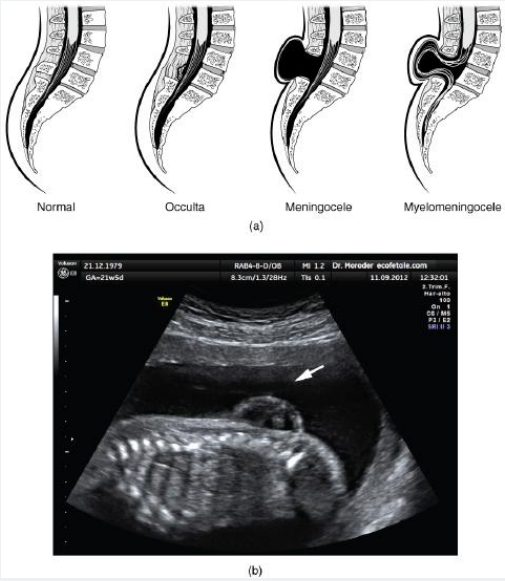

Figure 11.5.4: Spina Bifida. Spina bifida is a birth defect of the spinal cord caused when the neural tube does not completely close, but the rest of development continues. The result is the emergence of meninges and neural tissue through the vertebral column. Part (a) shows the difference between a normal spinal cord, and the three types of spina bifida: occulta, meningocele and myelomeningocele. In part (b), an ultrasound taken at 21 weeks shows a fetal myelomeningocele. (Image credit: "Spina Bifida" by OpenStax is licensed under CC BY-SA 3.0 / Ultrasound image: "Spina bifida lombare sagittale" by Moroder is licensed under CC BY-SA 3.0)

Concept Review

The development of the nervous system starts early in embryonic development. The outer layer of the embryo, the ectoderm, gives rise to the skin and the nervous system. A specialized region of this layer, the neuroectoderm, becomes a groove that folds in and becomes the neural tube beneath the dorsal surface of the embryo. The anterior end of the neural tube develops into the brain, and the posterior region becomes the spinal cord. Tissues at the edges of the neural groove, when it closes off, are called the neural crest and migrate through the embryo to give rise to PNS structures as well as some non-nervous tissues.

The brain develops from this early tube structure and gives rise to specific regions of the adult brain. As the neural tube grows and differentiates, it enlarges into three vesicles that correspond to the forebrain, midbrain, and hindbrain regions of the adult brain. Later in development, two of these three vesicles differentiate further, resulting in five vesicles. Those five vesicles can be aligned with the four major regions of the adult brain. The cerebrum is formed directly from the telencephalon. The diencephalon is the only region that keeps its embryonic name. The mesencephalon, metencephalon, and myelencephalon become the brainstem. The cerebellum also develops from the metencephalon and is a separate region of the adult brain.

The spinal cord develops out of the rest of the neural tube and retains the tube structure, with the nervous tissue thickening and the hollow center becoming a very small central canal through the cord. The rest of the hollow center of the neural tube corresponds to open spaces within the brain called the ventricles, where cerebrospinal fluid is found.

Multiple Choice

Q. Aside from the nervous system, which other organ system develops out of the ectoderm?

A. digestive

B. respiratory

C. integumentary

D. urinary

Answer

Answer: C

Q. Which primary vesicle of the embryonic nervous system does not differentiate into more vesicles at the secondary stage?

A. prosencephalon

B. mesencephalon

C. diencephalon

D. rhombencephalon

Answer

Answer: B

Q. Which adult structure(s) arises from the diencephalon?

A. thalamus, hypothalamus, retina

B. midbrain, pons, medulla

C. pons and cerebellum

D. cerebrum

Answer

Answer: A

Q. Which structure is associated with the embryologic development of the peripheral nervous system?

A. neural crest

B. neuraxis

C. rhombencephalon

D. neural tube

Answer

Answer: A

Critical Thinking Questions

Q. Studying the embryonic development of the nervous system makes it easier to understand the complexity of the adult nervous system. Give one example of how development in the embryonic nervous system explains a more complex structure in the adult nervous system.

Answer

A. The retina, a PNS structure in the adult, grows from the diencephalon in the embryonic nervous system. The mature connections from the retina through the optic nerve/tract are to the hypothalamus and thalamus of the diencephalon, and to the midbrain, which developed directly adjacent to the diencephalon as the mesencephalon in the embryo.

Glossary

brainstem
region of the adult brain that includes the midbrain, pons, and medulla oblongata and develops from the mesencephalon, metencephalon, and myelencephalon of the embryonic brain

cephalic flexure
curve in midbrain of the embryo that positions the forebrain ventrally

diencephalon
region of the adult brain that retains its name from embryonic development and includes the thalamus and hypothalamus

forebrain
anterior region of the adult brain that develops from the prosencephalon and includes the cerebrum and diencephalon

hindbrain
posterior region of the adult brain that develops from the rhombencephalon and includes the pons, medulla oblongata, and cerebellum

mesencephalon
primary vesicle of the embryonic brain that does not significantly change through the rest of embryonic development and becomes the midbrain

metencephalon
secondary vesicle of the embryonic brain that develops into the pons and the cerebellum

midbrain
middle region of the adult brain that develops from the mesencephalon

myelencephalon
secondary vesicle of the embryonic brain that develops into the medulla

neural crest
tissue that detaches from the edges of the neural groove and migrates through the embryo to develop into peripheral structures of both nervous and non-nervous tissues

neural fold
elevated edge of the neural groove

neural groove
region of the neural plate that folds into the dorsal surface of the embryo and closes off to become the neural tube

neural plate
thickened layer of neuroepithelium that runs longitudinally along the dorsal surface of an embryo and gives rise to nervous system tissue

neural tube
precursor to structures of the central nervous system, formed by the invagination and separation of neuroepithelium

neuraxis
central axis to the nervous system, from the posterior to anterior ends of the neural tube; the inferior tip of the spinal cord to the anterior surface of the cerebrum

primary vesicle
initial enlargements of the anterior neural tube during embryonic development that develop into the forebrain, midbrain, and hindbrain

prosencephalon
primary vesicle of the embryonic brain that develops into the forebrain, which includes the cerebrum and diencephalon

rhombencephalon
primary vesicle of the embryonic brain that develops into the hindbrain, which includes the pons, cerebellum, and medulla

secondary vesicle
five vesicles that develop from primary vesicles, continuing the process of differentiation of the embryonic brain

telencephalon
secondary vesicle of the embryonic brain that develops into the cerebrum

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12: CENTRAL AND PERIPHERAL NERVOUS SYSTEM

The central nervous system (CNS) comprehends the brain and spinal cord, while the peripheral nervous system (PNS) comprises ganglia, cranial and spinal nerves. The focus of this chapter is on these organs. First you will learn the structures that support and protect the nervous system. Then you will focus on the various regions of the brain and spinal cord. At the end you will look at cranial and spinal nerves.

12.1: Introduction to the Central and Peripheral Nervous System

12.2: Support and Protection of the Brain

12.3: Brain- Cerebrum

12.4: Brain- Diencephalon, Brainstem, Cerebellum and Limbic System

12.5: Cranial Nerves

12.6: Spinal Cord and Spinal Nerves

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12.1: Introduction to the Central and Peripheral Nervous System

Chapter Learning Objectives

After studying this chapter, you will be able to:

- Describe the structures that support and protect the brain and spinal cord
- Identify the regions and anatomical landmarks of the brain and spinal cord
- Describe the functions of the regions of the cerebrum, diencephalon, brainstem, cerebellum and limbic system
- List the cranial nerves in order of anatomical location and provide the central and peripheral connections
- List the spinal nerves by vertebral region and by which nerve plexus each supplies

Fresh, unstained nervous tissue can be described as gray or white matter, and within those two types of tissue it can be very hard to see any detail. However, as specific regions and structures have been discovered, they were related to specific functions. Understanding these structures and the functions they perform requires a detailed description of the anatomy of the nervous system, delving deep into what the central and peripheral structures are. While the structures are discovered thanks to dissections of cadavers, the functions of the individual part of our nervous system are gathered by lesion case studies which are part of cognitive neuroscience. In these studies, injuries or illnesses of the nervous system are studied to understand the relationship between the injured area and the function of it. The first, and most known, lesion case is the one of Phineas Gage (Figure 12.1.1), an American railroad worker. Phineas Gage was working on a railroad when an iron rod he was using exploded and went through his head, damaging the left prefrontal cortex. He survived the accident, but according to second-hand accounts, some aspects of his personality changed, suggesting that the prefrontal cortex is an area of the brain responsible for personality.

In this chapter, you will look at the structures that make the central and peripheral nervous system and correlate them with their functions. The central nervous system includes the brain and spinal cord, while the peripheral nervous system includes the cranial and spinal nerves, as well as the ganglia. First, you will take a look at how these structures are protected and supported.

Figure 12.1.1: Phineas Gage. Phineas Gage was a railroad constructor of the 19th century who lost part of his left frontal lobe to an explosion where an iron rod went through his brain. (Image credit: "Phineas Gage Cased Daguerreotype WilgusPhoto2008-12-19 EnhancedRetouched Color" by Jack and Beverly Wilgus, Warren Anatomical Museum is licensed under CC BY-SA 3.0)

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12.2: Support and Protection of the Brain

By the end of this section, you will be able to:

- Describe the meninges that protect the brain
- Describe the blood vessels that supply the brain
- Name the components of the ventricular system and the regions of the brain in which each is located
- Explain the production of cerebrospinal fluid and its flow through the ventricles

Protective Coverings of the Brain

The central nervous system (CNS) is crucial to the operation of the body and any compromise of function in the brain and spinal cord can lead to severe difficulties. The brain is protected by multiple structures. First, the bones of the skull enclose and house the brain. Underneath the skeletal structures, the brain is protected by membranes made by connective tissue, called **meninges**, that surround, support, stabilize and partition the nervous tissue (Figure 12.2.1). In addition, the brain has a privileged blood supply, as suggested by the blood-brain barrier. The function of the tissue is crucial to the survival of the organism, so the contents of the blood cannot simply pass into the central nervous tissue. To protect this region from the toxins and pathogens that may be traveling through the blood stream, there is strict control over what can move out of the general systems and into the brain. Because of this privilege, the brain needs specialized structures for the maintenance of circulation. This begins with a unique arrangement of blood vessels carrying fresh blood into the brain and venous sinuses carrying deoxygenated blood out of the brain. Beyond the supply of blood, the brain filters the blood into cerebrospinal fluid (CSF), which is then circulated through the cavities of the brain, such as the subarachnoid space and the ventricles.

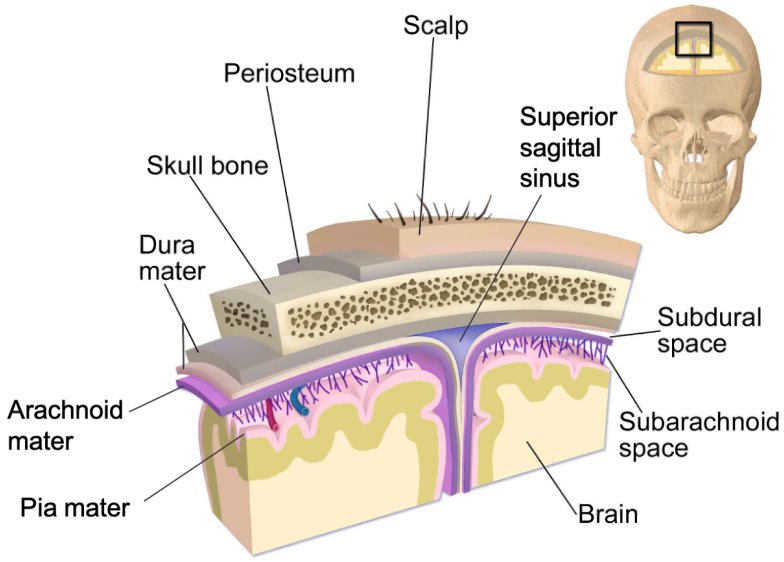

Figure 12.2.1: Protective structures of the brain. Superficially, the skin of the scalp and bones of the skull create the first layer of protection. Deep to these layers, the meninges (represented by the dura mater, arachnoid mater and pia mater) cover and partition the brain. Within the meninges, blood inside blood vessels and sinuses, and cerebrospinal fluid within the subarachnoid space and ventricles circulate to support the brain's function. (Image credit: "Cranial meninges" by Chiara Mazzasette is licensed under CC BY 4.0 / A derivative from the original work)

Cranial Meninges

The outer surface of the CNS is covered by a series of membranes composed of connective tissue called the meninges, which protect, stabilize and partition the brain. From superficial to deep, the meningeal layers are the dura mater, arachnoid mater and pia mater. The **dura mater** is a thick fibrous layer and a strong protective sheath over the entire brain. It is anchored to the inner surface of the cranium and vertebral cavity. The **arachnoid mater** is a membrane of thin fibrous tissue that forms a loose sac

around the brain. Beneath the arachnoid mater, there is a space called the **subarachnoid space** where a thin, filamentous mesh form the **arachnoid trabeculae**, that looking like a spider web give this layer its name. Directly adjacent to the surface of the brain is the **pia mater**, a thin fibrous membrane that follows the superficial convolutions of the brain and fits into other grooves and indentations (Figure 12.2.2).

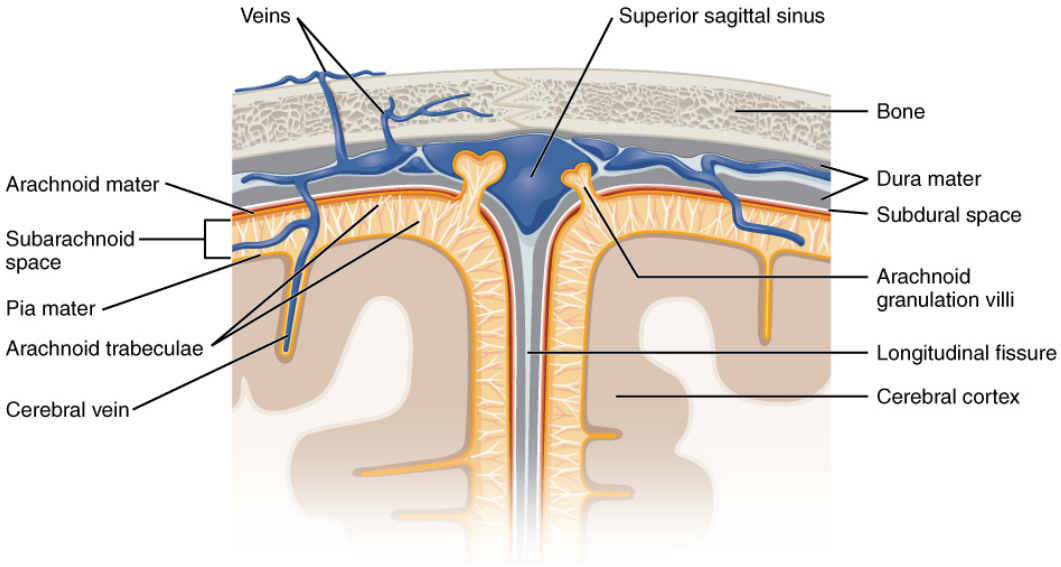

Figure 12.2.2: Meningeal Layers of the Brain. The layers of the meninges are shown under neath the bones of the skull. The dura mater is adjacent to the inner surface of the cranium. Within it, veins and the superior sagittal sinus lie. The pia mater is adjacent to the surface of the brain. The arachnoid and subarachnoid space are in-between. An arachnoid villus is shown emerging into the dural sinus to allow CSF to filter back into the blood for drainage. (Image credit: "Meningeal Layers" by OpenStax is licensed under CC BY 4.0)

Dura Mater

Like a thick cap covering the brain, the dura mater is a tough outer covering. The name comes from the Latin for “tough mother” to represent its physically protective role. It encloses the entire CNS and the major blood vessels that enter the cranium and vertebral cavity. It is directly attached to the inner surface of the bones of the cranium and to the very end of the vertebral cavity. The dura mater of the brain is made by two layers, the **periosteal layer** which is more superficial and attached to the skull, and the **meningeal layer**, which lies deep to the first layer. These two layers are usually fused together. However, in some regions of the brain they separate to form large space filled with venous blood called **dural sinuses**. The dura mater of the spinal cord is composed of only one layer. The region between the bones and the dura mater is called **epidural space**. In the cranium, the epidural space contains arteries and veins that supply and drain blood from the brain. In normal conditions, the cranial epidural space is a potential space and not a real space. However, trauma can cause the leakage of fluid (hematomas) which accumulates in the epidural space enlarging it and transforming it into a real space. In the vertebral column, the epidural space is a real space that contains areolar and adipose connective tissue for an extra layer of protection, as well as blood vessels. The spinal epidural space at the lumbar level is where epidural injections are administered. Deep to the dura mater, there is another potential space called the **subdural space**. As the epidural space, this space can be filled with fluid causing a subdural hematoma.

The meningeal layer of the dura mater extends into the cranial cavity at four locations. These flat partitions are called **cranial dural septa** and separate specific parts of the brain (Figure 12.2.3). The **falx cerebri** goes through the midline separation of the brain while the **falx cerebelli** separates the two cerebellar hemispheres. The **tentorium cerebelli** separates the cerebellum from the superior part of the brain (cerebrum), forming a shelf-like tent. Another partition called **diaphragma sellae** surrounds the pituitary gland.

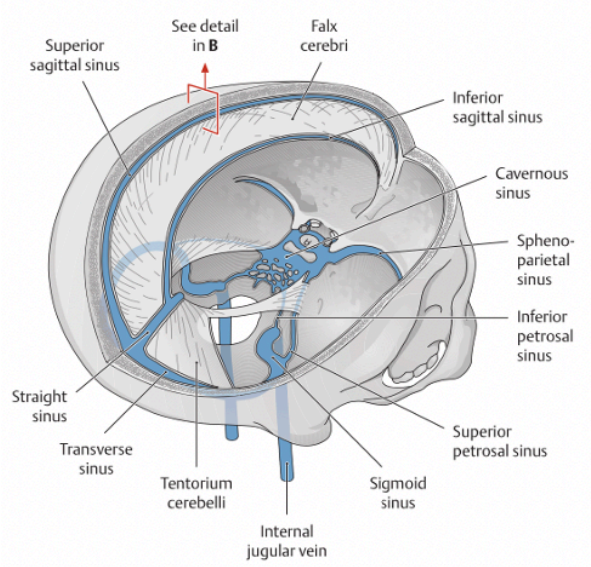

Figure 12.2.3: Cranial Dural Septa and Sinuses. The dura mater creates fours partitions called cranial dural septa: the falx cerebri, the falx cerebelli, the tentorium cerebelli and the diaphragma sellae (not shown in the figure). The two layers of tissue of the dura mater separate in various regions to create dural sinuses which are filled with venous blood. The main dural sinuses are: the superior sagittal sinus, inferior sagittal sinus, straight sinus, transverse sinus and sigmoid sinus. (Image credit: "Falx Cerebri and Tentorum Cerebelli" by Powellle is licensed under CC BY-SA 4.0)

Arachnoid Mater

Deep to the subdural space lies the middle layer of the meninges called the arachnoid mater. This layer is named for the spider-web–like projections called **arachnoid trabeculae** between this layer and the pia mater. The arachnoid defines a sac-like enclosure around the CNS. The trabeculae are found in the **subarachnoid space**, which is filled with circulating CSF, making it a real space. The arachnoid emerges into the dural sinuses as the **arachnoid granulations**, where the CSF is filtered back into the blood for drainage from the nervous system.

Pia Mater

The outer surface of the CNS is covered in the thin fibrous membrane of the pia mater. It is thought to have a continuous layer of cells providing a fluid-impermeable membrane. The name pia mater comes from the Latin for “tender mother,” suggesting the thin membrane is a gentle covering for the brain. The pia extends into every convolution of the CNS. Blood vessels that are nourishing the central nervous tissue are between the pia mater and the nervous tissue.

DISORDERS OF THE...

Meninges: Meningitis

Meningitis is an inflammation of the meninges, the three layers of fibrous membrane that surround the CNS. Meningitis can be caused by infection by bacteria or viruses. The particular pathogens are not special to meningitis; it is just an inflammation of that specific set of tissues from what might be a broader infection. Bacterial meningitis can be caused by Streptococcus, Staphylococcus, or the tuberculosis pathogen, among many others. Viral meningitis is usually the result of common enteroviruses (such as those that cause intestinal disorders), but may be the result of the herpes virus or West Nile virus. Bacterial meningitis tends to be more severe.

The symptoms associated with meningitis can be fever, chills, nausea, vomiting, light sensitivity, soreness of the neck, or severe headache. More important are the neurological symptoms, such as changes in mental state (confusion, memory deficits, and other dementia-type symptoms). A serious risk of meningitis can be damage to peripheral structures because of the nerves that pass through the meninges. Hearing loss is a common result of meningitis.

The primary test for meningitis is a lumbar puncture. A needle inserted into the lumbar region of the spinal column through the dura mater and arachnoid membrane into the subarachnoid space can be used to withdraw the fluid for chemical testing. Fatality occurs in 5 to 40 percent of children and 20 to 50 percent of adults with bacterial meningitis. Treatment of bacterial meningitis is through antibiotics, but viral meningitis cannot be treated with antibiotics because viruses do not respond to that type of drug. Fortunately, the viral forms are milder.

Blood Supply to the Brain

A lack of oxygen to the CNS can be devastating, and the cardiovascular system has specific regulatory reflexes to ensure that the blood supply is not interrupted. There are multiple routes for blood to get into the CNS, with specializations to protect that blood supply and to maximize the ability of the nervous tissue to get an uninterrupted perfusion.

Arterial Supply to the Brain

The major artery carrying recently oxygenated blood away from the heart is the aorta. The very first branches off the aorta supply the heart with nutrients and oxygen. The next branches give rise to the **common carotid arteries**, which further branch into the **internal carotid arteries**. The external carotid arteries supply blood to the tissues on the surface of the cranium. The internal carotid artery enters the cranium through the carotid canal in the temporal bone.

A second set of vessels that supply the CNS are the **vertebral arteries**, which are protected as they pass through the neck region by the transverse foramina of the cervical vertebrae. The vertebral arteries enter the cranium through the foramen magnum of the occipital bone. The two vertebral arteries then merge into the **basilar artery**, which gives rise to branches to the brainstem and cerebellum. The left and right internal carotid arteries and branches of the basilar artery all become the **circle of Willis**, a confluence of arteries that can maintain perfusion of the brain even if narrowing or a blockage limits flow through one part (Figure 12.2.4).

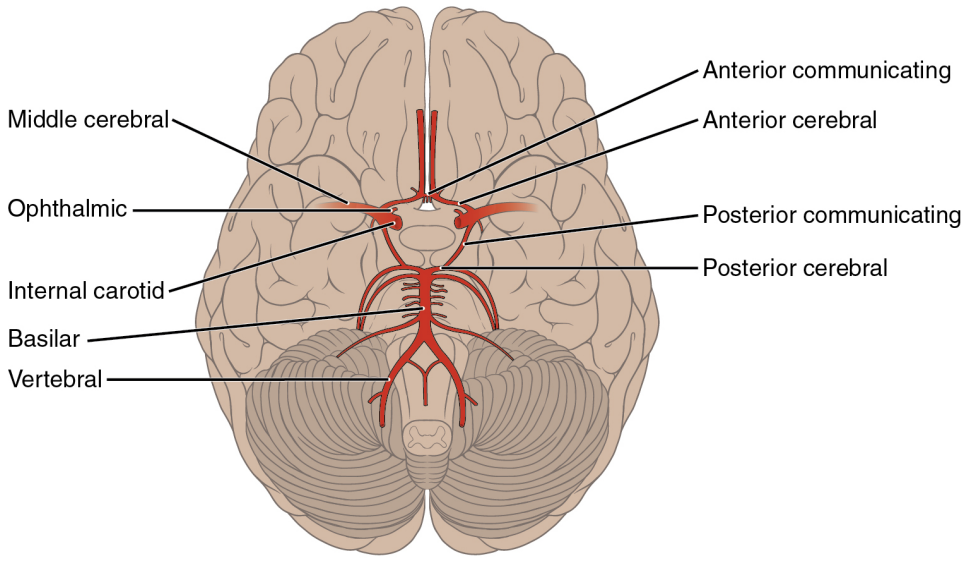

Figure 12.2.4: Circle of Willis. This inferior view shows the network of arteries serving the brain. The structure is referred to as the circle of Willis and is formed by branches of the internal carotid artery, vertebral artery and basilar artery. (Image credit: "Arteries of the Brain" by OpenStax is licensed under CC BY 3.0)

Interactive Link

Circle of Willis

Watch this animation of the Circle of Willis to see how blood flows to the brain and passes through it before being distributed through the tissues. The circle of Willis is a specialized arrangement of arteries that ensure constant perfusion of the brain even in the event of a blockage of one of the arteries in the circle. The animation shows the normal direction of flow through the circle of Willis to the middle cerebral artery. Where would the blood come from if there were a blockage just posterior to the middle cerebral artery on the left?

Answer available at the end of this section.

Venous Return from the Brain

After passing through the CNS, blood returns to the circulation through a series of **dural sinuses** and **cerebral veins** (Figure 12.2.5). The dural sinuses are housed within the two layers of the dura mater. The **superior sagittal sinus** runs in the medial groove of the brain, where it absorbs CSF from the meninges. The superior sagittal sinus drains to the **confluence of sinuses**, along with the **occipital sinuses** and **straight sinus**, to then drain into the **transverse sinuses**. The transverse sinuses connect to the **sigmoid sinuses**, which then connect to the **jugular veins**. From there, the blood continues toward the heart to be pumped to the lungs for reoxygenation.

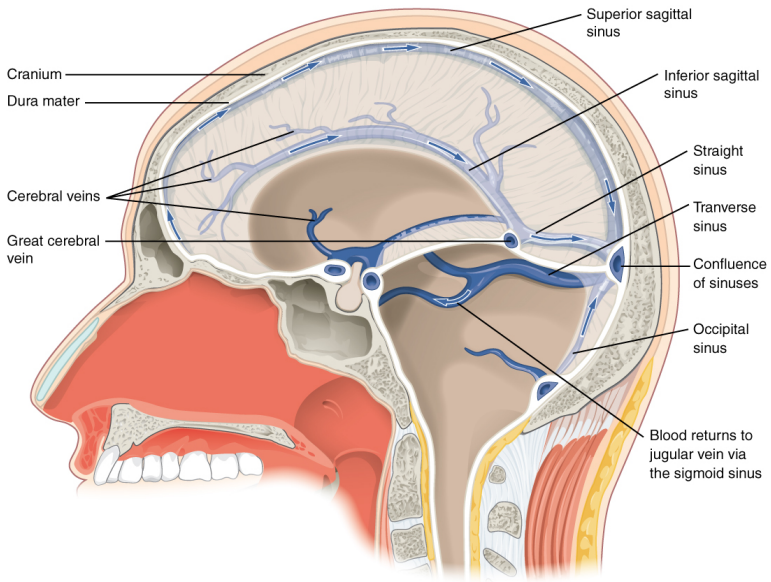

Figure 12.2.5: Dural Sinuses and Cerebral Veins. Blood drains from the brain through a series of sinuses and veins that connect to the jugular veins. (Image credit: "Brain Sinuses" by OpenStax is licensed under CC BY 4.0)

Ventricular System

Cerebrospinal fluid (CSF) is produced by a type of specialized membrane made of ependymal cells called a **choroid plexus**. Ependymal cells (one of the types of glial cells described in the introduction to the nervous system) surround blood capillaries

and filter the blood to make CSF. The fluid is a clear solution with a limited amount of the constituents of blood. It is essentially water, small molecules, and electrolytes and is continuous with the interstitial fluid. Oxygen and carbon dioxide are dissolved into the CSF, as they are in blood, and can diffuse between the fluid and the nervous tissue. CSF circulates through the nervous tissue to remove metabolic wastes from the interstitial fluids of nervous tissues and return them to the blood stream. The choroid plexus lines open spaces within the brain called **ventricles**. The CSF circulates through all of the ventricles to eventually emerge into the subarachnoid space where it will be reabsorbed into the blood.

Ventricles

There are four ventricles within the brain, all of which developed from the original hollow space within the neural tube, the **central canal**. The first two are named the **lateral ventricles** and are deep within the brain (Figure 12.2.6). The two lateral ventricles are shaped as a C and are located in the left and right hemispheres, and were at one time referred to as the first and second ventricles. These ventricles are connected to the **third ventricle** by two openings called the **interventricular foramina**. The third ventricle opens into a canal called the **cerebral aqueduct** that passes through the midbrain and connects the third ventricle to the **fourth ventricle**. The fourth ventricle is the space between the cerebellum and the pons and upper medulla. The ventricular system opens up to the subarachnoid space from the fourth ventricle. The single **median aperture** and the pair of **lateral apertures** connect to the subarachnoid space so that CSF can flow through the ventricles and around the outside of the CNS (Figure 12.2.7). From the fourth ventricle, CSF can continue down the central canal of the spinal cord.

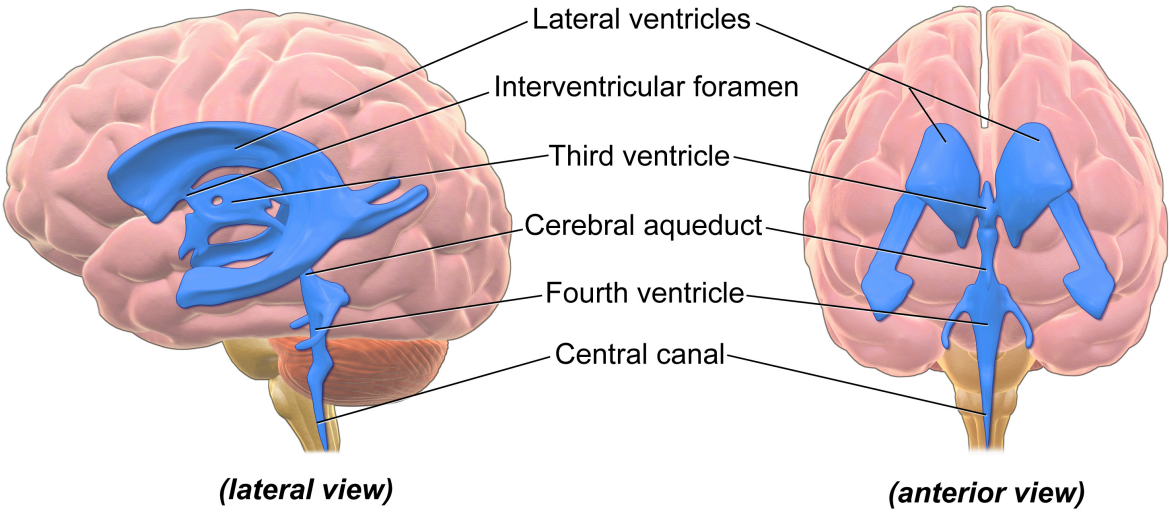

Figure 12.2.6: Ventricles. Within the brain, open spaces called ventricles are lined with ependymal cells that produce cerebrospinal fluid (CSF). Deep within the brain are the lateral ventricles, which are connected to the third ventricle by two openings called interventricular foramina. The third ventricle opens into a canal called the cerebral aqueduct which connects to the fourth ventricle. The fourth ventricle is connected to the central canal of the spinal cord. (Image credit: "Blausen 0896 Ventricles Brain" by BruceBlaus is in the Public Domain, CC0)

Cerebrospinal Fluid Circulation

The choroid plexuses are found in all four ventricles. Observed in dissection, they appear as soft, fuzzy structures that may still be pink, depending on how well the circulatory system is cleared in preparation of the tissue. The CSF is produced from components extracted from the blood, so its flow out of the ventricles is tied to the pulse of cardiovascular circulation.

From the lateral ventricles, the CSF flows into the third ventricle, where more CSF is produced, and then through the cerebral aqueduct into the fourth ventricle where even more CSF is produced (Figure 12.2.7). A very small amount of CSF is filtered at any one of the plexuses, for a total of about 500 milliliters daily, but it is continuously made and pulses through the ventricular system, keeping the fluid moving. From the fourth ventricle, CSF can continue down the central canal of the spinal cord, but this is essentially a cul-de-sac, so more of the fluid leaves the ventricular system and moves into the subarachnoid space through the median and lateral apertures.

Within the subarachnoid space, the CSF flows around all of the CNS, providing two important functions. As with elsewhere in its circulation, the CSF picks up metabolic wastes from the nervous tissue and moves it out of the CNS. It also acts as a liquid

cushion for the brain and spinal cord. By surrounding the entire system in the subarachnoid space, it provides a thin buffer around the organs within the strong, protective dura mater. The arachnoid granulations are outpocketings of the arachnoid membrane into the dural sinuses so that CSF can be reabsorbed into the blood, along with the metabolic wastes. From the dural sinuses, blood drains out of the head and neck through the jugular veins, along with the rest of the circulation for blood, to be reoxygenated by the lungs and wastes to be filtered out by the kidneys.

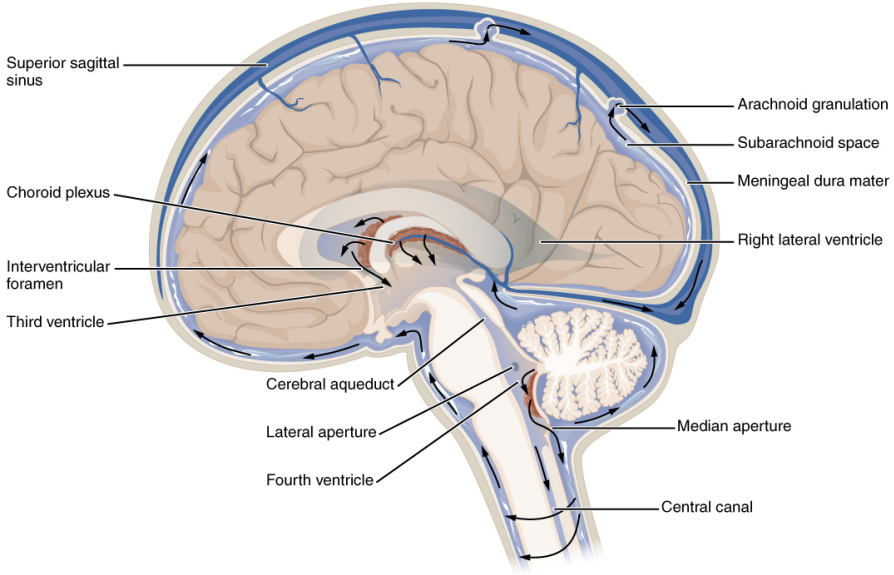

Figure 12.2.7: Cerebrospinal Fluid Circulation. The choroid plexus in all the ventricles produce CSF, which is circulated through the ventricular system and then enters the subarachnoid space through the median and lateral apertures. The CSF is then reabsorbed into the blood at the arachnoid granulations, where the arachnoid membrane emerges into the dural sinuses. (Image credit: "CSF Circulation" by OpenStax is licensed under CC BY 4.0)

DISORDERS OF THE...

Central Nervous System: Strokes

The supply of blood to the brain is crucial to its ability to perform many functions. Without a steady supply of oxygen, and to a lesser extent glucose, the nervous tissue in the brain cannot keep up its extensive electrical activity. These nutrients get into the brain through the blood, and if blood flow is interrupted, neurological function is compromised.

The common name for a disruption of blood supply to the brain is a stroke. It is caused by a blockage to an artery in the brain or by blood leaking out of blood vessels (hemorrhagic stroke), although less common. The blockage is caused by some type of embolus: a blood clot, a fat embolus, or an air bubble. When the blood cannot travel through the artery, the surrounding tissue that is deprived starves and dies. Strokes will often result in the loss of very specific functions. A stroke in the lateral medulla, for example, can cause a loss in the ability to swallow. Sometimes, seemingly unrelated functions will be lost because they are dependent on structures in the same region. Along with the swallowing in the previous example, a stroke in that region could affect sensory functions from the face or extremities because important white matter pathways also pass through the lateral medulla. Loss of blood flow to specific regions of the brain can lead to the loss of specific higher functions, from the ability to recognize faces to the ability to move a particular region of the body. Severe or limited memory loss can be the result of a temporal lobe stroke.

Related to strokes are transient ischemic attacks (TIAs), which can also be called “mini-strokes.” These are events in which a physical blockage may be temporary, cutting off the blood supply and oxygen to a region, but not to the extent that it causes cell death in that region. While the neurons in that area are recovering from the event, neurological function may be lost. TIAs usually resolve spontaneously by the body, that is why it is called "transient".

Recovery from a stroke (or TIA) is strongly dependent on the speed of treatment. Often, the person who is present and notices something is wrong must then make a decision. The mnemonic FAST helps people remember what to look for when someone is dealing with sudden losses of neurological function. If someone complains of feeling “funny,” check these things quickly: Look at the person’s face. Does he or she have problems moving Face muscles and making regular

facial expressions? Ask the person to raise his or her Arms above the head. Can the person lift one arm but not the other? Has the person's Speech changed? Is he or she slurring words or having trouble saying things? If any of these things have happened, then it is Time to call for help.

Sometimes, treatment with blood-thinning drugs can alleviate the problem, and recovery is possible. If the tissue is damaged, the amazing thing about the nervous system is that it is adaptable. With physical, occupational, and speech therapy, victims of strokes can recover, or more accurately relearn, functions.

Concept Review

The CNS has a privileged blood supply established by the blood-brain barrier. Establishing this barrier are anatomical structures that help to protect and isolate the CNS. The skull and vertebral column are the first mean of protection of the brain and spinal cord, respectively. Layers of connective tissue called meninges support and stabilize the brain and spinal cord, as well as partition the brain into specific regions. The outer layer is the dura mater, the middle layer is the arachnoid mater and the inner layer is the pia mater.

The arterial blood to the brain comes from the internal carotid and vertebral arteries, which both contribute to the unique circle of Willis that provides constant perfusion of the brain even if one of the blood vessels is blocked or narrowed. That blood is eventually filtered to make a separate medium, the CSF, that circulates within the spaces of the brain and then into the surrounding space defined by the meninges, the protective covering of the brain and spinal cord.

The blood that nourishes the brain and spinal cord is behind the glial-cell–enforced blood-brain barrier, which limits the exchange of material from blood vessels with the interstitial fluid of the nervous tissue. Thus, metabolic wastes are collected in cerebrospinal fluid that circulates through the CNS. This fluid is produced by filtering blood at the choroid plexuses in the four ventricles of the brain. It then circulates through the ventricles and into the subarachnoid space, between the pia mater and the arachnoid mater. From the arachnoid granulations, CSF is reabsorbed into the blood, removing the waste from the privileged central nervous tissue.

The blood, now with the reabsorbed CSF, drains out of the cranium through the dural sinuses. The dura mater is the tough outer covering of the CNS, which is anchored to the inner surface of the cranial and vertebral cavities. It surrounds the venous space known as the dural sinuses, which connect to the jugular veins, where blood drains from the head and neck.

Review Questions

Q. What blood vessel enters the cranium to supply the brain with fresh, oxygenated blood?

A. common carotid artery

B. jugular vein

C. internal carotid artery

D. aorta

Answer

C

Q. Which layer of the meninges surrounds and supports the sinuses that form the route through which blood drains from the CNS?

A. dura mater

B. arachnoid mater

C. subarachnoid

D. pia mater

Answer

A

Q. What type of glial cell is responsible for filtering blood to produce CSF at the choroid plexus?

A. ependymal cell

B. astrocyte

C. oligodendrocyte

D. Schwann cell

Answer

A

Critical Thinking Questions

Q. Why can the circle of Willis maintain perfusion of the brain even if there is a blockage in one part of the structure?

> A. The structure is a circular connection of blood vessels, so that blood coming up from one of the arteries can flow in either direction around the circle and avoid any blockage or narrowing of the blood vessels.

Q. Meningitis is an inflammation of the meninges that can have severe effects on neurological function. Why is infection of this structure potentially so dangerous?

> A. The nerves that connect the periphery to the CNS pass through these layers of tissue and can be damaged by that inflammation, causing a loss of important neurological functions.

Glossary

arachnoid granulation
: outpocket of the arachnoid membrane into the dural sinuses that allows for reabsorption of CSF into the blood

arachnoid mater
: middle layer of the meninges named for the spider-web–like trabeculae that extend between it and the pia mater

arachnoid trabeculae
: filaments between the arachnoid and pia mater within the subarachnoid space

basilar artery
: blood vessel from the merged vertebral arteries that runs along the dorsal surface of the brainstem

central canal
: hollow space within the spinal cord that is the remnant of the center of the neural tube

cerebral aqueduct
: connection of the ventricular system between the third and fourth ventricles located in the midbrain

choroid plexus
: specialized structures containing ependymal cells lining blood capillaries that filter blood to produce CSF in the four ventricles of the brain

circle of Willis
: unique anatomical arrangement of blood vessels around the base of the brain that maintains perfusion of blood into the brain even if one component of the structure is blocked or narrowed

common carotid artery
: blood vessel that branches off the aorta (or the brachiocephalic artery on the right) and supplies blood to the head and neck

confluence of sinuses
: connecting point of the superior sagittal sinus, straight sinus, and occipital sinus

cranial dura septa
: extensions of meningeal dura mater into the cranial cavity

diaphragma sellae
: extension of the dura that separates the pituitary from the neural structures located superiorly including the optic chiasm

dura mater
: tough, fibrous, outer layer of the meninges that is attached to the inner surface of the cranium and vertebral column and surrounds the entire CNS

dural sinus
: any of the venous structures surrounding the brain, enclosed within the dura mater, which drain blood from the CNS to the common venous return of the jugular veins

epidural space
: area between the dura mater and the above structures

falx cerebelli
: extension of dura mater, projecting to the cerebellum

falx cerebri
: extension of dura mater that lies between the cerebral hemispheres, in the longitudinal fissure

fourth ventricle
: the portion of the ventricular system that is in the region of the brainstem and opens into the subarachnoid space through the median and lateral apertures

internal carotid artery
: branch from the common carotid artery that enters the cranium and supplies blood to the brain

interventricular foramina
: openings between the lateral ventricles and third ventricle allowing for the passage of CSF

jugular veins
: blood vessels that return “used” blood from the head and neck

lateral apertures
: pair of openings from the fourth ventricle to the subarachnoid space on either side and between the medulla and cerebellum

lateral ventricles
: portions of the ventricular system that are deep within the brain

median aperture
: singular opening from the fourth ventricle into the subarachnoid space at the midline between the medulla and cerebellum

meningeal layer
: one of the two layers of the cranial dura mater

meninges
: protective outer coverings of the CNS composed of connective tissue

occipital sinuses
dural sinuses along the edge of the most posterior region of the brain

periosteal layer
one of the two layers of the cranial dura mater

pia mater
thin, innermost membrane of the meninges that directly covers the surface of the CNS

sigmoid sinuses
dural sinuses that drain directly into the jugular veins

straight sinus
dural sinus that drains blood from the deep center of the brain to collect with the other sinuses

subarachnoid space
space between the arachnoid mater and pia mater that contains CSF and the fibrous connections of the arachnoid trabeculae

subdural space
space between the dura mater and arachnoid mater

superior sagittal sinus
dural sinus that runs along the top of the longitudinal fissure and drains blood from the majority of the outer brain

tentorium cerebelli
extension of dura mater that covers the upper surface of the cerebellum

third ventricle
portion of the ventricular system that is in the region of the diencephalon

transverse sinuses
dural sinuses that drain along either side of the occipital–cerebellar space

ventricles
remnants of the hollow center of the neural tube that are spaces for cerebrospinal fluid to circulate through the brain

vertebral arteries
arteries that ascend along either side of the vertebral column through the transverse foramina of the cervical vertebrae and enter the cranium through the foramen magnum

Contributors and Attributions

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Answers

Interactive Link

If blood could not get to the middle cerebral artery through the posterior circulation, the blood would flow around the circle of Willis to reach that artery from an anterior vessel. Blood flow would just reverse within the circle.

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12.3: Brain- Cerebrum

By the end of this section, you will be able to:

- Name the major regions of the adult brain
- Identify the anatomical structures of the cerebrum
- Identify the tracts associated with the white matter of the cerebrum and describe their functions
- Describe the components of the cerebral nuclei
- Describe the functional areas of the cerebral cortex and their locations

The organs of the central nervous system are the brain and spinal cord. The brain is described in terms of four major regions: the cerebrum, the diencephalon, the brainstem, and the cerebellum (Figure 12.3.1). The iconic gray mantle of the human brain, which appears to make up most of the mass of the brain, is the **cerebrum**. Many of the higher neurological functions, such as memory, emotion, and consciousness, are the result of cerebral function. The cerebrum is divided into different regions called lobes. Overall, the functions of the cerebrum are initiation and coordination of movement, processing of general and special senses, and high level functions such as judgment, reasoning, problem solving, and learning.

Cerebrum

The cerebrum is covered by a continuous layer of gray matter that wraps around either side of the forebrain—the cerebral cortex. This thin, extensive region of wrinkled gray matter is responsible for the higher functions of the nervous system. A **gyrus** (plural = gyri) is the ridge of one of those wrinkles, and a **sulcus** (plural = sulci) is the groove between two gyri (Figure 12.3.1). The pattern of these folds of tissue indicates specific regions of the cerebral cortex. The brain must fit inside the cranial cavity of the skull. Extensive folding in the cerebral cortex enables more gray matter to fit into this limited space. If the gray matter of the cortex were peeled off of the cerebrum and laid out flat, its surface area would be roughly equal to one square meter. The folding of the cortex maximizes the amount of gray matter in the cranial cavity. During embryonic development, as the telencephalon expands within the skull, the brain goes through a regular course of growth that results in everyone's brain having a similar pattern of folds.

The surface of the brain can be mapped on the basis of the locations of large gyri and sulci. Three deep sulci are visible: the **central sulcus**, the **lateral sulcus** and the **parieto-occipital sulcus**. Anterior to the central sulcus is the **precentral gyrus**, while posterior to the central sulcus is the **postcentral gyrus** (Figure 12.3.1). There is a large separation between the two sides of the cerebrum called the **longitudinal fissure** (Figure 12.3.2). It separates the cerebrum into two distinct halves, a right and left **cerebral hemisphere**.

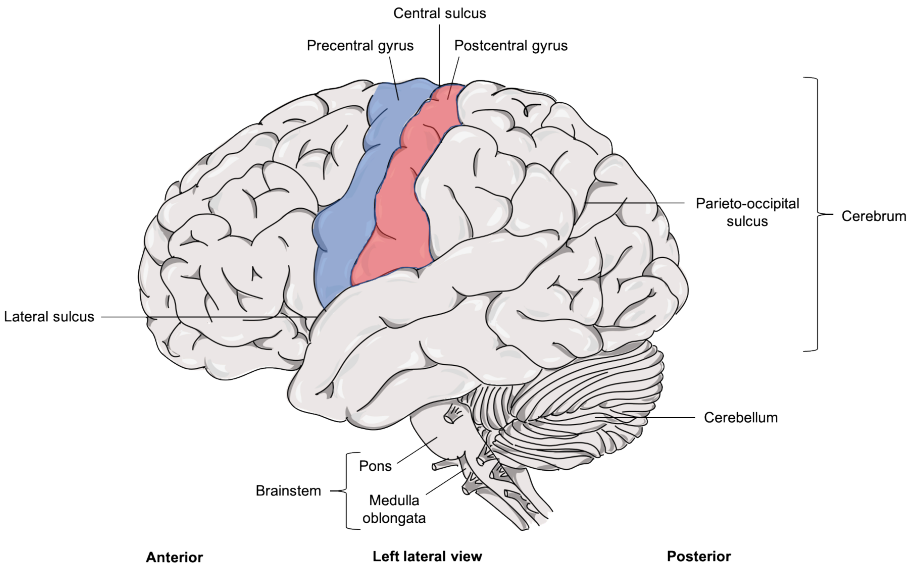

Figure 12.3.1: Lateral View of the Brain. The regions of the brain visible from a lateral view are the cerebrum, brainstem and cerebellum. The cerebrum presents ridges called gyri and grooves called sulci. The main sulci are the central sulcus, lateral sulcus and parieto-occipital sulcus. The gyrus anterior to the central sulcus is called precentral gyrus (in blue), while the posterior one is the postcentral gyrus (in red). (Image credit: "Brain Lateral View" by Chiara Mazzasette is a derivative from the original work of Daniel Donnelly and is licensed by CC BY 4.0)

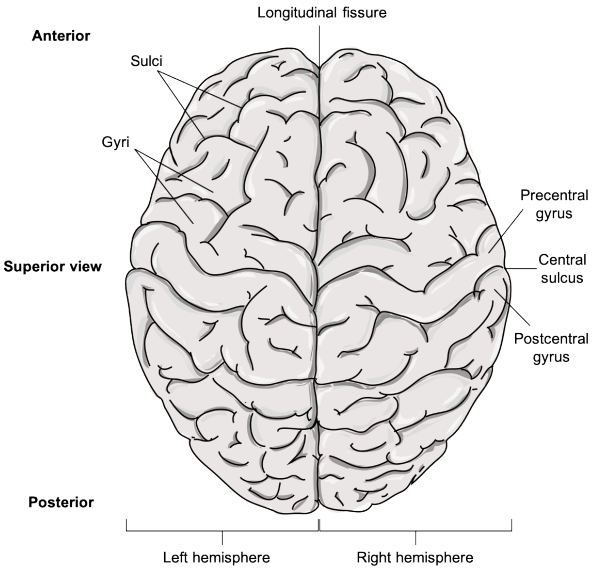

Figure 12.3.2: Superior View of the Brain. The cerebrum is medially divided by the longitudinal fissure into left and right hemispheres. The central sulcus is visible cutting the cerebrum in a coronal section. The gyrus anterior to the central sulcus is called precentral gyrus, while the posterior one is the postcentral gyrus. (Image credit: "Brain Superior View" by Chiara Mazzasette is a derivative from the original work of Daniel Donnelly and is licensed by CC BY 4.0)

The cerebrum comprises the outer wrinkled gray matter that is the **cerebral cortex** (from the Latin word meaning “bark of a tree”), the inner white matter that forms **tracts**, and several deep (subcortical) nuclei called **basal nuclei** (Figure 12.3.3). Deep within the cerebrum, the white matter of the **corpus callosum** provides the major pathway for communication between the two hemispheres of the cerebral cortex.

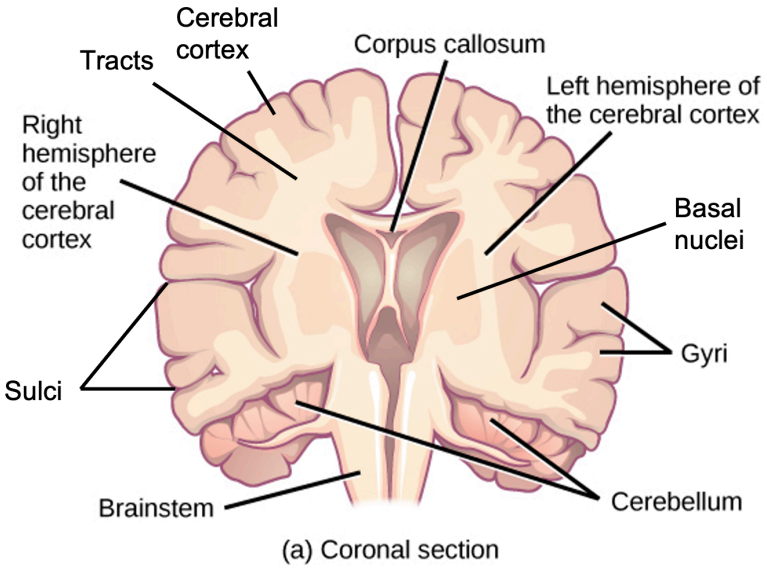

Figure 12.3.3: Coronal Section of the Brain. The coronal section shows the layers of the cerebrum. The superficial gray matter is called cerebral cortex, while the deep gray matter is organized in basal nuclei. The superficial and deep regions are connected by myelinated axons (white matter) called tracts. The corpus callosum is one of these tracts and connect the left and right hemispheres. (Image credit: "Brain Coronal Section" by Chiara Mazzasette is licensed under CC BY 4.0 / A derivative from the original work)

Cerebral Cortex

The cortex can be separated into major regions called lobes (Figure 12.3.4). The lateral sulcus separates the **temporal lobe** from the other regions. Deep to the lateral sulcus is another lobe called **insula** (shown in Figure 12.3.5). Superior to the lateral sulcus are the **parietal lobe** and **frontal lobe**, which are separated from each other by the central sulcus. The posterior region of the cortex is the **occipital lobe**, which has no obvious anatomical border between it and the parietal or temporal lobes on the lateral surface of the brain. From the medial surface, an obvious landmark separating the parietal and occipital lobes is called the parieto-occipital sulcus.

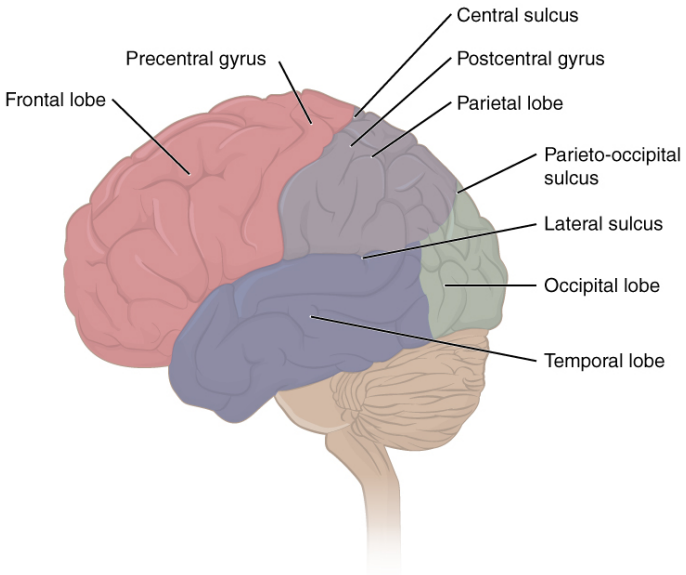

Figure 12.3.4: Lobes of the Cerebral Cortex. The cerebral cortex is divided into four lobes by the major sulci. The central sulcus separates the frontal and parietal lobes. The parieto-occipital sulcus separates the parietal and occipital lobes. The lateral sulcus separated the temporal and parietal lobes. The fifth lobe is the insula which is deep to the frontal and temporal lobes (not shown here). Each lobe corresponds to specific functions of the cerebral cortex. (Image credit: "Lobes of Cerebral Cortex" by OpenStax is licensed under CC BY 4.0)

Basal Nuclei

Beneath the cerebral cortex are sets of nuclei known as **basal nuclei** that augment cortical processes. The basal nuclei are also referred to as the basal ganglia, although that is potentially confusing because the term ganglia is typically used for peripheral nervous system structures. The basal nuclei include the caudate, putamen, and globus pallidus in the cerebrum, the subthalamic nucleus in the diencephalon, the substantia nigra in the midbrain of the brainstem and the limbic system.

The major structures of the basal nuclei that control movement are the **caudate**, **putamen**, and **globus pallidus**, which are located deep in the cerebrum. The caudate is a long nucleus that follows the basic C-shape of the cerebrum from the frontal lobe, through the parietal and occipital lobes, into the temporal lobe. The putamen is mostly deep in the anterior regions of the frontal and parietal lobes. Together, the caudate and putamen are called the **striatum**. The globus pallidus is a layered nucleus that lies just medial to the putamen; they are called the lenticular nuclei because they look like curved pieces fitting together like lenses. The globus pallidus has two subdivisions, the external and internal segments, which are lateral and medial, respectively. These nuclei are depicted in a frontal section of the brain in Figure 12.3.5. The basal nuclei in the cerebrum are connected with a few more nuclei in the brainstem that together act as a functional group that forms a motor pathway. The basal nuclei are responsible for comparing cortical processing with the general state of activity in the nervous system to influence the likelihood of movement taking place. For example, while a student is sitting in a classroom listening to a lecture, the basal nuclei will keep the urge to jump up and scream from actually happening.

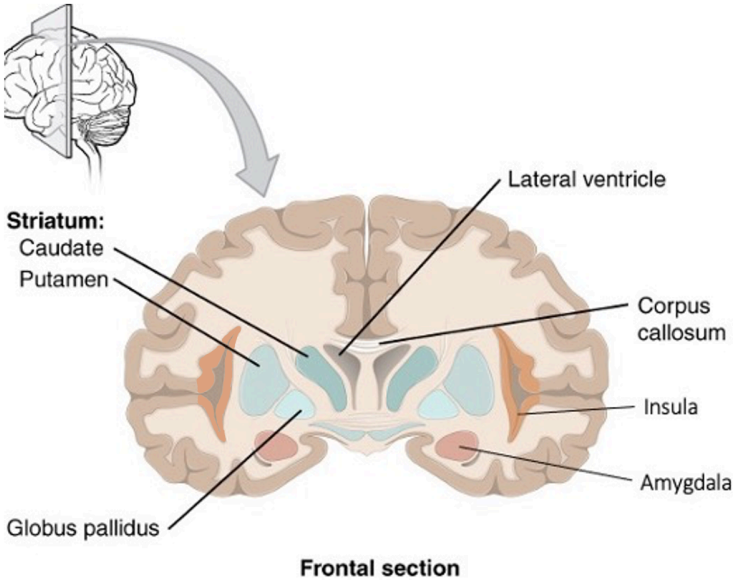

Figure 12.3.5: Frontal Section of Cerebral Cortex and Basal Nuclei. The major components of the basal nuclei, shown in a frontal section of the brain, are deep within the cerebrum. The caudate is just lateral to the lateral ventricle. The putamen is inferior to the caudate and separated by the large white-matter structure called the internal capsule. The globus pallidus is medial to the putamen. The insula is one of the five lobes of the cerebral cortex and is located deep to the lateral sulcus, between the parietal and temporal lobes. (Image credit: "Cerebral Nuclei" by Chiara Mazzasette is licensed under CC BY 4.0 / A derivative from the original work)

White Matter Tracts

The white matter lies deep to the cerebral cortex and is mainly made by myelinated axons, which gives the white appearance. The axons are grouped into bundles called **tracts** that connect different regions of the cerebral cortex to integrate information and motor response. The white matter tracts of the cerebrum can be classified into three groups: **commissural tracts**, **association tracts** and **projection tracts** (Figure 12.3.6).

Commissural tracts extend between the two hemispheres to connect left and right regions of the cerebrum. The most prominent commissural tract, and largest white matter structure, is the **corpus callosum**. Association tracts connect different regions within the same hemisphere. Association tracts can be classified into **arcuate fibers** when they connect gyri of the same lobe or **longitudinal fasciculi** when they connect gyri in different lobes of the same hemisphere. Projection tracts extend from the cerebral cortex to the inferior regions of the brain and to the spinal cord.

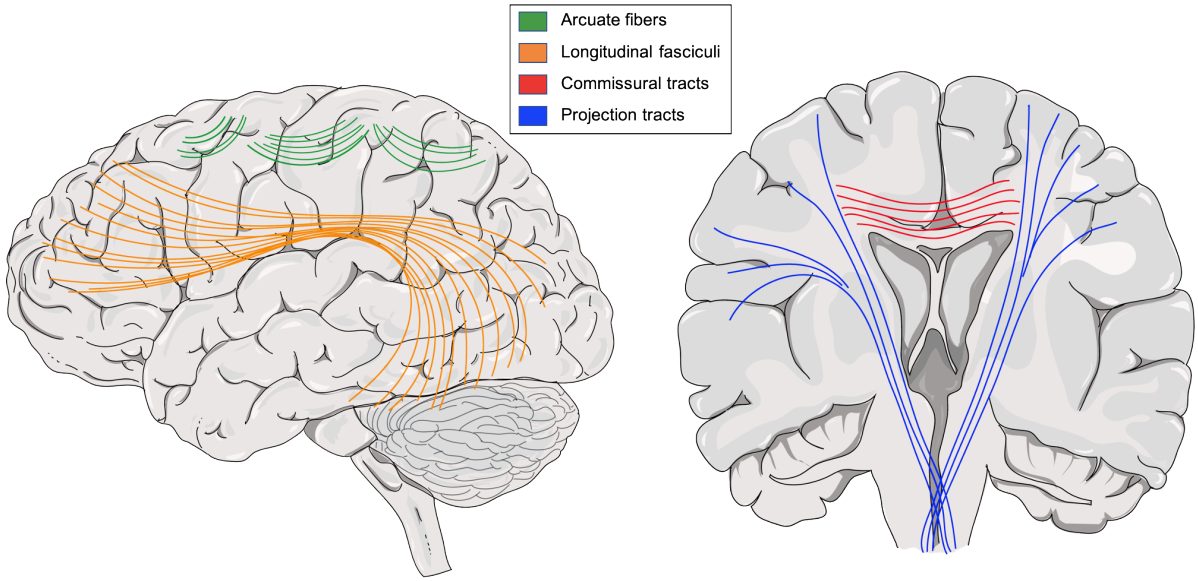

Figure 12.3.6: White Matter Tracts. The white matter of the cerebrum is organized in tracts that connect lobes and gyri within lobes. Association tracts can be divided into arcuate fibers (in green) and longitudinal fasciculi (in orange). Arcuate fibers connect gyri of the same lobe, while longitudinal fasciculi connect regions of the same hemisphere. Commissural tracts (such as the corpus callosum, in red) connect the two hemispheres. Projection tracts (in blue) connect the cerebral cortex to inferior regions of the brain or spinal cord. (Image credit: "White Matter Tracts" by Chiara Mazzasette is a derivative from the original work of Daniel Donnelly and is licensed by CC BY 4.0)

Everyday Connections

Left Brain, Right Brain

Popular media often refer to right-brained and left-brained people, as if the brain were two independent halves that work differently for different people. This is a popular misinterpretation of an important neurological phenomenon. As an extreme measure to deal with a debilitating condition, the corpus callosum may be sectioned to overcome intractable epilepsy. When the connections between the two cerebral hemispheres are cut, interesting effects can be observed.

If a person with an intact corpus callosum is asked to put their hands in their pockets and describe what is there on the basis of what their hands feel, they might say that they have keys in their right pocket and loose change in the left. They may even be able to count the coins in their pocket and say if they can afford to buy a candy bar from the vending machine. If a person with a sectioned corpus callosum is given the same instructions, they will do something quite peculiar. They will only put their right hand in their pocket and say they have keys there. They will not even move their left hand, much less report that there is loose change in the left pocket.

The reason for this is that the language functions of the cerebral cortex are localized to the left hemisphere in 95 percent of the population. Additionally, the left hemisphere is connected to the right side of the body through the corticospinal tract and the ascending tracts of the spinal cord. Motor commands from the precentral gyrus control the opposite side of the body, whereas sensory information processed by the postcentral gyrus is received from the opposite side of the body. For a verbal command to initiate movement of the right arm and hand, the left side of the brain needs to be connected by the corpus callosum. Language is processed in the left side of the brain and directly influences the left brain and right arm motor functions, but is sent to influence the right brain and left arm motor functions through the corpus callosum. Likewise, the left-handed sensory perception of what is in the left pocket travels across the corpus callosum from the right brain, so no verbal report on those contents would be possible if the hand happened to be in the pocket.

Functional Areas of the Cerebrum

The cerebrum is responsible for the perception of sensation and for controlling the skeletal muscles. The cerebrum is also the seat of many of the higher mental functions, such as memory and learning, and language. These higher functions are distributed

across various regions of the cortex, and specific locations can be said to be responsible for particular functions.

The frontal lobe is responsible for motor functions, from planning movements through executing commands to be sent to the spinal cord and periphery. The most anterior portion of the frontal lobe is the prefrontal cortex, which is associated with aspects of personality through its influence on motor responses in decision-making. The other lobes are responsible for sensory functions. The main sensation associated with the parietal lobe is **somatosensation**, meaning the general sensations associated with the body. The occipital lobe is where visual processing begins, although the other parts of the brain can contribute to visual function. The temporal lobe contains the cortical area for auditory processing, but also has regions crucial for memory formation. The insula is responsible for processing of taste sensation.

In the early 1900s, a German neuroscientist named Korbinian Brodmann performed an extensive study of the microscopic anatomy—the cytoarchitecture—of the cerebral cortex and divided the cortex into 52 separate regions on the basis of the histology of the cortex. His work resulted in a system of classification known as **Brodmann's areas**, which is still used today to describe the anatomical distinctions within the cortex (Figure 12.3.7). Continued investigation into these anatomical areas over the subsequent 100 or more years has demonstrated a strong correlation between the structures and the functions attributed to those structures. Today, we more frequently refer to these regions by their function (i.e., primary visual cortex) than by the number Brodmann assigned to them, but in some situations the use of Brodmann numbers persists. Areas 1, 2, 3, 4, 17, and 22 are each described as **primary cortical areas**. Primary areas are where sensory information is initially received for conscious perception, or where descending commands are sent down to the brainstem or spinal cord to execute movements. The regions near the primary areas are each referred to as **association areas**.

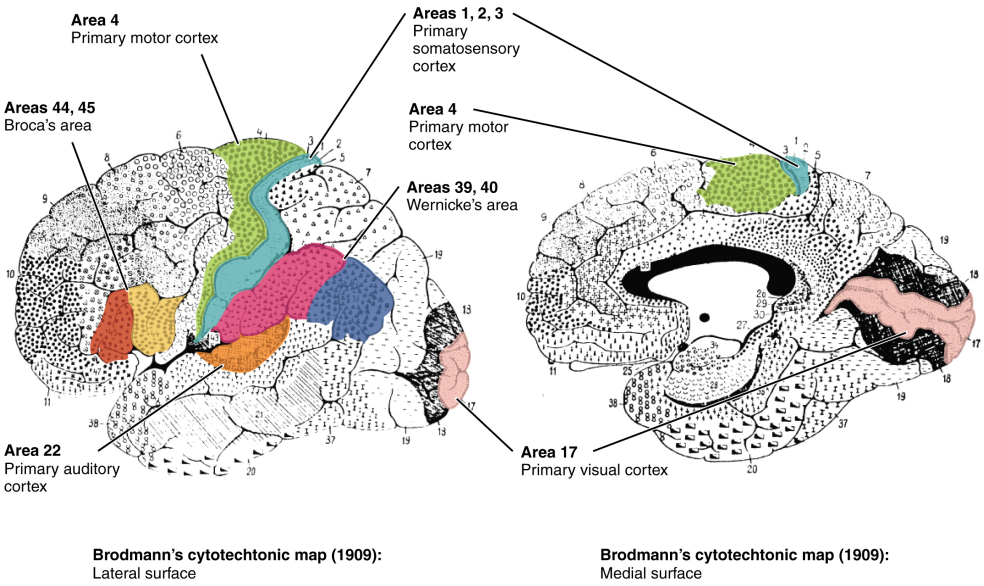

Figure 12.3.7: Brodmann's Areas of the Cerebral Cortex. On the basis of cytoarchitecture, the anatomist Korbinian Brodmann described the extensive array of cortical regions called areas and assigned to them a number, as illustrated in this figure. Subsequent investigations found that these areas corresponded very well to functional differences in the cerebral cortex and associated Brodmann's areas with the various cortices. (Image credit: "Brodmann Areas" by Looie496 is licensed under CC BY 3.0 / A derivative from the original work by Korvinian Brodmann)

Conscious Sensation and Voluntary Motor Control

The cortical areas in the parietal, temporal, and occipital lobes are involved in conscious sensation of stimuli. In the postcentral gyrus of the parietal lobe, we find the first three areas in Brodmann's list which compose the **primary somatosensory cortex** (Figure 12.3.8). All of the tactile senses are processed in this area, including touch, pressure, tickle, pain, itch, and vibration, as well as more general senses of the body such as proprioception and kinesthesia, which are the senses of body position and movement, respectively. Next to it in the parietal lobe there is the **sensory association area** which helps the primary area to process somatosensation. In the most posterior part of the occipital lobe (specifically area 17), the **primary visual cortex** receives and processes visual information. Adjacent to that are **visual association areas**, which constitute subsequent regions of visual processing. Area 22 in the temporal lobe is the **primary auditory cortex**, and it is followed by the **auditory association area** (area 23), which further processes auditory information. In the same temporal lobe, the **primary olfactory cortex** is located and processes smell. Finally, the **primary gustatory cortex** is located in the insula and is responsible for processing taste

information. The regions that control motor functions are located within the frontal lobes. In the precentral gyrus (area 4) is the **primary motor cortex**. Cells from this region of the cerebral cortex are the upper motor neurons that instruct cells in the spinal cord to move skeletal muscles. Area 6 anterior to it is the motor association area or **premotor cortex**, which aids the primary area in its function. Anterior to the premotor cortex, the **frontal eye field** controls eye movements that require both eyes, such as reading and binocular vision.

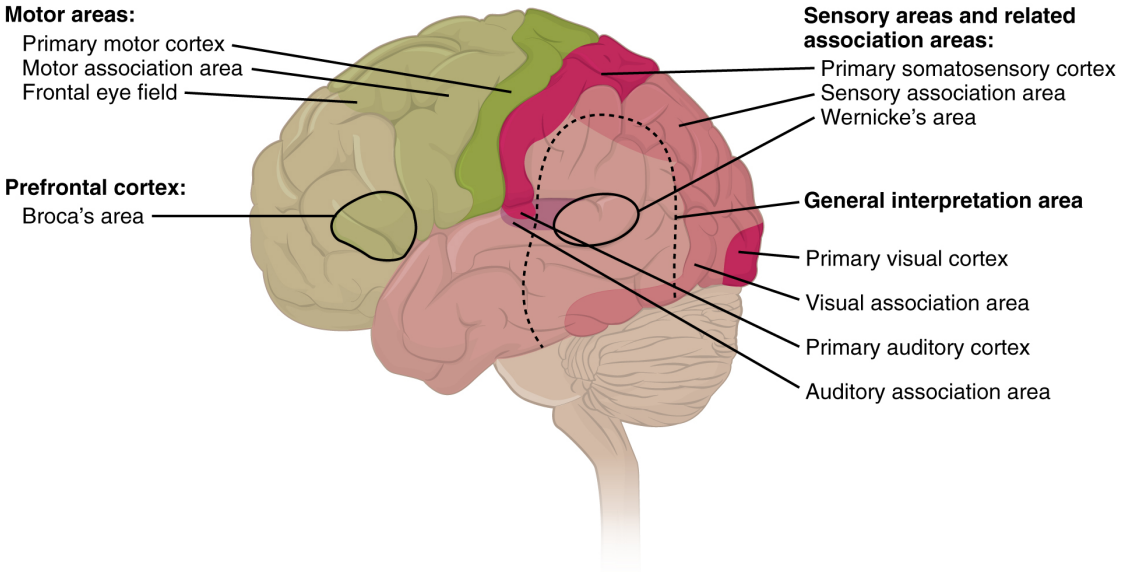

Figure 12.3.8: Types of Cortical Areas. The cerebral cortex can be described as containing three types of processing regions: primary, association, and integration areas. Here, the location of the various areas is shown. In the frontal lobe, primary motor areas and related association areas are found, such as the primary motor cortex, frontal eye field and Broca's area are found, as well as motor association area. In the parietal lobe, primary sensory areas and related association areas are found, such as the primary somatosensory cortex, Wernicke's area and sensory association area. In the occipital lobe, there are the primary visual cortex and its association area. In the temporal lobe, there are the primary auditory cortex and its association area. (Image credit: "Types of Cortical Areas" by OpenStax is licensed under CC BY 3.0)

The somatosensory and motor cortex provides an example of the mapping of the human body in different regions of the cortex. The term homunculus comes from the Latin word for “little man” and refers to a map of the human body that is laid across a portion of the cerebral cortex. The sensory receptors are mapped onto the somatosensory cortex and this mapping is called a **sensory homunculus** (Figure 12.3.9). In the somatosensory cortex, the external genitals, feet, and lower legs are represented on the medial face of the gyrus within the longitudinal fissure. As the gyrus curves out of the fissure and along the surface of the parietal lobe, the body map continues through the thighs, hips, trunk, shoulders, arms, and hands. The head and face are just lateral to the fingers as the gyrus approaches the lateral sulcus. The representation of the body in this topographical map is medial to lateral from the lower to upper body. Note that this correspondence does not result in a perfectly miniature scale version of the body, but rather exaggerates the more sensitive areas of the body, such as the fingers and lower face. Less sensitive areas of the body, such as the shoulders and back, are mapped to smaller areas on the cortex. Likewise, the motor cortex contains a similar representation of neurons that control the respective body regions. This mapping is called **motor homunculus** (not shown here).

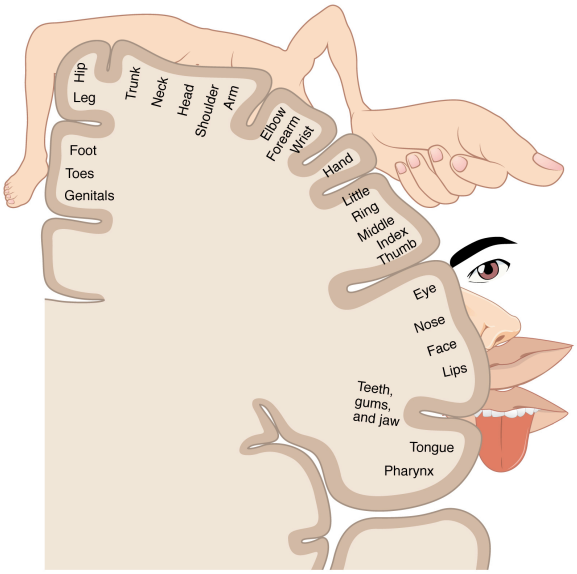

Figure 12.3.9: Sensory Homunculus. A cartoon representation of the sensory homunculus is shown. The homunculus refers to a map of the human body that is laid across a portion of the cerebral cortex. In this case, the sensory receptors from various areas of the body are mapped adjacent to the cortical region in which the processing takes place. The most medial region of the somatosensory cortex processes sensory information regarding the toes and feet, while the most lateral region processes sensory information regarding the face, and in particular the mouth. (Image credit: "Sensory Homunculus" by OpenStax is licensed under CC BY 3.0)

A number of other regions, which extend beyond these primary or association areas of the cortex, are referred to as integrative areas. These areas are found in the spaces between the domains for particular sensory or motor functions, and they integrate multisensory information, or process sensory or motor information in more complex ways. Consider, for example, the posterior parietal cortex that lies between the somatosensory cortex and visual cortex regions. This area is called **gnostic area** and has been ascribed to the coordination of visual and motor functions, such as reaching to pick up a glass. The somatosensory function that would be part of this is the proprioceptive feedback from moving the arm and hand. The weight of the glass, based on what it contains, will influence how those movements are executed.

Memory and Learning

There are other cognitive abilities of the cerebral cortex. For example, memory is largely a function of the frontal and temporal lobes, along with structures beneath the cerebral cortex. Short-term memory (also called working or active memory) is localized to the prefrontal lobe. Memory is essentially a sensory function: memories are recalled sensations such as the smell of Mom's baking or the sound of a barking dog. Even memories of movement are really the memory of sensory feedback from those movements, such as stretching muscles or the movement of the skin around a joint. Structures in the temporal lobe are responsible for establishing long-term memory, but the ultimate location of those memories is usually in the region in which the sensory perception was processed.

Language and Speech

Adjacent to the auditory association cortex, at the end of the lateral sulcus just anterior to the visual cortex, is **Wernicke's area** (Figure 12.3.10). Wernicke's area is responsible for the understanding of language, both written and verbal. In the lateral aspect of the frontal lobe, just anterior to the region of the motor cortex associated with the head and neck, is **Broca's area**. Broca's area is responsible for the production of language, or controlling movements responsible for speech. Both area are located only in the left hemisphere in the majority of people. The tendency for some brain functions to be specialized in one side of the brain is called **lateralization of function**. The language areas are not the only example of lateralization. Another example of lateralization is the somatic sensation of one side of the body crossing at the brainstem to send the information to the hemisphere on the opposite side. Exact math calculation and memory retrieval, for example, tend to be on the left parietal lobe. Both regions were originally described on the basis of losses of speech and language, which is called **aphasia**. The aphasia associated with Broca's area is known as an **expressive aphasia**, which means that speech production is compromised. This type of aphasia is often described as non-fluency because the ability to say some words leads to broken or halting speech. Grammar can also appear to be lost. The aphasia associated with Wernicke's area is known as a **receptive aphasia**, which is not a loss of speech production, but a loss of understanding of content. Patients, after recovering from acute forms of this aphasia, report not being able to understand what is

said to them or what they are saying themselves, but they often cannot keep from talking.

The two regions are connected by white matter tracts that run between the posterior temporal lobe and the lateral aspect of the frontal lobe. **Conduction aphasia** associated with damage to this connection refers to the problem of connecting the understanding of language to the production of speech. This is a very rare condition, but is likely to present as an inability to faithfully repeat spoken language.

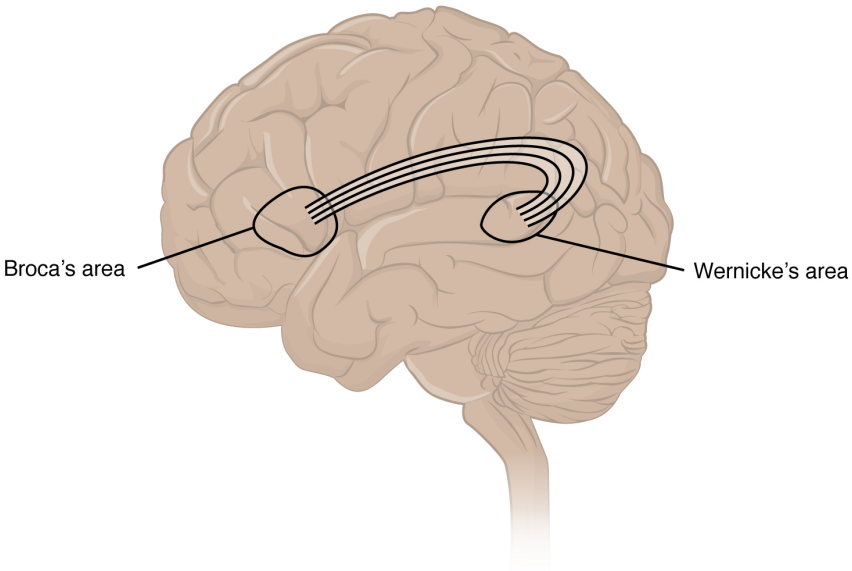

Figure 12.3.10: Broca's and Wernicke's Areas. Two important integration areas of the cerebral cortex associated with language function are Broca's and Wernicke's areas. The two areas are connected through the deep white matter running from the posterior temporal lobe where Wernicke's are is located to the frontal lobe where Broca's area is located. (Image credit: "Brocas and Wernickes Areas" by OpenStax is licensed under CC BY 3.0)

Judgment and Abstract Reasoning

Planning and producing responses requires an ability to make sense of the world around us. Making judgments and reasoning in the abstract are necessary to produce movements as part of larger responses. For example, when your alarm goes off, do you hit the snooze button or jump out of bed? Is 10 extra minutes in bed worth the extra rush to get ready for your day? Will hitting the snooze button multiple times lead to feeling more rested or result in a panic as you run late? How you mentally process these questions can affect your whole day.

The prefrontal cortex is responsible for the functions responsible for planning and making decisions. The prefrontal cortex is composed of the regions of the frontal lobe that are not directly related to specific motor functions. The most posterior region of the frontal lobe, the precentral gyrus, is the primary motor cortex. Anterior to that are the premotor cortex, Broca's area, and the frontal eye fields, which are all related to planning certain types of movements. Anterior to what could be described as motor association areas are the regions of the prefrontal cortex. They are the regions in which judgment, abstract reasoning, and working memory are localized. The antecedents to planning certain movements are judging whether those movements should be made, as in the example of deciding whether to hit the snooze button.

A psychiatric practice to deal with various disorders was the **prefrontal lobotomy**. This procedure was common in the 1940s and early 1950s, until antipsychotic drugs became available. The connections between the prefrontal cortex and other regions of the brain were severed. The disorders associated with this procedure included some aspects of what are now referred to as personality disorders, but also included mood disorders and psychoses. Depictions of lobotomies in popular media suggest a link between cutting the white matter of the prefrontal cortex and changes in a patient's mood and personality, though this correlation is not well understood.

Interactive Link

Human Brain Size

Compared with the nearest evolutionary relative, the chimpanzee, the human has a brain that is huge. At a point in the past, a common ancestor gave rise to the two species of humans and chimpanzees. That evolutionary history is long and is still an area of intense study. But something happened to increase the size of the human brain relative to the chimpanzee. Read the article "How did human brains get so big?" in which the author explores the current understanding of why this happened.

According to one hypothesis about the expansion of brain size, what tissue might have been sacrificed so energy was available to grow our larger brain? Based on what you know about that tissue and nervous tissue, why would there be a trade-off between them in terms of energy use?

Answer available at the end of this section.

Concept Review

The adult brain is separated into four major regions: the cerebrum, the diencephalon, the brainstem, and the cerebellum. The cerebrum is the largest portion and contains the cerebral cortex, subcortical nuclei and white matter tracts. It is divided into two halves called hemispheres by the longitudinal fissure.

The cerebral cortex is the location of important cognitive functions. It is separated into the frontal, parietal, temporal, and occipital lobes. The frontal lobe is responsible for motor functions, from planning movements through executing commands to be sent to the spinal cord and periphery. The most anterior portion of the frontal lobe is the prefrontal cortex, which is associated with aspects of personality through its influence on motor responses in decision-making. The other lobes are responsible for sensory functions. The parietal lobe is where somatosensation is processed. The occipital lobe is where visual processing begins, although the other parts of the brain can contribute to visual function. The temporal lobe contains the cortical area for auditory processing, but also has regions crucial for memory formation.

Subcortical nuclei beneath the cerebral cortex, known as the subcortical or basal nuclei nuclei, are responsible for augmenting cortical functions. The subcortical or basal nuclei receive input from cortical areas and compare it with the general state of the individual. The output influences the activity of part of the thalamus that can then increase or decrease cortical activity that often results in changes to motor commands.

White matter tracts are bundles of myelinated axons that connect different regions of the brain. Commissural tracts such as the corpus callosum extend between the two hemispheres to connect left and right regions of the cerebrum. Association tracts connect different regions within the same hemisphere. Association tracts can be classified into arcuate fibers when they connect gyri of the same lobe or longitudinal fasciculi when they connect gyri in different lobes of the same hemisphere. Projection tracts extend from the cerebral cortex to the inferior regions of the brain and to the spinal cord.

Losses of language and speech functions, known as aphasias, are associated with damage to the important integration areas in the left hemisphere known as Broca's or Wernicke's areas, as well as the connections in the white matter between them. Different types of aphasia are named for the particular structures that are damaged.

Review Questions

Q. Brodmann's areas map different regions of the _____ to particular functions.

A. cerebellum

B. cerebral cortex

C. basal forebrain

D. corpus callosum

Answer

B

Q. Which lobe of the cerebral cortex is responsible for generating motor commands?

A. temporal

B. parietal

C. occipital

D. frontal

Answer

D

Q. Which type of aphasia is more like hearing a foreign language spoken?

A. receptive aphasia

B. expressive aphasia

C. conductive aphasia

D. Broca's aphasia

Answer

A

Glossary

aphasia
loss of language function

arcuate fibers
white matter tract that connect gyri of the same lobe

association area
region of cortex connected to a primary sensory cortical area that further processes the information to generate more complex sensory perceptions

association tract
white matter tract that connect different regions within the same hemisphere

basal nuclei
: nuclei of the cerebrum (with a few components in the upper brainstem and diencephalon) that are responsible for assessing cortical movement commands and comparing them with the general state of the individual through broad modulatory activity of dopamine neurons; largely related to motor functions, as evidenced through the symptoms of Parkinson's and Huntington's diseases

Broca's area
: region of the frontal lobe associated with the motor commands necessary for speech production and located only in the cerebral hemisphere responsible for language production, which is the left side in approximately 95 percent of the population

Brodmann's areas
: mapping of regions of the cerebral cortex based on microscopic anatomy that relates specific areas to functional differences, as described by Brodmann in the early 1900s

caudate
: nucleus deep in the cerebrum that is part of the basal nuclei; along with the putamen, it is part of the striatum

central sulcus
: surface landmark of the cerebral cortex that marks the boundary between the frontal and parietal lobes

cerebral cortex
: outer gray matter covering the forebrain, marked by wrinkles and folds known as gyri and sulci

cerebral hemisphere
: one half of the bilaterally symmetrical cerebrum

cerebrum
: region of the adult brain that develops from the telencephalon and is responsible for higher neurological functions such as memory, emotion, and consciousness

commissural tract
: white matter tract that extend between the two hemispheres to connect left and right regions of the cerebrum

conduction aphasia
: loss of language function related to connecting the understanding of speech with the production of speech, without either specific function being lost

corpus callosum
: large white matter structure that connects the right and left cerebral hemispheres

expressive aphasia
: loss of the ability to produce language; usually associated with damage to Broca's area in the frontal lobe

frontal eye field
: region of the frontal lobe associated with motor commands to orient the eyes toward an object of visual attention

globus pallidus
: nuclei deep in the cerebrum that are part of the basal nuclei and can be divided into the internal and external segments

gnostic area
: posterior parietal cortex that lies between the somatosensory cortex and visual cortex regions

gyrus
: ridge formed by convolutions on the surface of the cerebrum or cerebellum

insula
: small region of the cerebral cortex located deep within the lateral sulcus

lateral sulcus
surface landmark of the cerebral cortex that marks the boundary between the temporal lobe and the frontal and parietal lobes

lateralization of function
tendency for some brain functions to be specialized in one side of the brain

longitudinal fasciculi
white matter tract that connect gyri in different lobes of the same hemisphere

longitudinal fissure
large separation along the midline between the two cerebral hemispheres

motor homunculus
topographical representation in the precentral gyrus of motor neurons that control the respective body regions

occipital lobe
region of the cerebral cortex directly beneath the occipital bone of the cranium

parietal lobe
region of the cerebral cortex directly beneath the parietal bone of the cranium

parieto-occipital sulcus
groove in the cerebral cortex representing the border between the parietal and occipital cortices

postcentral gyrus
ridge just posterior to the central sulcus, in the parietal lobe, where the primary somatosensory cortex is located

precentral gyrus
ridge just anterior to the central sulcus, in the frontal lobe, where the primary motor cortex is located

prefrontal lobotomy
Surgical operation where connections between the prefrontal cortex and other regions of the brain are severed

premotor cortex
region of the frontal lobe responsible for planning movements that will be executed through the primary motor cortex

primary auditory cortex
region of the cerebral cortex within the temporal lobe responsible for the perception of sounds

primary cortical areas
primary areas are where sensory information is initially received for conscious perception, or where descending commands are sent down to the brainstem or spinal cord to execute movements

primary gustatory cortex
region of the cerebral cortex within the insula responsible for the perception of taste

primary motor cortex
located in the precentral gyrus and responsible for the movement of skeletal muscles

primary olfactory cortex
region of the cerebral cortex within the temporal lobe responsible for the perception of smell

primary somatosensory cortex
located in the postcentral gyrus and responsible for the perception of somatosensation

primary visual cortex
region of the cerebral cortex within the occipital lobe responsible for the perception of vision

projection tract
white matter tract that extend from the cerebral cortex to the inferior regions of the brain and to the spinal cord

putamen
nucleus deep in the cerebrum that is part of the basal nuclei; along with the caudate, it is part of the striatum

receptive aphasia
loss of the ability to understand received language, such as what is spoken to the subject or given in written form

sensory association area
region of cortex connected to the primary somatosensory cortex that further processes the information to generate more complex sensory perceptions

sensory homunculus
topographical representation in the postcentral gyrus of somatosensory neurons that sense the respective body regions

somatosensation
general senses related to the body, usually thought of as the senses of touch, which would include pain, temperature, and proprioception

striatum
the caudate and putamen collectively, as part of the basal nuclei, which receive input from the cerebral cortex

sulcus
groove formed by convolutions in the surface of the cerebral cortex

temporal lobe
region of the cerebral cortex directly beneath the temporal bone of the cranium

tract
bundle of axons in the central nervous system having the same function and point of origin

visual association area
region of cortex connected to the primary visual cortex that further processes the information to generate more complex sensory perceptions

Wernicke's area
region at the posterior end of the lateral sulcus in which speech comprehension is localized

Contributors and Attributions

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Answers

Interactive Link

Energy is needed for the brain to develop and perform higher cognitive functions. That energy is not available for the muscle tissues to develop and function. The hypothesis suggests that humans have larger brains and less muscle mass, and chimpanzees have the smaller brains but more muscle mass.

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12.4: Brain- Diencephalon, Brainstem, Cerebellum and Limbic System

By the end of this section, you will be able to:

- Identify the components of the diencephalon and describe their functions
- Identify the structures of the brainstem and describe their functions
- Describe the structure and function of the cerebellum
- Identify the major structures of the limbic system and describe their functions

Diencephalon

The diencephalon is the one region of the adult brain that retains its name from embryologic development. The etymology of the word diencephalon translates to “through brain.” It is the connection between the cerebrum and the rest of the nervous system, with one exception. The rest of the brain, the spinal cord, and the PNS all send information to the cerebrum through the diencephalon. Output from the cerebrum passes through the diencephalon. The single exception is the system associated with olfaction, or the sense of smell, which connects directly with the cerebrum. In the earliest vertebrate species, the cerebrum was not much more than olfactory bulbs that received peripheral information about the chemical environment (to call it smell in these organisms is imprecise because they lived in the ocean).

The diencephalon is deep beneath the cerebrum and constitutes the walls of the third ventricle. The diencephalon can be described as any region of the brain with “thalamus” in its name. The major regions of the diencephalon are the **thalamus** itself, the **hypothalamus**, the **epithalamus**, which contains the pineal gland, and the **subthalamus**, which includes part of the basal nuclei (Figure 12.4.1).

Epithalamus

The epithalamus forms the posterior roof of the third ventricle and houses the **pineal gland**, an endocrine gland responsible for the secretion of melatonin. Melatonin regulates day-night cycles. Nuclei within the epithalamus help relay signals to the limbic system and are involved in emotional responses to odors.

Thalamus

The thalamus is a pair of oval-shaped structures that each contain a dozen nuclei, called **thalamic nuclei**. The thalamus covers the superior and lateral walls of the third ventricle. The right and left thalami are connected by a mass of gray matter called the **interthalamic adhesion**. All sensory information, except for the sense of smell, passes through the thalamus before processing by the cortex. Axons from the peripheral sensory organs, or intermediate nuclei, synapse in the thalamus, and thalamic neurons project directly to the cerebrum. It is a requisite synapse in any sensory pathway, except for olfaction. The thalamus does not just pass the information on, it also processes that information. For example, the portion of the thalamus that receives visual information will influence what visual stimuli are important, or what receives attention. The cerebrum also sends information down to the thalamus, which usually communicates motor commands. This involves interactions with the cerebellum and other nuclei in the brainstem. Inferior to the thalamus lies the **subthalamic nucleus**, which is part of the basal nuclei. The subthalamic nucleus connects various basal nuclei and modulate their activity.

Hypothalamus

Inferior and slightly anterior to the thalamus is the hypothalamus, the other major region of the diencephalon. The hypothalamus is a collection of nuclei that are largely involved in regulating homeostasis. The hypothalamus is the executive region in charge of the autonomic nervous system and the endocrine system through its regulation of the anterior pituitary gland. Other parts of the hypothalamus are involved in memory and emotion as part of the limbic system. Two groups of nuclei called the the **mammillary bodies** are located on the posterior part of the hypothalamus and are important for episodic memory, which is the memory of

every day events that you can recollect.

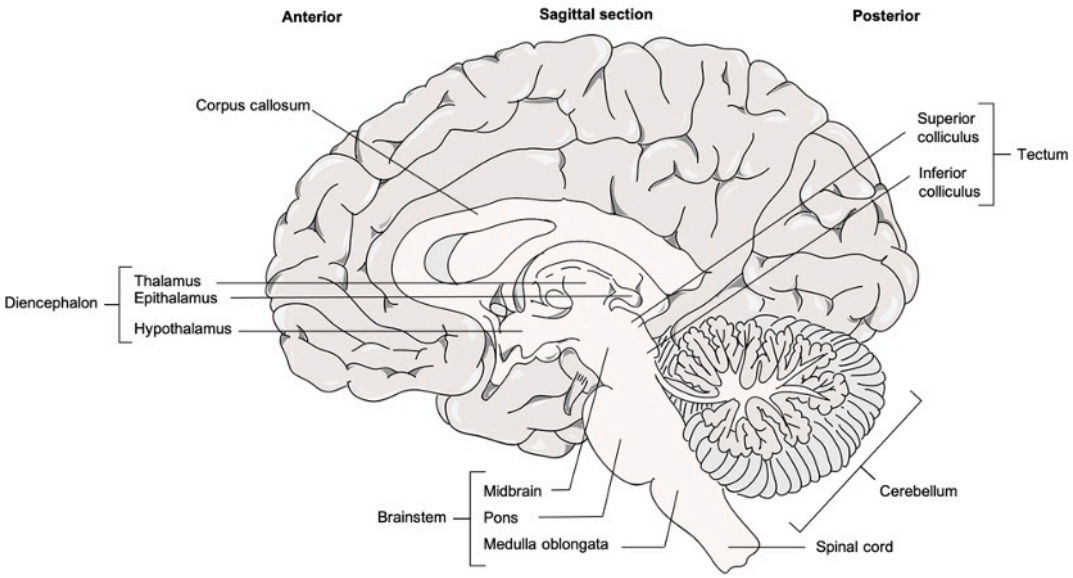

Figure 12.4.1: Midsagittal Section of the Brain. The diencephalon is composed of the thalamus, hypothalamus, and epithalamus and defines the walls of the third ventricle. The brainstem comprises three regions: the midbrain, the pons, and the medulla. Within the midbrain, the tectum is composed of the superior and inferior colliculi. (Image credit: "Brain Midsagittal Section" by Chiara Mazzasette is a derivative from the original work of Daniel Donnelly and is licensed by CC BY 4.0)

Brainstem

The **midbrain** and hindbrain (composed of the **pons** and the **medulla oblongata**) are collectively referred to as the brainstem (Figure 12.4.1 and Figure 12.4.2). The structure emerges from the ventral surface of the forebrain as a tapering cone that connects the brain to the spinal cord. Attached to the brainstem, but considered a separate region of the adult brain, is the cerebellum. The midbrain coordinates sensory representations of the visual, auditory, and somatosensory perceptual spaces. The pons is the main connection with the cerebellum. The pons and the medulla regulate several crucial functions, including the cardiovascular and respiratory systems (such as heart rhythm or breathing rate). The **reticular activating system** is found in the midbrain, pons, medulla and part of the thalamus and controls levels of wakefulness, maintains consciousness, enables people to pay attention to their environments, and is involved in sleep patterns and regulating the sleep cycle.

The cranial nerves connect through the brainstem and provide the brain with the sensory input and motor output associated with the head and neck, including most of the special senses. The major ascending and descending pathways between the spinal cord and brain, specifically the cerebrum, pass through the brainstem.

Midbrain

The mesencephalon, one of the original region of the embryonic brain, becomes the midbrain, a small region between the thalamus and pons. The **cerebral aqueduct** passes through the center of the midbrain, such that these regions are the roof and floor of that canal. Indeed, the midbrain is separated into the tectum and tegmentum, from the Latin words for roof and floor, respectively.

The **tectum** is composed of four bumps known together as the **corpora quadrigemina** or colliculi (singular = colliculus), which means “little hill” in Latin. The **superior colliculus** is the superior pair and combines sensory information about visual space, auditory space, and somatosensory space. At this level, the nucleus for the oculomotor nerve (CN III) is found. The **inferior colliculus** is the inferior pair of these enlargements and is part of the auditory pathway (trochlear nerve, CN IV). Neurons of the inferior colliculus project to the thalamus, which then sends auditory information to the cerebrum for the conscious perception of sound.

The **tegmentum** is continuous with the gray matter of the rest of the brainstem. The **substantia nigra** consists of basal nuclei with a black appearance due to melanin production. These nuclei control movement, emotional response, and the ability to experience pleasure and pain. Degeneration of the neurons within the substantia nigra is a hallmark of Parkinson disease.

The midbrain is connected to both the cerebrum and the cerebellum. On the anterolateral surfaces of the midbrain, motor tracts called **cerebral peduncles** run from the cerebrum to the spinal cord. Moreover, the midbrain is connected to the cerebellum through the **superior cerebellar peduncle (SCP)**, a bundle of myelinated axons.

Pons

The pons is visible on the anterior surface of the brainstem as the thick bundle of white matter attached to the cerebellum. The name of the pons is derived from its connection to the cerebellum. The word means “bridge” and refers to the thick bundle of myelinated axons that form a bulge on its ventral surface. Those fibers are axons that project from the gray matter of the pons into the contralateral cerebellar cortex. These fibers make up the **middle cerebellar peduncle (MCP)** and are the major physical connection of the cerebellum to the brainstem (Figure 12.4.3). Gray matter regions of the pons contain neurons receiving descending input from the forebrain that is sent to the cerebellum. The pons houses autonomic nuclei important for respiration. The pons is also involved in sensory and motor information of some cranial nerves and houses the nuclei for cranial nerve V to VIII.

Medulla Oblongata

The medulla oblongata is the region known as the myelencephalon in the embryonic brain. The initial portion of the name, “myel,” refers to the significant white matter found in this region—especially on its exterior, which is continuous with the white matter of the spinal cord. The anterior region of the medulla oblongata shows two longitudinal ridges called **pyramids**, which house motor projection tracts (Figure 12.4.2). In the posterior region of the medulla oblongata, these pyramids cross to the opposite side at a point called the **decussation of pyramids**. Due to this crossing, each hemisphere controls motor responses of the opposite side of the body. Inferior to each pyramid, a nucleus called **inferior olive**, is located and functions as a relay point for information on **proprioception** coming from the spinal cord and going into the cerebellum. Indeed, the medulla oblongata send information to the cerebellum through tracts called **inferior cerebellar peduncle (ICP)** (Figure 12.4.3). The medulla oblongata contains several nuclei that are associated with last five cranial nerves (CN VIII to XII). It also contains autonomic nuclei important for vital functions such as respiration, heart rate, and blood pressure, among others.

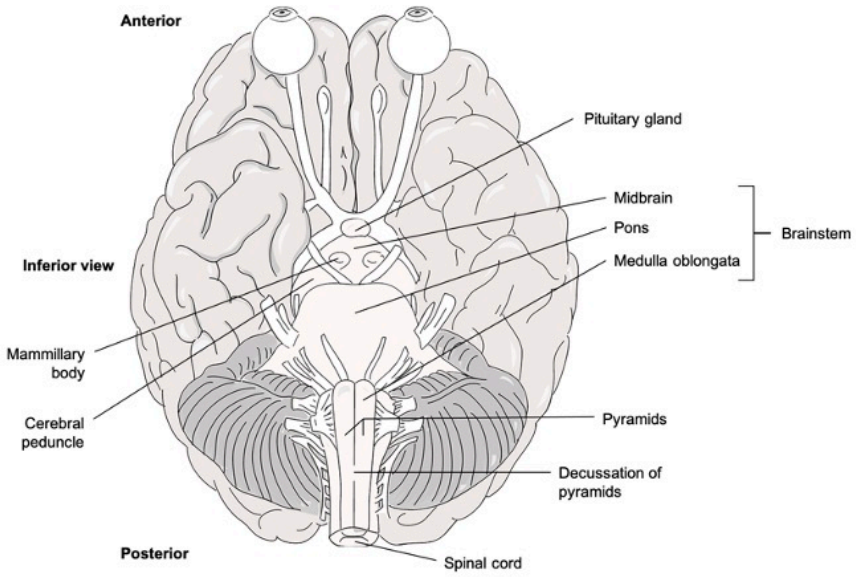

Figure 12.4.2: Inferior View of the Brain. The inferior view of the brain shows the brainstem, cerebellum and cranial nerves. From anterior to posterior, the midbrain, pons and medulla oblongata form the brainstem. The cerebral peduncles of the midbrain and pyramids and their decussation of the medulla oblongata are also visible. The pituitary gland is attached to the hypothalamus, as are the mammillary bodies. (Image credit: "Brain Inferior View" by Chiara Mazzasette is a derivative from the original work of Daniel Donnelly and is licensed by CC BY 4.0)

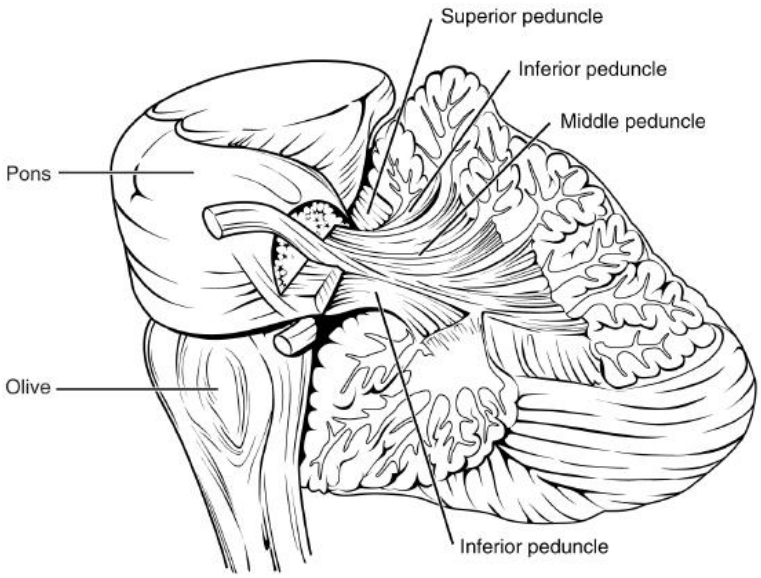

Figure 12.4.3: Cerebellar Peduncles. The connections to the cerebellum are the three cerebellar peduncles, which are close to each other. The superior cerebellar peduncle projects into the midbrain. The middle cerebellar peduncle is the ventral surface of the pons. The inferior cerebellar peduncle arises from the medulla—specifically from the inferior olive, which is visible as a bulge on the ventral surface of the brainstem. (Image credit: "Cerebellar Peduncles" by OpenStax is licensed under CC BY 3.0)

DISORDERS OF THE...Basal Nuclei: Parkinson's Disease

Parkinson's disease is a disorder of the basal nuclei, specifically of the substantia nigra, that demonstrates the effects of the direct and indirect pathways. Parkinson's disease is the result of neurons in the substantia nigra pars compacta dying. These neurons release dopamine into the striatum. Without that modulatory influence, the basal nuclei are stuck in the indirect pathway, without the direct pathway being activated. The direct pathway is responsible for increasing cortical movement commands. The increased activity of the indirect pathway results in the hypokinetic disorder of Parkinson's disease.

Parkinson's disease is neurodegenerative, meaning that neurons die that cannot be replaced, so there is no cure for the disorder. Treatments for Parkinson's disease are aimed at increasing dopamine levels in the striatum. Currently, the most common way of doing that is by providing the amino acid L-DOPA, which is a precursor to the neurotransmitter dopamine and can cross the blood-brain barrier. With levels of the precursor elevated, the remaining cells of the substantia nigra pars compacta can make more neurotransmitter and have a greater effect. Unfortunately, the patient will become less responsive to L-DOPA treatment as time progresses, and it can cause increased dopamine levels elsewhere in the brain, which are associated with psychosis or schizophrenia.

Visit this site for a thorough explanation of Parkinson's disease.

Cerebellum

The **cerebellum**, as the name suggests, is the "little brain". Similar to the brain, the cerebellum contains an outer layer of gray matter, an inner layer of white matter and deep **cerebellar nuclei** (Figure 12.4.4). The white matter of the cerebellum is called **arbor vitae** ("tree of life") for its appearance that reminds that of branches of a tree. The folds of the cerebellar cortex are called **folia**, which means "leaf".

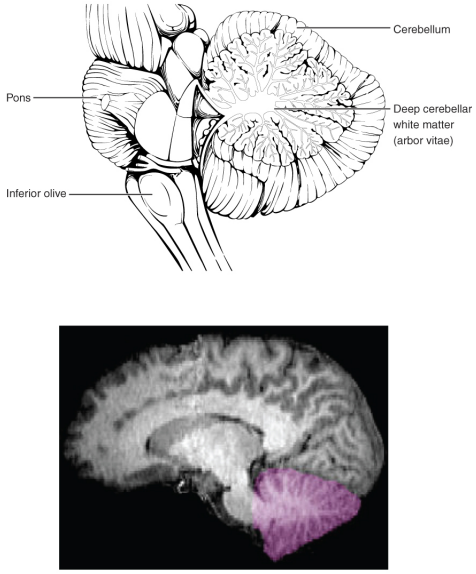

Figure 12.4.4: Cerebellum. The cerebellum is situated on the posterior surface of the brainstem. This lateral view of a section of cerebellum shows the deep white matter forming the arbor vitae, which means "tree of life", while the cerebellar cortex is superficial. Descending input from the cerebellum enters through the large white matter structure of the pons. Ascending input from the periphery and spinal cord enters through the fibers of the inferior olive. Output goes to the midbrain, which sends a descending signal to the spinal cord. (Image credit: "Cerebellum" by OpenStax is licensed under CC BY 4.0)

The cerebellum is divided into regions that are based on the particular functions and connections involved. The midline region of the cerebellum, called the **vermis**, is involved in comparing visual information, equilibrium, and proprioceptive feedback to maintain balance and coordinate movements such as walking, or gait (Figure 12.4.5). The vermis connects the two **cerebellar hemispheres**. Each hemisphere consists of two lobes, the **anterior lobe** and the **posterior lobe**, separated by the **primary fissure**. The lateral hemispheres are primarily concerned with planning motor functions through frontal lobe inputs that are returned through the thalamic projections back to the premotor and motor cortices. Processing in the midline regions targets movements of the axial musculature, whereas the lateral regions target movements of the appendicular musculature.

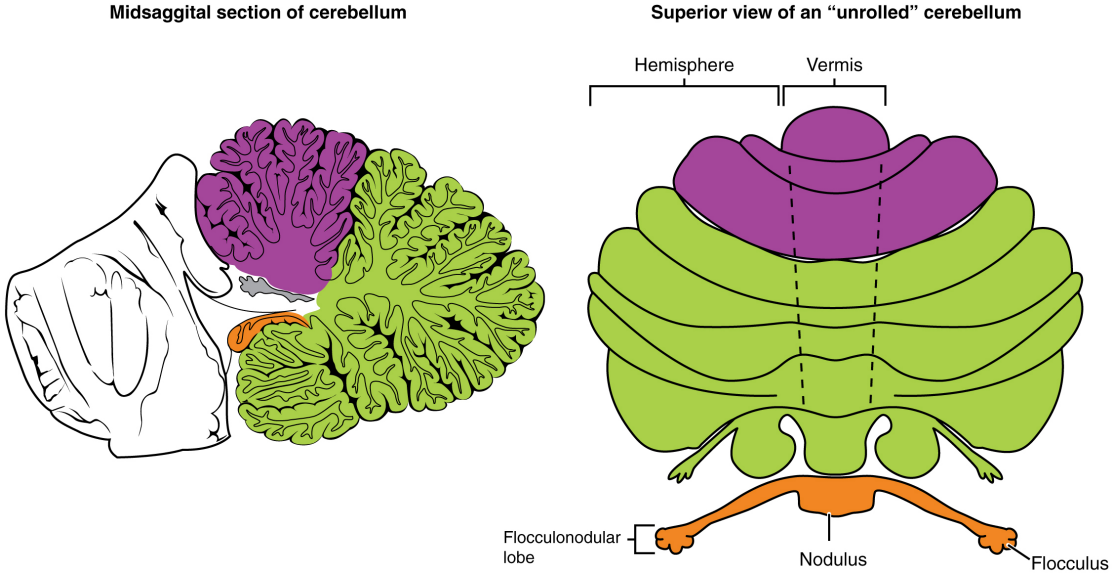

Figure 12.4.5: Major Regions of the Cerebellum. The cerebellum can be divided into two basic regions: the vermis, which is the midline, and the hemispheres, which are lateral to the vermis. Each cerebellar hemisphere consists of two lobes. The anterior lobe (in purple) and posterior lobe (in green) are separated by the primary fissure. (Image credit: "Major Regions of the Cerebellum" by OpenStax is licensed under CC BY 3.0)

The cerebellum is responsible for coordination of movement, alternating movement of arms and legs, balance, posture and gait. If the primary motor cortex of the frontal lobe sends a command down to the spinal cord to initiate walking, a copy of that instruction is sent to the cerebellum. Sensory feedback from the muscles and joints, proprioceptive information about the movements of

walking, and sensations of balance are sent to the cerebellum through the inferior olive and the cerebellum compares them. If walking is not coordinated, perhaps because the ground is uneven or a strong wind is blowing, then the cerebellum sends out a corrective command to compensate for the difference between the original cortical command and the sensory feedback. The output of the cerebellum is into the midbrain, which then sends a descending input to the spinal cord to correct the messages going to skeletal muscles.

There is also strong evidence of the cerebellar role in procedural memory. The two are not incompatible; in fact, procedural memory is motor memory, such as learning to ride a bicycle. Significant work has been performed to describe the connections within the cerebellum that result in learning.

DISORDERS OF THE...Cerebellum: Ataxia

A movement disorder of the cerebellum is referred to as **ataxia**. It presents as a loss of coordination in voluntary movements. Ataxia can also refer to sensory deficits that cause balance problems, primarily in proprioception and equilibrium. When the problem is observed in movement, it is ascribed to cerebellar damage. Sensory and vestibular ataxia would likely also present with problems in gait and station.

Ataxia is often the result of exposure to exogenous substances, focal lesions, or a genetic disorder. Focal lesions include strokes affecting the cerebellar arteries, tumors that may impinge on the cerebellum, trauma to the back of the head and neck, or MS. Alcohol intoxication or drugs such as ketamine cause ataxia, but it is often reversible. Mercury in fish can cause ataxia as well. Hereditary conditions can lead to degeneration of the cerebellum or spinal cord, as well as malformation of the brain, or the abnormal accumulation of copper seen in Wilson's disease.

Limbic System

The **limbic system** is a collection of structures of the cerebrum and diencephalon involved in emotion, motivation and memory associated with emotions. Although still debated, the structures mostly recognized in this system are the cingulate gyrus, hippocampus, amygdala, olfactory structures, and various nuclei of the diencephalon. Here we will focus on the cingulate gyrus, the hippocampus and amygdala as major structures (Figure 12.4.6). The **cingulate gyrus** is located in the longitudinal fissure, superior to the corpus callosum, surrounding the diencephalon. The cingulate gyrus focuses the attention to events that are emotionally important. The **hippocampus** is a nucleus shaped like a seahorse, hence its name. The hippocampus is essential in forming memories and storing them long-term. Lastly, the **amygdala** (or amygdaloid body) is connected to the hippocampus and is involved in multiple aspects of emotions, especially fear. It helps encoding memories based on the state of emotion that the person is in.

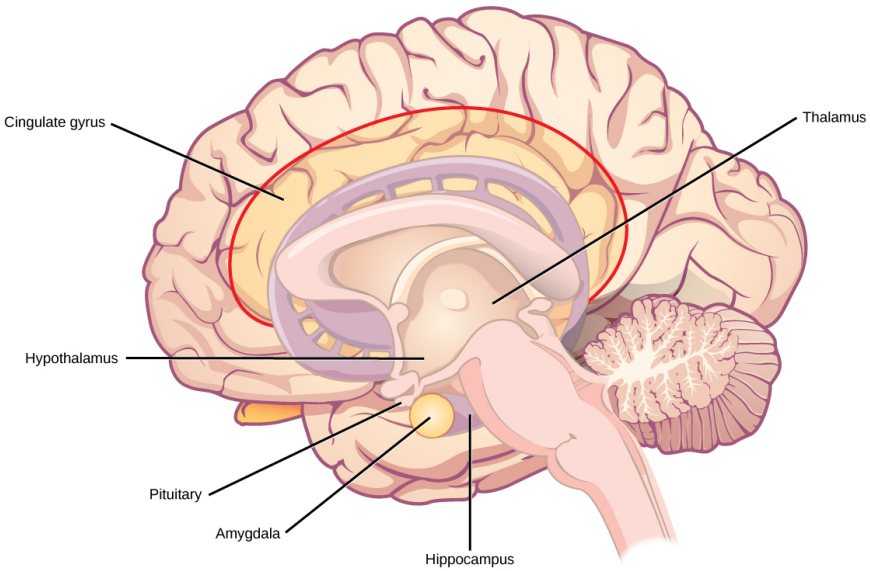

Figure 12.4.6: Limbic System. The limbic system regulates emotion and other behaviors. It includes parts of the cerebral cortex located near the center of the brain, including the cingulate gyrus and the hippocampus as well as the thalamus, hypothalamus and amygdala. The amygdala is inferior to the hypothalamus. (Image credit: "Figure 35 03 06" by OpenStax is licensed under CC BY 4.0)

Concept Review

The diencephalon includes the thalamus and the hypothalamus, along with some other structures. The thalamus is a relay between the cerebrum and the rest of the nervous system. The hypothalamus coordinates homeostatic functions through the autonomic and endocrine systems.

The brainstem is composed of the midbrain, pons, and medulla. It controls the head and neck region of the body through the cranial nerves. There are control centers in the brainstem that regulate the cardiovascular and respiratory systems.

The cerebellum is connected to the brainstem, primarily at the pons, where it receives a copy of the descending input from the cerebrum to the spinal cord. It can compare this with sensory feedback input through the medulla and send output through the midbrain that can correct motor commands for coordination. The cerebellum is an important part of motor function in the nervous system. It apparently plays a role in procedural learning, which would include motor skills such as riding a bike or throwing a football. The basis for these roles is likely to be tied into the role the cerebellum plays as a comparator for voluntary movement.

The limbic system includes structures of the cerebral cortex and diencephalon that are responsible for emotion and memory. The main structures are the cingulate gyrus, hippocampus and amygdala.

Review Questions

Q. What level of the brainstem is the major input to the cerebellum?

A. midbrain

B. pons

C. medulla

D. spinal cord

Answer

B

Q. Which region of the cerebellum receives proprioceptive input from the spinal cord?

A. vermis

B. left hemisphere

C. flocculonodular lobe

D. right hemisphere

Answer

A

Critical Thinking Questions

Q. Why do the anatomical inputs to the cerebellum suggest that it can compare motor commands and sensory feedback?

A. A copy of descending input from the cerebrum to the spinal cord, through the pons, and sensory feedback from the spinal cord and special senses like balance, through the medulla, both go to the cerebellum. It can therefore send output through the midbrain that will correct spinal cord control of skeletal muscle movements.

Glossary

amygdala
nucleus deep in the temporal lobe of the cerebrum that is related to memory and emotional behavior

anterior lobe
region of the cerebellum

arbor vitae
deep white matter of the cerebellum

cerebellar hemisphere
region of the cerebellum lateral to the vermis

cerebellar nuclei
regions of gray matter within the cerebellum

cerebellum
region of the adult brain connected primarily to the pons that developed from the metencephalon (along with the pons) and is largely responsible for comparing information from the cerebrum with sensory feedback from the periphery through the spinal cord

cerebral aqueduct
connection of the ventricular system between the third and fourth ventricles located in the midbrain

cerebral peduncle
segments of the descending motor pathway that make up the white matter of the ventral midbrain

cingulate gyrus
a medial gyrus of each cerebral hemisphere that partly surrounds the corpus callosum and is part of the limbic system

corpora quadrigemina
four colliculi, two inferior and two superior, that sit on the posterior surface of the midbrain

decussation of pyramids
location at which corticospinal tract fibers cross the midline and segregate into the anterior and lateral divisions of the pathway

epithalamus
region of the diencephalon containing the pineal gland

folia
gyri of the cerebellum

hippocampus
gray matter deep in the temporal lobe that is very important for long-term memory formation

hypothalamus
major region of the diencephalon that is responsible for coordinating autonomic and endocrine control of homeostasis

inferior cerebellar peduncle (ICP)
input to the cerebellum, largely from the inferior olive, that represents sensory feedback from the periphery

inferior colliculus
half of the midbrain tectum that is part of the brainstem auditory pathway

inferior olive
nucleus in the medulla that is involved in processing information related to motor control

interthalamic adhesion
connection within the thalamus

limbic system
structures at the edge (limit) of the boundary between the forebrain and hindbrain that are most associated with emotional behavior and memory formation

mammillary bodies
small round bodies, located in the diencephalon, that are part of the limbic system

medulla oblongata
continuation of the spinal cord, forming the most inferior part of the brainstem

midbrain
middle region of the adult brain that develops from the mesencephalon

middle cerebellar peduncle (MCP)
large, white-matter bridge from the pons that constitutes the major input to the cerebellar cortex

pineal gland
endocrine gland located in the epithalamus that secretes melatonin, which is important in regulating the sleep-wake cycle

pons
part of the brainstem that connects the thalamus and medulla

posterior lobe
region of the cerebellum

primary fissure
a fissure of the cerebellum that marks the boundary between the anterior lobe and the posterior lobe

proprioception
sense of position and movement of the body

pyramids
segment of the descending motor pathway that travels in the anterior position of the medulla

reticular activating system
diffuse region of gray matter throughout the brainstem that regulates sleep, wakefulness, and states of

consciousness

substantia nigra
nuclei within the basal nuclei; part of the motor pathway

subthalamic nucleus
small collection of neurons situated ventral to the thalamus

subthalamus
nucleus within the basal nuclei that is part of the indirect pathway

superior cerebellar peduncle (SCP)
white-matter tract representing output of the cerebellum to the red nucleus of the midbrain

superior colliculus
half of the midbrain tectum that is responsible for aligning visual, auditory, and somatosensory spatial perceptions

tectum
region of the midbrain, thought of as the roof of the cerebral aqueduct, which is subdivided into the inferior and superior colliculi

tegmentum
region of the midbrain, thought of as the floor of the cerebral aqueduct, which continues into the pons and medulla as the floor of the fourth ventricle

thalamic nuclei
collection of neurons within the thalamus

thalamus
major region of the diencephalon that is responsible for relaying information between the cerebrum and the hindbrain, spinal cord, and periphery

vermis
prominent ridge along the midline of the cerebellum that is referred to as the spinocerebellum

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12.5: Cranial Nerves

By the end of this section, you will be able to:

- Describe the structures found in the PNS
- Distinguish between somatic and autonomic structures, including the special peripheral structures of the enteric nervous system
- Name the twelve cranial nerves and explain the functions associated with each

The PNS is not as contained as the CNS because it is defined as everything that is not the CNS. Some peripheral structures are incorporated into the other organs of the body. In describing the anatomy of the PNS, it is necessary to describe the common structures, the nerves and the ganglia, as they are found in various parts of the body. Many of the neural structures that are incorporated into other organs are features of the digestive system; these structures are known as the enteric nervous system and are a special subset of the PNS.

Nerves

Bundles of axons in the PNS are referred to as nerves. These structures in the periphery are different than the central counterpart, called a tract. Nerves are composed of more than just nervous tissue. They have connective tissues invested in their structure, as well as blood vessels supplying the tissues with nourishment. The outer surface of a nerve is a surrounding layer of fibrous connective tissue called the **epineurium**. Within the nerve, axons are further bundled into **fascicles**, which are each surrounded by their own layer of fibrous connective tissue called **perineurium**. Finally, individual axons are surrounded by loose connective tissue called the **endoneurium** (Figure 12.5.1 and Figure 12.5.2). These three layers are similar to the connective tissue sheaths for muscles. Nerves are associated with the region of the CNS to which they are connected, either as cranial nerves connected to the brain or spinal nerves connected to the spinal cord.

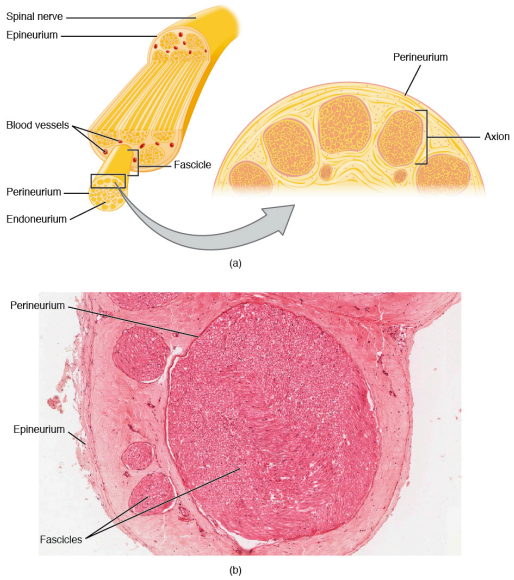

Figure 12.5.1: Nerve Structure. In (a), diagram of the organization of a nerve. The structure of a nerve is organized by the layers of connective tissue on the outside, around each fascicle, and surrounding the individual nerve fibers. In (b), micrograph of a nerve showing fascicles covered by perineurium, and the nerve covered by epineurium (tissue source: simian). LM x 40. (Image credit: "Nerve Structure" by OpenStax is licensed under CC BY 3.0/Micrograph provided by the Regents of University of Michigan Medical School 2012)

Figure 12.5.2: Close-Up of Nerve. Magnified micrograph of a nerve trunk where individual axons are visible as circular structures covered by endoneurium (tissue source: simian). Axons are bundled into a fascicle covered by perineurium. LM x 1600. (Image credit: "Nerve Mag" by OpenStax is licensed under CC BY 4.0/Micrograph provided by the Regents of University of Michigan Medical School 2012)

Interactive Link

Peripheral Nerve

View a virtual slide of a nerve in longitudinal section at the University of Michigan WebScope to explore the tissue sample in greater detail. With what structures in a skeletal muscle are the endoneurium, perineurium, and epineurium comparable?

Answer available at the end of this section.

Cranial Nerves

The nerves attached to the brain are the cranial nerves, which are primarily responsible for the sensory and motor functions of the head and neck (with the exception of one that targets organs in the thoracic and abdominal cavities as part of the parasympathetic nervous system). There are twelve cranial nerves, which are designated CNI through CNXII for “Cranial Nerve,” using Roman numerals for 1 through 12, based on the anatomical location on the inferior view of the brain, from anterior to posterior (Figure 12.5.3). They can be classified as sensory nerves, motor nerves, or a combination of both, meaning that the axons in these nerves originate out of sensory ganglia external to the cranium or motor nuclei within the brainstem. Sensory axons enter the brain to synapse in a nucleus. Motor axons connect to skeletal muscles of the head or neck. Three of the nerves are solely composed of sensory fibers; five are strictly motor; and the remaining four are mixed nerves.

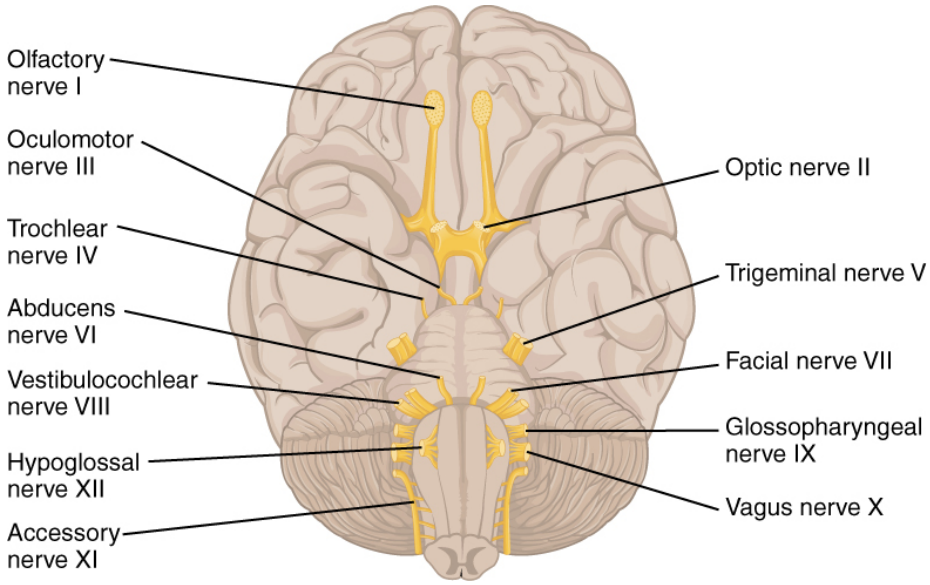

Figure 12.5.3: Cranial Nerves. The anatomical arrangement of the roots of the cranial nerves observed from an inferior view of the brain. Cranial nerves are numbered with Roman numbers from 1 to 12 based on their exit from the brain, from anterior to posterior. (Image credit: "The Cranial Nerves" by OpenStax is licensed under CC BY 4.0)

Learning the cranial nerves is a tradition in anatomy courses, and students have always used mnemonic devices to remember the nerve names. A traditional mnemonic is the rhyming couplet, “Oh Oh Oh To Touch And Feel Very Good Velvet Ah Heaven,” in which the initial letter of each word corresponds to the initial letter in the name of each nerve. The names of the nerves have changed over the years to reflect current usage and more accurate naming. An exercise to help learn this sort of information is to generate a mnemonic using words that have personal significance. The names of the cranial nerves are listed in Table 12.5.1 along with a brief description of their function, their source (sensory ganglion or motor nucleus), and their target (sensory nucleus or skeletal muscle). The **olfactory nerve** and **optic nerve** are responsible for the sense of smell and vision, respectively. The **oculomotor nerve** is responsible for eye movements by controlling four of the extraocular muscles. It is also responsible for lifting the upper eyelid when the eyes point up, and for pupillary constriction. The **trochlear nerve** and the **abducens nerve** are both responsible for eye movement, but do so by controlling different extraocular muscles. The **trigeminal nerve** is responsible for cutaneous sensations of the face and controlling the muscles of mastication. The **facial nerve** is responsible for the muscles involved in facial expressions, as well as part of the sense of taste and the production of saliva. The **vestibulocochlear nerve** is responsible for the senses of hearing and balance. The **glossopharyngeal nerve** is responsible for controlling muscles in the oral cavity and upper throat, as well as part of the sense of taste and the production of saliva. The **vagus nerve** is responsible for contributing to homeostatic control of the organs of the thoracic and upper abdominal cavities. The **accessory nerve** is responsible for controlling the muscles of the neck, along with cervical spinal nerves. The **hypoglossal nerve** is responsible for controlling the muscles of the lower throat and tongue.

Four of these cranial nerves make up the cranial component of the autonomic nervous system responsible for pupillary constriction (oculomotor nerve), salivation and lacrimation (facial and glossopharyngeal nerves), and the regulation of the organs of the thoracic and upper abdominal cavities (vagus nerve).

Three of the cranial nerves also contain autonomic fibers, and a fourth is almost purely a component of the autonomic system. The oculomotor, facial, and glossopharyngeal nerves contain fibers that contact autonomic ganglia. The oculomotor fibers initiate pupillary constriction, whereas the facial and glossopharyngeal fibers both initiate salivation. The vagus nerve primarily targets autonomic ganglia in the thoracic and upper abdominal cavities.

Another important aspect of the cranial nerves that lends itself to a mnemonic is the functional role each nerve plays. The nerves fall into one of three basic groups. They are sensory, motor, or both (see Table 12.5.1). The sentence, “Some Say Marry Money But My Brother Says Brains Beauty Matter More,” corresponds to the basic function of each nerve. The first, second, and eighth nerves are purely sensory: the olfactory (CNI), optic (CNII), and vestibulocochlear (CNVIII) nerves. The three eye-movement nerves are all motor: the oculomotor (CNIII), trochlear (CNIV), and abducens (CNVI). The accessory (CNXI) and hypoglossal (CNXII) nerves are also strictly motor. The remainder of the nerves contain both sensory and motor fibers. They are the trigeminal (CNV), facial (CNVII), glossopharyngeal (CNIX), and vagus (CNX) nerves. The nerves that convey both are often related to each other. The trigeminal and facial nerves both concern the face; one concerns the sensations and the other concerns the muscle movements. The facial and glossopharyngeal nerves are both responsible for conveying gustatory, or taste, sensations as well as controlling

salivary glands. The vagus nerve is involved in visceral responses to taste, namely the gag reflex. This is not an exhaustive list of what these combination nerves do, but there is a thread of relation between them.

Table 12.5.1: Cranial Nerves

Mnemonic	#	Name	Function (S/M/B)	Central connection (nuclei)	Peripheral connection (ganglion or muscle)
Oh	I	Olfactory	Smell (S)	Olfactory bulb	Olfactory epithelium
Oh	II	Optic	Vision (S)	Hypothalamus/thalamus/midbrain	Retina (retinal ganglion cells)
Oh	III	Oculomotor	Eye movements (M)	Oculomotor nucleus	Extraocular muscles (other 4), levator palpebrae superioris, ciliary ganglion (autonomic)
To	IV	Trochlear	Eye movements (M)	Trochlear nucleus	Superior oblique muscle
Touch	V	Trigeminal	Sensory/motor – face (B)	Trigeminal nuclei in the midbrain, pons, and medulla	Trigeminal
And	VI	Abducens	Eye movements (M)	Abducens nucleus	Lateral rectus muscle
Feel	VII	Facial	Motor – face, Taste (B)	Facial nucleus, solitary nucleus, superior salivatory nucleus	Facial muscles, Geniculate ganglion, Pterygopalatine ganglion (autonomic)
Very	VIII	Vestibulocochlear	Hearing/balance (S)	Cochlear nucleus, Vestibular nucleus/cerebellum	Spiral ganglion (hearing), Vestibular ganglion (balance)
Good	IX	Glossopharyngeal	Motor – throat Taste (B)	Solitary nucleus, inferior salivatory nucleus, nucleus ambiguus	Pharyngeal muscles, Geniculate ganglion, Otic ganglion (autonomic)
Velvet	X	Vagus	Motor/sensory – viscera (autonomic) (B)	Medulla	Terminal ganglia serving thoracic and upper abdominal organs (heart and small intestines)
Ah	XI	Accessory	Motor – head and neck (M)	Spinal accessory nucleus	Neck muscles
Heaven	XII	Hypoglossal	Motor – lower throat (M)	Hypoglossal nucleus	Muscles of the larynx and lower pharynx

Cranial Nerve Ganglia

A ganglion (ganglia for plural) is a group of neuron cell bodies in the peripheral nervous system. Ganglia can be categorized, for the most part, as either sensory ganglia or autonomic ganglia, referring to their primary functions. A type of sensory ganglion is a **cranial nerve ganglion**. The roots of cranial nerves are within the cranium, whereas the ganglia are outside the skull. For example, the **trigeminal ganglion** is superficial to the temporal bone whereas its associated nerve is attached to the mid-pons region of the brainstem. The neurons of cranial nerve ganglia are also unipolar in shape with associated satellite cells.

Interactive Link

Vision Loss

Read this article about a man who wakes with a headache and a loss of vision. His regular doctor sent him to an ophthalmologist to address the vision loss. The ophthalmologist recognizes a greater problem and immediately sends him to the emergency room. Once there, the patient undergoes a large battery of tests, but a definite cause cannot be found. A specialist recognizes the problem as meningitis, but the question is what caused it originally. How can that be cured? The loss of vision comes from swelling around the optic nerve, which probably presented as a bulge on the inside of the eye. Why is swelling related to meningitis going to push on the optic nerve?

Answer available at the end of this section.

AGING AND THE...

Nervous System: Anosmia

Anosmia is the loss of the sense of smell. It is often the result of the olfactory nerve being severed, usually because of blunt force trauma to the head. The sensory neurons of the olfactory epithelium have a limited lifespan of approximately one to four months, and new ones are made on a regular basis. The new neurons extend their axons into the CNS by growing along the existing fibers of the olfactory nerve. The ability of these neurons to be replaced is lost with age. Age-related anosmia is not the result of impact trauma to the head, but rather a slow loss of the sensory neurons with no new neurons born to replace them.

Smell is an important sense, especially for the enjoyment of food. There are only five tastes sensed by the tongue, and two of them are generally thought of as unpleasant tastes (sour and bitter). The rich sensory experience of food is the result of odor molecules associated with the food, both as food is moved into the mouth, and therefore passes under the nose, and when it is chewed and molecules are released to move up the pharynx into the posterior nasal cavity. Anosmia results in a loss of the enjoyment of food.

As the replacement of olfactory neurons declines with age, anosmia can set in. Without the sense of smell, many sufferers complain of food tasting bland. Often, the only way to enjoy food is to add seasoning that can be sensed on the tongue, which usually means adding table salt. The problem with this solution, however, is that this increases sodium intake, which can lead to cardiovascular problems through water retention and the associated increase in blood pressure.

Concept Review

The PNS is composed of the groups of neurons (ganglia) and bundles of axons (nerves) that are outside of the brain and spinal cord. Nerves are organized into structures by layers of connective tissue that cover them. The epineurium covers the nerve, the perineurium covers the fascicles and the endoneurium covers the individual axon.

Nerves are classified as cranial nerves or spinal nerves on the basis of their connection to the brain or spinal cord, respectively. The twelve cranial nerves can be strictly sensory in function, strictly motor in function, or a combination of the two functions. The olfactory nerve (CN I) and optic nerve (CN II) are responsible for the sense of smell and vision, respectively. The oculomotor nerve (CN III) is responsible for eye movements, lifting the upper eyelid and size of the pupil. The trochlear nerve (CN IV) and

the abducens nerve (CN VI) are both responsible for eye movement, but do so by controlling different extraocular muscles. The trigeminal nerve (CN V) is responsible for cutaneous sensations of the face and controlling the muscles of mastication. The facial nerve (VII) is responsible for the muscles involved in facial expressions, as well as part of the sense of taste and the production of saliva. The vestibulocochlear nerve (VIII) is responsible for the senses of hearing and balance. The glossopharyngeal nerve (IX) is responsible for controlling muscles in the oral cavity and upper throat, as well as part of the sense of taste and the production of saliva. The vagus nerve (CN X) is responsible for contributing to homeostatic control of the organs of the thoracic and upper abdominal cavities. The accessory nerve (CN XI) is responsible for controlling the muscles of the neck, along with cervical spinal nerves. The hypoglossal nerve (CN XII) is responsible for controlling the muscles of the lower throat and tongue.

Ganglia are of two types, sensory or autonomic. Sensory ganglia contain unipolar sensory neurons and are associated with many of the cranial nerves.

Review Questions

Q. What type of ganglion contains neurons that control homeostatic mechanisms of the body?

A. sensory ganglion

B. dorsal root ganglion

C. autonomic ganglion

D. ventral root ganglion

Answer

C

Q. Which ganglion is responsible for cutaneous sensations of the face?

A. otic ganglion

B. vestibular ganglion

C. geniculate ganglion

D. trigeminal ganglion

Answer

D

Q. What is the name for a bundle of axons within a nerve?

A. fascicle

B. tract

C. nerve root

D. epineurium

Answer

A

Q. Which cranial nerve does not control organs in the head and neck?

A. olfactory

B. trochlear

C. glossopharyngeal

D. vagus

Answer

D

Critical Thinking Questions

Q. Why are ganglia and nerves not surrounded by protective structures like the meninges of the CNS?

A. The peripheral nervous tissues are out in the body, sometimes part of other organ systems. There is not a privileged blood supply like there is to the brain and spinal cord, so peripheral nervous tissues do not need the same sort of protections.

Q. Testing for neurological function involves a series of tests of functions associated with the cranial nerves. What functions, and therefore which nerves, are being tested by asking a patient to follow the tip of a pen with their eyes?

A. The contraction of extraocular muscles is being tested, which is the function of the oculomotor, trochlear, and abducens nerves.

Glossary

abducens nerve
sixth cranial nerve; responsible for contraction of one of the extraocular muscles

accessory nerve
eleventh cranial nerve; responsible for contraction of neck muscles

cranial nerve
one of twelve nerves connected to the brain that are responsible for sensory or motor functions of the head and neck

cranial nerve ganglion
sensory ganglion of cranial nerves

endoneurium
innermost layer of connective tissue that surrounds individual axons within a nerve

epineurium
outermost layer of connective tissue that surrounds an entire nerve

facial nerve
seventh cranial nerve; responsible for contraction of the facial muscles and for part of the sense of taste, as well as causing saliva production

fascicle
small bundles of nerve or muscle fibers enclosed by connective tissue

glossopharyngeal nerve
ninth cranial nerve; responsible for contraction of muscles in the tongue and throat and for part of the sense of taste, as well as causing saliva production

hypoglossal nerve
twelfth cranial nerve; responsible for contraction of muscles of the tongue

oculomotor nerve
: third cranial nerve; responsible for contraction of four of the extraocular muscles, the muscle in the upper eyelid, and pupillary constriction

olfactory nerve
: first cranial nerve; responsible for the sense of smell

optic nerve
: second cranial nerve; responsible for visual sensation

perineurium
: layer of connective tissue surrounding fascicles within a nerve

trigeminal ganglion
: sensory ganglion that contributes sensory fibers to the trigeminal nerve

trigeminal nerve
: fifth cranial nerve; responsible for cutaneous sensation of the face and contraction of the muscles of mastication

trochlear nerve
: fourth cranial nerve; responsible for contraction of one of the extraocular muscles

vagus nerve
: tenth cranial nerve; responsible for the autonomic control of organs in the thoracic and upper abdominal cavities

vestibulocochlear nerve
: eighth cranial nerve; responsible for the sensations of hearing and balance

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Answers

Interactive Link

The endoneurium surrounding individual nerve fibers is comparable to the endomysium surrounding myofibrils, the perineurium bundling axons into fascicles is comparable to the perimysium bundling muscle fibers into fascicles, and the epineurium surrounding the whole nerve is comparable to the epimysium surrounding the muscle.

Interactive Link

The optic nerve enters the CNS in its projection from the eyes in the periphery, which means that it crosses through the meninges. Meningitis will include swelling of those protective layers of the CNS, resulting in pressure on the optic nerve, which can compromise vision.

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12.6: Spinal Cord and Spinal Nerves

By the end of this section, you will be able to:

- Describe the structures that protect and supply the spinal cord
- Describe the structures of the spinal cord and their functions
- Explain the arrangement of gray and white matter in the spinal cord
- Compare and contrast how white and gray matter process information
- Describe the sensory and motor components of spinal nerves and the plexuses that they pass through
- Explain what a dermatome is and its clinical significance

The spinal cord is continuous with the brain and transmits sensory information from the periphery of the body to the brain, and motor information from the brain to the periphery. It is also a center for coordination of reflexes, as well as control of reflexes independently from the brain. Along the spinal cord, spinal nerves emerge that carry both sensory and motor information.

Protective Coverings of the Spinal Cord

The spinal cord, as the brain, is protected by meninges, which are continuous with the cranial meninges. From outermost to innermost, the spinal meninges are: **dura mater**, **arachnoid mater** and **pia mater**. The spinal meninges are similar to the cranial ones, except for the dura mater. The spinal dura mater consists of a single layer of connective tissue, differing from the cranial dura mater. Moreover, at each intervertebral foramen, the dura mater extends and fuses with the connective tissue that covers spinal nerves.

One space between the spinal meninges also differs slightly from the ones present around the brain. The **epidural space** between the periosteum and dura mater is a real space around the spinal cord and houses areolar and adipose connective tissues, and blood vessels (shown in Figure 12.6.2). Epidural anesthesia is injected in this space. The subarachnoid space is filled with circulating CSF, which also provides a liquid cushion to the brain and spinal cord. Similar to clinical blood work, a sample of CSF can be withdrawn to find chemical evidence of neuropathology or metabolic traces of the biochemical functions of nervous tissue. Because the spinal cord does not extend through the lower lumbar region of the vertebral column, a needle can be inserted through the dura and arachnoid layers to withdraw CSF. This procedure is called a **lumbar puncture** and avoids the risk of damaging the central tissue of the spinal cord.

Blood Supply to the Spinal Cord

The spinal cord is supported by an extensive collateral supply and drainage of blood. Three longitudinal **spinal arteries** supply the anterior and posterior regions of the spinal cord. The anterior and posterior spinal arteries are connected by cross-connections of pia mater called the **arterial vasocorona** which encircles the cord and supplies the lateral portion of the spinal cord. The blood supply is reinforced by numerous arteries that pass through the intervertebral foramina and divide into anterior and posterior **radicular arteries** and have variable connections with the spinal arteries. Numerous veins and venous plexuses surround the spinal cord and drain the blood from it. These veins share the same names as the arteries that supply the spinal cord.

Spinal Cord

The description of the CNS is concentrated on the structures of the brain, but the spinal cord is another major organ of the system. The length of the spinal cord is divided into regions that correspond to the regions of the vertebral column. As shown in Figure 12.6.1, immediately inferior to the medulla oblongata is the **cervical region** of the spinal cord that contains motor neurons whose axons, together with sensory axons, extend into cervical spinal nerves. Inferior to the cervical region is the **thoracic region**, that contains neurons for the thoracic spinal nerves. The **lumbar region** is a short segment that contains neurons for the lumbar spinal nerves. Finally the **sacral region** contain neurons for the sacral nerves. The spinal cord is not the full length of the vertebral column because the spinal cord does not grow significantly longer after the first or second year, but the skeleton continues to grow. For this reason, the names of the spinal cord regions and vertebral regions to not match up. The lumbar and sacral spinal

cord segments are found between vertebral levels T9 and L2. The spinal cord ends around the L1/L2 vertebral level, forming a tapered structure known as the **conus medullaris**, which corresponds to the sacral spinal cord. The nerves that emerge from the spinal cord pass through the intervertebral foramina at the corresponding vertebral segments. For example, lumbar nerves exit the vertebral canal at the respective lumbar vertebrae. As the vertebral column grows, these nerves grow with it and result in a long bundle of nerves inferior to the conus medullaris that resembles a horse's tail and therefore is named the **cauda equina**. Within the cauda equina, there is a thin strand of pia mater called **filum terminale** that helps anchoring the conus medullaris to the coccyx. At each intervertebral foramen, the spinal dura mater extends between vertebrae and surrounds the spinal nerves.

The spinal cord has a diameter of approximately 3/4 of an inch (just less than 2 cm) and its length ranges between 16 to 18 inches (41-45 cm). However, its diameter changes between the different regions because the ratio of white and gray matter changes to reflect the functions of the different regions. The cervical and lumbar regions of the spinal cord show a larger diameter compared to the rest of the regions. The **cervical enlargement** and **lumbar enlargement** represent an increased amount of neurons in the gray matter and axons in the white matter that serve the upper limbs and lower limbs, respectively.

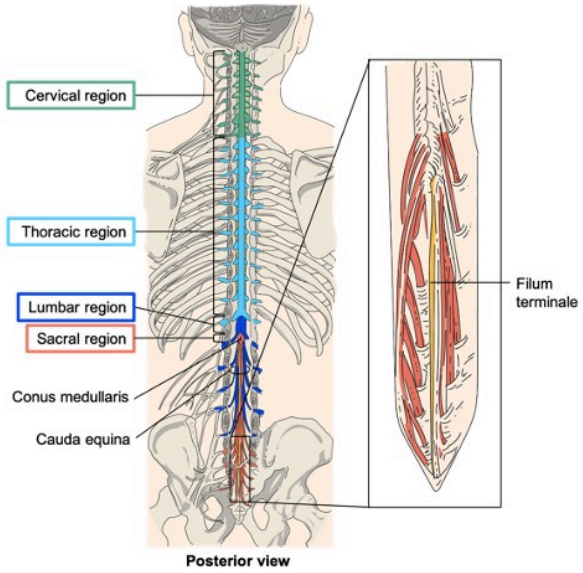

Figure 12.6.1: Gross Anatomy of the Spinal Cord. The spinal cord is divided into four regions: cervical, thoracic, lumbar and sacral. The sacral region has a tapered end called the conus medullaris. The bundle of axons inferior to the conus medullaris is the cauda equina. The cauda equina is anchored to the coccyx by the filum terminale, a thin strand of pia mater. (Image credit: "Spinal Cord" by Chiara Mazzasette is a derivative from the original work of Daniel Donnelly and is licensed by CC BY 4.0)

Whereas the brain develops out of expansions of the neural tube into primary and then secondary vesicles, the spinal cord maintains the tube structure and is only specialized into certain regions. As the spinal cord continues to develop in the newborn, anatomical features mark its surface. Viewed in cross section, the anterior midline is marked by the **anterior median fissure**, and the posterior midline is marked by the **posterior median sulcus**. As shown in Figure 12.6.2, axons coming from the **dorsal (posterior) root ganglion** enter the posterior side through the **dorsal (posterior) nerve root**, which marks the **posterolateral sulcus** on either side. The axons emerging from the anterior side do so through the **ventral (anterior) nerve root**. Note that it is common to see the terms dorsal (dorsal = "back") and ventral (ventral = "belly") used interchangeably with posterior and anterior, particularly in reference to nerves and the structures of the spinal cord. You should learn to be comfortable with both. The posterior and anterior nerve roots fuse together to form the **spinal nerves**. In the central region of the spinal cord, a **central canal** is the continuation of the fourth ventricle of the brain and contains cerebrospinal fluid (CSF).

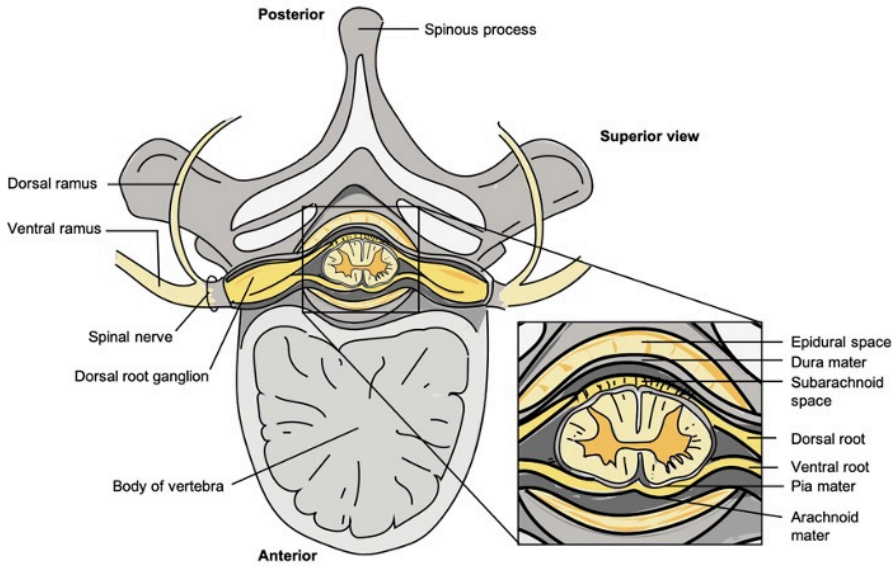

Figure 12.6.2: Spinal Cord within Vertebra. The superior view of a cross section of spinal cord within the vertebra shows the dorsal and ventral roots emerging from the spinal cord and fusing to form the spinal nerve. On the dorsal root, a dorsal root ganglion contain sensory neurons. The spinal cord is wrapped in meninges, as shown in the figure enlargement. (Image credit: "Spinal Cord within Vertebra" by Chiara Mazzasette is a derivative from the original work of Daniel Donnelly and is licensed by CC BY 4.0)

On the whole, the posterior regions are responsible for sensory functions and the anterior regions are associated with motor functions. This comes from the initial development of the spinal cord, which is divided into the basal plate and the alar plate. The basal plate is closest to the ventral midline of the neural tube, which will become the anterior face of the spinal cord and gives rise to motor neurons. The alar plate is on the dorsal side of the neural tube and gives rise to neurons that will receive sensory input from the periphery.

Gray Horns

In cross-section, the gray matter of the spinal cord has the appearance of an ink-blot test, with the spread of the gray matter on one side replicated on the other—a shape reminiscent of a bulbous capital “H.” As shown in Figure 12.6.3, the gray matter is subdivided into regions that are referred to as horns. The **posterior horn** is responsible for sensory processing and contain the axons of sensory neurons and the cell bodies of interneurons. The axons of sensory neurons are bundled into the posterior nerve root and are coming directly from the posterior root ganglion which contains cell bodies of sensory neurons. The **lateral horn**, which is only found in the thoracic, upper lumbar, and sacral regions, is a central component of the autonomic nervous system and contains cell bodies of autonomic motor neurons which innervate cardiac muscle, smooth muscle and glands.The **anterior horn** contains the cell bodies of somatic motor neurons that control skeletal muscles. The somatic motor neurons are the largest neurons of the body and are classified as multipolar neurons. The fibers that cause contraction of skeletal muscles are the axons of these neurons, which exit the spinal cord through the anterior nerve root. The posterior and anterior nerve roots fuse to form the spinal nerve, which contains mixed sensory and motor information.The motor neuron that causes contraction of the big toe, for example, is located in the sacral spinal cord. The axon that has to reach all the way to the belly of that muscle may be a meter in length. The neuronal cell body that maintains that long fiber must be quite large, possibly several hundred micrometers in diameter, making it one of the largest cells in the body. The neurons of the spinal cord are organized into functional groups called nuclei representing their respective functions (somatic sensory, visceral sensory, somatic motor and autonomic motor). Surrounding the central canal, a horizontal line of gray matter called the **gray commissure** connects the left and right sides of the spinal cord.

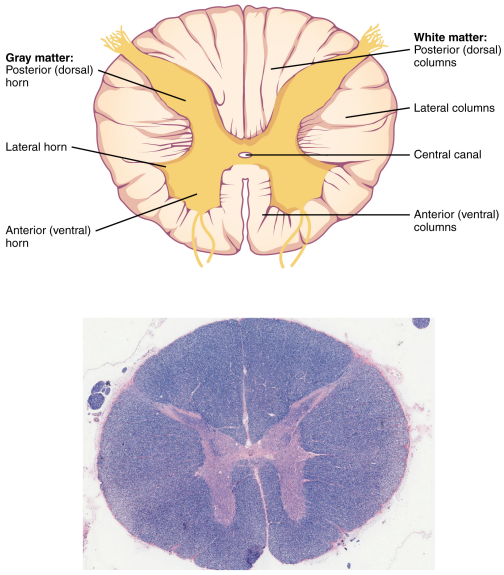

Figure 12.6.3: Cross-section of Spinal Cord. The cross-section of a thoracic spinal cord segment shows the posterior, anterior, and lateral horns of gray matter, as well as the posterior, anterior, and lateral columns of white matter. A micrograph shows the histology of the spinal cord. LM × 40. (Image credit: "Spinal Cord Cross Section" by OpenStax is licensed under CC BY 4.0/Micrograph provided by the Regents of University of Michigan Medical School © 2012)

White Columns

Just as the gray matter is separated into horns, the white matter of the spinal cord is separated into columns. **Ascending tracts** of nervous system fibers in these columns carry sensory information up to the brain, whereas **descending tracts** carry motor commands from the brain. Looking at the spinal cord longitudinally, the columns extend along its length as continuous bands of white matter. Between the two posterior horns of gray matter are the **posterior columns**. The posterior columns are composed of axons of ascending tracts. Between the two anterior horns, and bounded by the axons of motor neurons emerging from that gray matter area, are the **anterior columns**. The white matter on either side of the spinal cord, between the posterior horn and the axons of the anterior horn neurons, are the **lateral columns**. The anterior and lateral columns are composed of many different groups of axons of both ascending and descending tracts—the latter carrying motor commands down from the brain to the spinal cord to control output to the periphery. The anterior columns are connected by a bundle of axons called **white commissure** that crosses the central region of the spinal cord.

Dorsal Root Ganglion

A ganglion (ganglia for plural) is a group of neuron cell bodies in the peripheral nervous system. Ganglia can be categorized, for the most part, as either sensory ganglia or autonomic ganglia, referring to their primary functions. The most common type of sensory ganglion is a dorsal (posterior) root ganglion. These ganglia are the cell bodies of neurons with axons that are sensory endings in the periphery, such as in the skin, and that extend into the CNS through the dorsal nerve root. The ganglion is an enlargement of the nerve root. Under microscopic inspection, it can be seen to include the cell bodies of the neurons, as well as bundles of fibers that are the posterior nerve root (Figure 12.6.4). The cells of the dorsal root ganglion are unipolar cells. Also, the small round nuclei of satellite cells can be seen surrounding—as if they were orbiting—the neuron cell bodies (Figure 12.6.5).

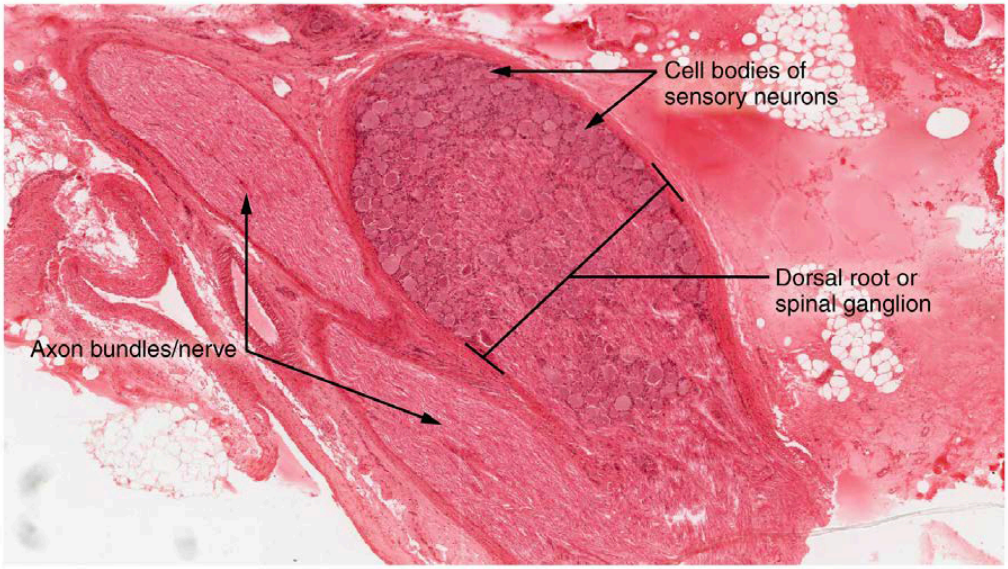

Figure 12.6.4: Dorsal Root Ganglion. The cell bodies of sensory neurons, which are unipolar neurons by shape, are seen in this micrograph. Also, the fibrous region is composed of the axons of these neurons that are passing through the ganglion to be part of the dorsal nerve root (tissue source: canine). LM x 40. (Image credit: "Dorsal Root Ganglion" by OpenStax is licensed under CC BY 4.0/Micrograph provided by the Regents of University of Michigan Medical School 2012)

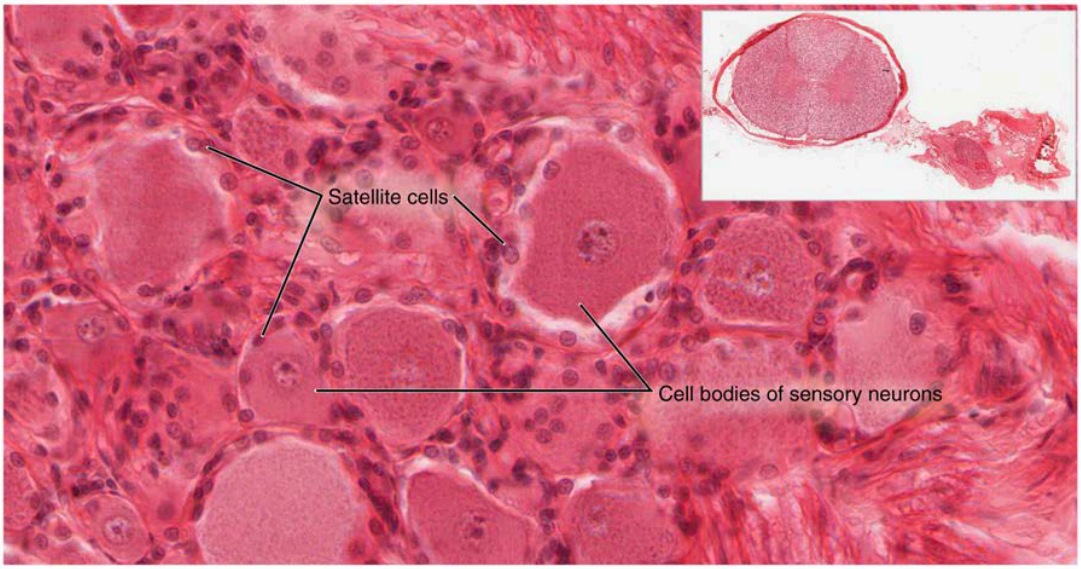

Figure 12.6.5: Close-Up of Dorsal Root Ganglion. The micrograph includes both a cross-section of the lumbar spinal cord and a magnified section of the dorsal root ganglion showing cell bodies of sensory neurons surrounded by satellite cells (tissue source: canine). LM x 1600. (Image credit: "DRG" by OpenStax is licensed under CC BY 4.0/Micrograph provided by the Regents of University of Michigan Medical School 2012)

Spinal Nerves

The nerves connected to the spinal cord are the spinal nerves. The arrangement of these nerves is much more regular than that of the cranial nerves. All of the spinal nerves are combined sensory and motor axons that separate into two nerve roots. The sensory axons enter the spinal cord as the dorsal nerve root. The motor fibers, both somatic and autonomic, emerge as the ventral nerve root.

There are 31 spinal nerves, named for the level of the spinal cord at which each one emerges. There are eight pairs of cervical nerves designated C1 to C8, twelve thoracic nerves designated T1 to T12, five pairs of lumbar nerves designated L1 to L5, five pairs of sacral nerves designated S1 to S5, and one pair of coccygeal nerves. The nerves are numbered from the superior to inferior positions, and each emerges from the vertebral column through the intervertebral foramen at its level. The first nerve, C1,

emerges between the first cervical vertebra and the occipital bone. The second nerve, C2, emerges between the first and second cervical vertebrae. The same occurs for C3 to C7, but C8 emerges between the seventh cervical vertebra and the first thoracic vertebra. For the thoracic and lumbar nerves, each one emerges between the vertebra that has the same designation and the next vertebra in the column. The sacral nerves emerge from the sacral foramina along the length of that unique vertebra.

Spinal nerves extend outward from the vertebral column to innervate the periphery. The nerves in the periphery are not straight continuations of the spinal nerves, but rather the reorganization of the axons in those nerves to follow different courses. Axons from different spinal nerves will come together into a **systemic nerve**. This occurs at four places along the length of the vertebral column, each identified as a **nerve plexus**, whereas the other spinal nerves directly correspond to nerves at their respective levels. In this instance, the word plexus is used to describe networks of nerve fibers with no associated cell bodies.

After exiting the intervertebral foramen, each spinal nerve splits into two branches called **rami** (ramus for singular) (Figure 12.6.6). On the posterior side, the **dorsal ramus** is a short nerve that innervates the deep muscle and skin of the back. On the anterior side, the **ventral ramus** splits into multiple branches that eventually can form nerve plexuses. The ventral ramus innervates the anterior and lateral portions of the trunk, the upper and the lower limbs. Spinal nerves are also associated with other branches called **rami communicantes** which are formed by the gray and white rami and connect the spinal nerve to the autonomic ganglia.

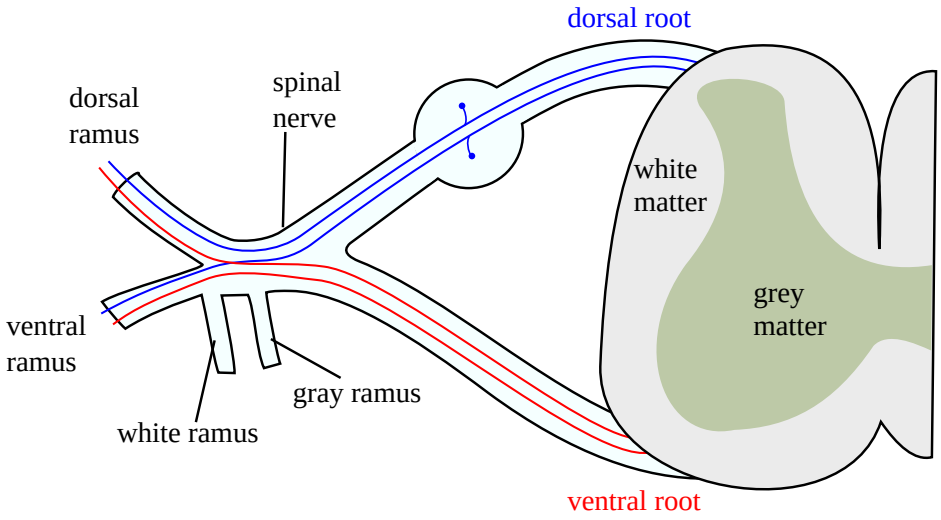

Figure 12.6.6: Spinal Nerve. The ventral and dorsal nerve roots exiting a cross section of spinal cord fuse together to form a spinal nerve, which then splits into the dorsal and ventral rami. The white and gray ramus form the rami communicantes that connect spinal nerves to autonomic ganglia. (Image credit: "Spinal Nerve" by Mysid and Tristanb is licensed under CC BY 4.0)

Of the four nerve plexuses, two are found at the cervical level, one at the lumbar level, and one at the sacral level (Figure 12.6.7). The **cervical plexus** is composed of axons from spinal nerves C1 through C5 and branches into nerves in the posterior neck and head, as well as the **phrenic nerve**, which connects to the diaphragm at the base of the thoracic cavity.

The other plexus from the cervical level is the **brachial plexus**. Spinal nerves C5 through T1 reorganize through this plexus to give rise to the nerves of the arms, as the name brachial suggests. The ventral rami of the brachial plexus rearrange to form the superior, middle and inferior **trunks**. At the clavicle, the trunks split into an **anterior division** and **posterior division**, which innervate the anterior and posterior parts of the upper limbs, respectively. At the axilla, the divisions converge to form the posterior, medial and lateral **cords**. Finally, the cords split into five **terminal branches**: the axillary, median, musculocutaneous, radial and ulnar nerves. The **axillary nerve** innervates the deltoid and teres minor muscles, and receives sensation from the superolateral side of the arm. The **median nerve** innervates the most anterior forearm muscles as well as muscles that move the thumb. It receives sensation from the palmar region and dorsal tips of the lateral 3 and a half digits. The **musculocutaneous nerve** innervate the anterior arm muscles and receives sensation from the lateral region of the forearm. The **radial nerve** innervates muscles and receives sensation from the posterior arm and forearm, including the dorsal region of the lateral three digits (not including their tips). The **ulnar nerve** innervates anterior forearm muscles as well as intrinsic hand muscles. It receives sensation from the dorsal and palmar regions of the medial one and a half digits.

The **lumbar plexus** arises from all the lumbar spinal nerves (L1 to L5) and gives rise to nerves innervating the pelvic region and the anterior leg. The **femoral nerve** is one of the major nerves from this plexus, which gives rise to the **saphenous nerve** as

a branch that extends through the anterior lower leg. The femoral nerve innervates anterior thigh muscles and receives sensory information from the anterior and medial aspects of the thigh.

The **sacral plexus** comes from the lower lumbar nerves L4 and L5 and the sacral nerves S1 to S4. The most significant systemic nerve to come from this plexus is the **sciatic nerve**, which is a combination of the **tibial nerve** and the **fibular nerve**. The sciatic nerve extends across the hip joint and is the largest and longest nerve of the body. Through the tibial and fibular nerves, the sciatic nerve innervates the muscles and receives sensation of the posterior thigh and lower leg. It is most commonly associated with the condition **sciatica**, which is the result of compression or irritation of the nerve or any of the spinal nerves giving rise to it.

Spinal nerves of the thoracic region, T2 through T11, are not part of the plexuses but rather emerge and give rise to the **intercostal nerves** found between the ribs, which articulate with the vertebrae surrounding the spinal nerve. The intercostal nerves innervate the intercostal muscles and receive sensation from the skin of the anterior and lateral sides of the thoracic region. The last nerves (T7 to T12) also innervate the abdominal muscles and their overlying skin.

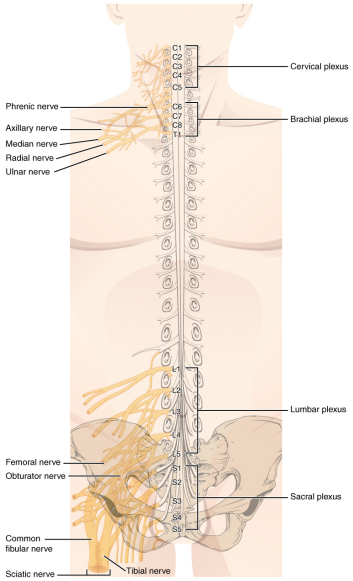

Figure 12.6.7: Nerve Plexuses of the Body. There are four main nerve plexuses in the human body. The cervical plexus supplies nerves to the posterior head and neck, as well as to the diaphragm. The brachial plexus supplies nerves to the arm. The lumbar plexus supplies nerves to the anterior leg. The sacral plexus supplies nerves to the posterior leg. (Image credit: "Spinal Nerve Plexuses" by OpenStax is licensed under CC BY 4.0)

Dermatomes

The spinal nerves, which contain sensory fibers with endings in the skin, connect with the skin in a topographically organized manner, illustrated as **dermatomes** (Figure 12.6.8). For example, the fibers of eighth cervical nerve innervate the medial surface of the forearm and extend out to the fingers. All spinal nerves except C1 innervates a region on the skin. Dermatomes are important in a clinical setting as they can help identify potential damage to spinal nerves. In a sensory exam, the dermatome of a specific area is tested for sensation (for example the stroking of a cotton ball) to evaluate the functioning of the spinal nerve connected to that dermatome. Dermatomes are also associated with referred visceral pain, as the spinal nerves innervated the regions of the skin also innervate internal organs. Pain from the internal organ can then be mistakenly referred to a dermatome. For example, myocardial infarction is perceived as referred pain in the chest, left shoulder and left arm. This is because the sensory fibers that innervate the cardiac tissue travel through the T1-T4 spinal nerves, which also innervate the medial and anterior side of the body.

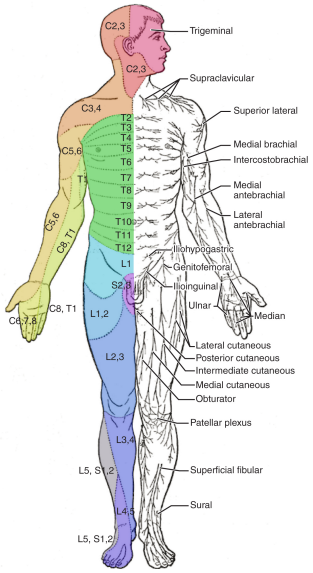

Figure 12.6.8: Dermatomes. The surface of the skin can be divided into topographic regions that relate to the location of sensory endings in the skin based on the spinal nerve that contains those fibers. (Image credit: "Spinal Nerve Plexuses" by OpenStax is licensed under CC BY 4.0/Modification of work by Mikael Häggström)

Concept Review

The spinal cord is covered and protected by the spinal meninges, similar to the cranial ones. However, the spinal dura mater presents only one layer of tissue. Moreover, the epidural space is a real space that houses areolar and adipose connective tissues, and blood vessels.

The spinal cord is divided into segments that take the same name as the vertebral regions. However, the sacral spinal cord ends at the vertebral lumbar level (L1/L2) with the conus medullaris, while the spinal nerves continue exiting at their respective region of the vertebral column. Inferior to the conus medullaris, the spinal nerves form a bundle called the cauda equina. The spinal cord presents two enlargements at the cervical and lumbar level.

In cross section, the gray matter is deep within the spinal cord and is separated into horns. The sensory axons coming from the posterior root ganglia enter the spinal cord through the posterior nerve root and synapse in the posterior horn, where interneurons are found. Autonomic motor neurons are found in the lateral horns, while somatic motor neurons are found in the anterior horns. Motor neurons send their axons out of the spinal cord through the anterior nerve root. The posterior and anterior root fuse to form the spinal nerve, which contains mixed sensory and motor information. The white matter is separated into columns which contain axons of sensory and motor neurons. The posterior columns contain ascending sensory tracts which are bundles of axons going towards the brain. The lateral and anterior column contain ascending sensory tracts as well as descending motor tracts, which carry the motor responses from the brain. Overall, the posterior regions of the spinal cord are responsible for ascending sensory information, while the anterior regions are responsible for descending motor information.

Spinal nerves are all mixed nerves with both sensory and motor fibers. Spinal nerves emerge from the spinal cord and reorganize through plexuses, which then give rise to systemic nerves. Thoracic spinal nerves are not part of any plexus, but give rise to the intercostal nerves directly.

Review Questions

Q. What region of the spinal cord contains motor neurons that direct the movement of skeletal muscles?

A. anterior horn

B. posterior horn

C. lateral horn

D. alar plate

Answer

A

Glossary

anterior column
white matter between the anterior horns of the spinal cord composed of many different groups of axons of both ascending and descending tracts

anterior division
anterior branches of the brachial plexus originating from the trunks

anterior horn
gray matter of the spinal cord containing multipolar motor neurons, sometimes referred to as the ventral horn

anterior median fissure
deep midline feature of the anterior spinal cord, marking the separation between the right and left sides of the cord

arachnoid mater
middle layer of the meninges named for the spider-web–like trabeculae that extend between it and the pia mater

arterial vasocorona
blood supply to the spinal cord formed by pial anastomoses between the anterior and posterior spinal arteries on the surface of the spinal cord

ascending tract
central nervous system fibers carrying sensory information from the spinal cord or periphery to the brain

axillary nerve
systemic nerve of the arm that arises from the brachial plexus

brachial plexus
nerve plexus associated with the lower cervical spinal nerves and first thoracic spinal nerve

cauda equina
bundle of spinal nerve roots that descend from the lower spinal cord below the first lumbar vertebra and lie within the vertebral cavity; has the appearance of a horse's tail

central canal
hollow space within the spinal cord that is the remnant of the center of the neural tube

cervical enlargement
region of the ventral (anterior) horn of the spinal cord that has a larger population of motor neurons for the greater number of and finer control of muscles of the upper limb

cervical plexus
nerve plexus associated with the upper cervical spinal nerves

cervical region
region of the spinal cord where cervical spinal nerves originate from

conus medullaris
tapered end of the spinal cord at the lumbar vertebral level, corresponding to the sacral region of the spinal cord

cord
branch of the brachial plexus originating from the divisions

dermatome
topographical area of skin in which sensory nerves end

descending tract
central nervous system fibers carrying motor commands from the brain to the spinal cord or periphery

dorsal (posterior) nerve root
axons entering the posterior horn of the spinal cord

dorsal ramus
dorsal branch of a spinal nerve that forms from the dorsal root of the nerve after it emerges from the spinal cord

dorsal root ganglion
cluster of cell bodies in the dorsal root of a spinal nerve containing sensory neurons

dura mater
tough, fibrous, outer layer of the meninges that is attached to the inner surface of the cranium and vertebral column and surrounds the entire CNS

epidural space
area between the dura mater and the above structures

femoral nerve
systemic nerve of the anterior leg that arises from the lumbar plexus

fibular nerve
systemic nerve of the posterior leg that begins as part of the sciatic nerve

filum terminale
thin strand of pia mater that helps anchoring the conus medullaris to the coccyx

gray commissure
horizontal line of gray matter that connects the left and right sides of the spinal cord

intercostal nerve
systemic nerve in the thoracic cavity that is found between two ribs

lateral column
white matter of the spinal cord between the posterior horn on one side and the axons from the anterior horn on the same side; composed of many different groups of axons, of both ascending and descending tracts, carrying motor commands to and from the brain

lateral horn
region of the spinal cord gray matter in the thoracic, upper lumbar, and sacral regions that is the central component of the autonomic nervous system

lumbar enlargement
region of the ventral (anterior) horn of the spinal cord that has a larger population of motor neurons for the greater number of muscles of the lower limb

lumbar plexus
nerve plexus associated with the lumbar spinal nerves

lumbar puncture
procedure of taking fluid from the spine in the lumbar vertebral region through a hollow needle

lumbar region
region of the spinal cord where lumbar spinal nerves originate from

median nerve
systemic nerve of the arm, located between the ulnar and radial nerves

musculocutaneous nerve
systemic nerve of the arm, located lateral to the other nerves of the brachial plexus

nerve plexus
network of nerves without neuronal cell bodies included

phrenic nerve
systemic nerve from the cervical plexus that innervates the diaphragm

pia mater
thin, innermost membrane of the meninges that directly covers the surface of the CNS

posterior columns
white matter of the spinal cord that lies between the posterior horns of the gray matter, sometimes referred to as the dorsal column; composed of axons of ascending tracts that carry sensory information up to the brain

posterior division
posterior branches of the brachial plexus originating from the trunks

posterior horn
gray matter region of the spinal cord in which sensory input arrives, sometimes referred to as the dorsal horn

posterior median sulcus
midline feature of the posterior spinal cord, marking the separation between right and left sides of the cord

posterolateral sulcus
feature of the posterior spinal cord marking the entry of posterior nerve roots and the separation between the posterior and lateral columns of the white matter

radial nerve
systemic nerve of the arm, the distal component of which is located near the radial bone

radicular arteries
blood supply to the spinal cord that runs along the posterior and anterior roots of the spinal nerves

ramus
branch of a spinal nerve

rami communicantes
structures that provide a short connection from an autonomic ganglion to the spinal nerve

sacral plexus
nerve plexus associated with the lower lumbar and sacral spinal nerves

sacral region
region of the spinal cord where sacral spinal nerves originate from

saphenous nerve
systemic nerve of the lower anterior leg that is a branch from the femoral nerve

sciatic nerve
systemic nerve from the sacral plexus that is a combination of the tibial and fibular nerves and extends across the hip joint and gluteal region into the upper posterior leg

sciatica
painful condition resulting from inflammation or compression of the sciatic nerve or any of the spinal nerves that contribute to it

spinal arteries
blood supply to the anterior and posterior regions of the spinal cord

spinal nerve
one of 31 nerves connected to the spinal cord

systemic nerve
nerve in the periphery distal to a nerve plexus or spinal nerve

terminal branch
branch of the brachial plexus originating from the cords

thoracic region
region of the spinal cord where intercostal nerves originate from

tibial nerve
systemic nerve of the posterior leg that begins as part of the sciatic nerve

trunk
branch of the brachial plexus originating from the spinal roots

ulnar nerve
systemic nerve of the arm located close to the ulna, a bone of the forearm

ventral (anterior) nerve root
axons emerging from the anterior or lateral horns of the spinal cord

ventral ramus
ventral branch of a spinal nerve that forms from the ventral root of the nerve after it emerges from the spinal cord

white commissure
bundle of myelinated axons that crosses the central region of the spinal cord

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13: SOMATIC SENSES, INTEGRATION AND MOTOR RESPONSES

The somatic nervous system (SNS) is the part of the peripheral nervous system responsible for our conscious perception of the environment through general and special senses as well as for our voluntary motor responses to that perception by means of skeletal muscles. In this chapter, you will look at the peripheral sensory structures that receive input from environmental stimuli, how the information is integrated in the CNS and at the motor neurons of the CNS that react to those stimuli sending motor responses to skeletal muscles.

13.1: Introduction to the Somatic Nervous System

13.2: Touch, Taste and Smell

13.3: Hearing, Balance and Vision

13.4: Integration of Somatic Functions

13.5: Somatic Motor Responses

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13.1: Introduction to the Somatic Nervous System

Chapter Learning Objectives

After studying this chapter, you will be able to:

- Describe the components of the somatic nervous system
- Describe the structures of general and special senses
- Describe regions of the central nervous system that contribute to somatic functions
- Explain the stimulus-response motor pathway
- Describe the components of a basic reflex arc and distinguish between different types of reflexes

The somatic nervous system includes all the afferent, sensory receptors from the skin, skeletal muscles, joints and special senses which are responsible for our conscious perception of the environment. It also includes the efferent, motor division which reaches the skeletal muscles and is responsible for our voluntary motor response. In contrast, the autonomic nervous system, which is discussed in the next chapter, includes afferent sensory receptors that are from visceral organs and are responsible for unconscious perception as well as an efferent motor division that reaches cardiac muscle, smooth muscle or glands for involuntary motor responses.

Our somatic senses make us aware of our surroundings or state of our body through peripheral sensory receptors. These receptors send sensory information through cranial and spinal nerves to the central nervous system. The neurons of the central nervous system need to process the information, a step called integration. Once processed, if a motor response is required, the neurons of the central nervous system will send a signal to skeletal muscles to move. Let's take the example of touching a hot stove (Figure 13.1.1). Sensory receptors in the skin sense extreme temperature and the early signs of tissue damage. This triggers an action potential (a change in electrical properties of a neuron), which travels along the sensory fiber from the skin through the dorsal spinal root to the spinal cord, and directly activates a ventral horn motor neuron. That neuron sends a signal along its axon to excite the biceps brachii, causing contraction of the muscle and flexion of the forearm at the elbow to withdraw the hand from the hot stove. The basic withdrawal reflex explained above includes afferent somatosensory input (the painful stimulus), central processing (the synapse in the spinal cord), and efferent motor output (activation of a ventral motor neuron that causes contraction of the biceps brachii).

In this chapter, we will examine all the components of the somatic nervous system. For the sensory input, we will look at sensory receptors of general and special senses and how the sensory information is sent to the CNS. Once the information is received in the appropriate region of the CNS, central processing takes place to integrate the various information. Lastly, the CNS will send a motor response to the periphery.

Figure 13.1.1: Too Hot to Touch. When high temperature is sensed in the skin, a withdrawal is initiated by the muscles of the arm. Sensory neurons are activated by a stimulus, which is sent to the central nervous system, and a motor response is sent out to the skeletal muscles that control this movement. (Image Credit: "Flame" by Steve Buissinne, Pixabay is in the Public Domain)

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13.2: Touch, Taste and Smell

By the end of this section, you will be able to:

- Describe the different types of sensory receptors
- Describe the somatosensory receptors
- Describe the gross and microscopic structures responsible for the special senses of taste and smell

A major role of sensory receptors is to help us learn about the environment around us, or about the state of our internal environment. Stimuli from varying sources, and of different types, are received and changed into the electrochemical signals of the nervous system. This occurs when a stimulus changes the cell membrane of a sensory neuron. The stimulus causes the sensory cell to produce an action potential that is relayed into the central nervous system (CNS), where it is integrated with other sensory information—or sometimes higher cognitive functions—to become a conscious perception of that stimulus. The central integration may then lead to a motor response.

Describing sensory function with the term sensation or perception is a deliberate distinction. Sensation is the activation of sensory receptor cells at the level of the stimulus. Perception is the central processing of sensory stimuli into a meaningful pattern. Perception is dependent on sensation, but not all sensations are perceived. Receptors are the cells or structures that detect sensations. A receptor cell is changed directly by a stimulus, such as opening of ion channels in the plasma membrane.

Sensory Receptors

Stimuli in the environment activate specialized receptor cells in the peripheral nervous system. Different types of stimuli are sensed by different types of receptor cells. Receptor cells can be classified into types on the basis of three different criteria: cell type, position, and function. Receptors can be classified structurally on the basis of cell type and their position in relation to stimuli they sense. They can also be classified functionally on the basis of the **transduction** of stimuli, or how the mechanical stimulus, light, or chemical changed the cell membrane electrical properties.

Structural Receptor Types

The first structural classification of sensory receptors is based on the cell type. The cells that interpret information about the environment can be either (1) a neuron that has a **free nerve ending**, with dendrites embedded in tissue that would receive a sensation; (2) a neuron that has an **encapsulated ending** in which the sensory nerve endings are covered in connective tissue that enhances their sensitivity; or (3) a specialized **receptor cell**, which has distinct structural components that interpret a specific type of stimulus (Figure 13.2.1). The pain and temperature receptors in the dermis of the skin are examples of neurons that have free nerve endings. Also located in the dermis of the skin are lamellated corpuscles, neurons with encapsulated nerve endings that respond to pressure and touch. The cells in the retina that respond to light stimuli are an example of a specialized receptor, a **photoreceptor**.

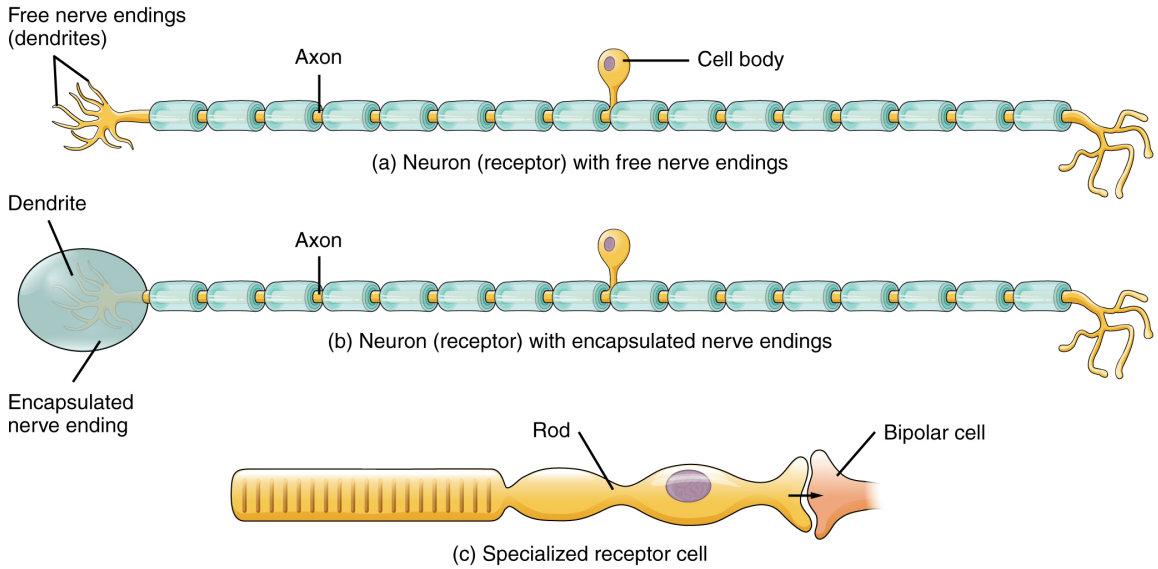

Figure 13.2.1: Receptor Classification by Cell Type. Sensory receptors can be classified on the basis of their structure. Sensory neurons can have either free nerve endings on their dendritic side such as in a or encapsulated endings where dendrites are covered by connective tissue such as in b. In c, photoreceptors in the eyes, such as rod cells depicted here, are examples of specialized receptor cells. These cells release neurotransmitters onto a bipolar cell, which then synapses with the optic nerve neurons. (Image Credit: "Receptor Types" by OpenStax is licensed under CC BY 4.0)

Another way that receptors can be classified is based on their location relative to the stimuli. An **exteroceptor** is a receptor that is located near a stimulus in the external environment, such as the somatosensory receptors that are located in the skin. An **interoceptor** is one that interprets stimuli from internal organs and tissues, such as the receptors that sense the increase in blood pressure in the aorta or carotid sinus. Finally, a **proprioceptor** is a receptor located near a moving part of the body, such as a muscle, that interprets the positions of the tissues as they move.

Functional Receptor Types

A third classification of receptors is by how the receptor transduces stimuli into electrical changes. Stimuli are of three general types. Some stimuli are ions and macromolecules that affect transmembrane receptor proteins when these chemicals diffuse across the cell membrane, for example the ones found in food. Some stimuli are physical variations in the environment that affect the electrical properties of the receptor cell membrane, for example touch. Other stimuli include the electromagnetic radiation from visible light. For humans, the only electromagnetic energy that is perceived by our eyes is visible light. Some other organisms have receptors that humans lack, such as the heat sensors of snakes, the ultraviolet light sensors of bees, or magnetic receptors in migratory birds.

Receptor cells can be further categorized on the basis of the type of stimuli they transduce. Chemical stimuli can be interpreted by a **chemoreceptor** that interprets chemical stimuli, such as an object's taste or smell. **Osmoreceptors** respond to solute concentrations of body fluids. Additionally, pain is primarily a chemical sense that interprets the presence of chemicals from tissue damage, or similar intense stimuli, through a **nociceptor**. Physical stimuli, such as pressure and vibration, as well as the sensation of sound and body position (balance), are interpreted through a **mechanoreceptor**. Another physical stimulus that has its own type of receptor is temperature, which is sensed through a **thermoreceptor** that is either sensitive to temperatures above (heat) or below (cold) normal body temperature.

Sensory Modalities

Ask anyone what the senses are, and they are likely to list the five major senses—taste, smell, touch, hearing, and sight. However, these are not all of the senses. The most obvious omission from this list is balance. Also, what is referred to simply as touch can be further subdivided into pressure, vibration, stretch, and hair-follicle position, on the basis of the type of mechanoreceptors that perceive these touch sensations. Other overlooked senses include temperature perception by thermoreceptors and pain perception by nociceptors.

Senses can be classified as either general or special. A **general sense** is one that is distributed throughout the body and

has receptor cells within the structures of other organs. Mechanoreceptors in the skin, muscles, or the walls of blood vessels are examples of this type. General senses often contribute to the sense of touch, as described above, or to **proprioception** (awareness of body position) and **kinesthesia** (awareness of body movement), or to a **visceral sense**, which is most important to autonomic functions. A **special sense** is one that has a specific organ devoted to it, namely the eye, inner ear, tongue, or nose.

Each of the senses is referred to as a **sensory modality**. Modality refers to the way that information is encoded, which is similar to the idea of transduction. The main sensory modalities can be described on the basis of how each is transduced. The chemical senses are taste and smell. The general sense that is usually referred to as touch includes chemical sensation in the form of nociception, or pain. Pressure, vibration, muscle stretch, and the movement of hair by an external stimulus, are all sensed by mechanoreceptors. Hearing and balance are also sensed by mechanoreceptors. Finally, vision involves the activation of photoreceptors.

Listing all the different sensory modalities, which can number as many as 17, involves separating the five major senses into more specific categories, or **submodalities**, of the larger sense. An individual sensory modality represents the sensation of a specific type of stimulus. For example, the general sense of touch, which is known as **somatosensation**, can be separated into light pressure, deep pressure, vibration, itch, pain, temperature, or hair movement.

Somatosensation (Touch)

Somatosensation is considered a general sense, as opposed to the special senses discussed in this section. Somatosensation is the group of sensory modalities that are associated with touch, proprioception, and interoception. These modalities include pressure, vibration, light touch, tickle, itch, temperature, pain, proprioception, and kinesthesia. This means that its receptors are not associated with a specialized organ, but are instead spread throughout the body in a variety of organs. Many of the somatosensory receptors are located in the skin, but receptors are also found in muscles, tendons, joint capsules, ligaments, and in the walls of visceral organs.

Two types of somatosensory signals that are transduced by free nerve endings are pain and temperature. These two modalities use thermoreceptors and nociceptors to transduce temperature and pain stimuli, respectively. Temperature receptors are stimulated when local temperatures differ from body temperature. Some thermoreceptors are sensitive to just cold and others to just heat. Nociception is the sensation of potentially damaging stimuli. Mechanical, chemical, or thermal stimuli beyond a set threshold will elicit painful sensations. Stressed or damaged tissues release chemicals that activate receptor proteins in the nociceptors.

If you drag your finger across a textured surface, the skin of your finger will vibrate. Such low frequency vibrations are sensed by mechanoreceptors called Merkel cells, also known as type I cutaneous mechanoreceptors. Merkel cells are located in the stratum basale of the epidermis. Deep pressure and vibration is transduced by lamellated (Pacinian) corpuscles, which are receptors with encapsulated endings found deep in the dermis, or subcutaneous tissue. Light touch is transduced by the encapsulated endings known as tactile (Meissner) corpuscles. Follicles are also wrapped in a plexus of nerve endings known as the hair follicle plexus. These nerve endings detect the movement of hair at the surface of the skin, such as when an insect may be walking along the skin. Stretching of the skin is transduced by stretch receptors known as bulbous corpuscles. Bulbous corpuscles are also known as Ruffini corpuscles, or type II cutaneous mechanoreceptors.

Other somatosensory receptors are found in the joints and muscles. Stretch receptors monitor the stretching of tendons, muscles, and the components of joints. For example, have you ever stretched your muscles before or after exercise and noticed that you can only stretch so far before your muscles spasm back to a less stretched state? This spasm is a reflex that is initiated by stretch receptors to avoid muscle tearing. Such stretch receptors can also prevent over-contraction of a muscle. In skeletal muscle tissue, these stretch receptors are called muscle spindles. Golgi tendon organs similarly transduce the stretch levels of tendons. Bulbous corpuscles are also present in joint capsules, where they measure stretch in the components of the skeletal system within the joint. The types of nerve endings, their locations, and the stimuli they transduce are presented in Table 13.2.1.

Table 13.2.1

Mechanoreceptors of Somatosensation		
Name	**Location(s)**	**Stimuli**
Free nerve endings	Dermis, cornea, tongue, joint capsules, visceral organs	Pain, temperature, mechanical deformation

Mechanoreceptors of Somatosensation		
Name	**Location(s)**	**Stimuli**
Mechanoreceptors or Merkel's discs	Epidermal–dermal junction, mucosal membranes	Low frequency vibration (5–15 Hz)
Bulbous (or Ruffini's) corpuscle	Dermis, joint capsules	Stretch
Tactile (or Meissner's) corpuscle	Papillary dermis, especially in the fingertips and lips	Light touch, vibrations below 50 Hz
Lamellated (or Pacinian) corpuscle	Deep dermis, subcutaneous tissue	Deep pressure, high-frequency vibration (around 250 Hz)
Hair follicle plexus	Wrapped around hair follicles in the dermis	Movement of hair
Muscle spindle	In line with skeletal muscle fibers	Muscle contraction and stretch
Tendon stretch (or Golgi tendon) organ	In line with tendons	Stretch of tendon

Gustation (Taste)

Only a few recognized submodalities exist within the sense of taste, or **gustation**. Until recently, only four tastes were recognized: sweet, salty, sour, and bitter. Research at the turn of the 20th century led to recognition of the fifth taste, umami, during the mid-1980s. **Umami** is a Japanese word that means “delicious taste,” and is often translated to mean savory. Very recent research has suggested that there may also be a sixth taste for fats, or lipids.

Gustation is the special sense associated with the tongue. The surface of the tongue, along with the rest of the oral cavity, is lined by a stratified squamous epithelium. Raised bumps called **papillae** (singular = papilla) contain the structures for gustatory transduction. There are four types of papillae, based on their appearance (Figure 13.2.2): circumvallate, foliate, filiform, and fungiform. Circumvallate papillae are the largest papillae on the tongue and are located towards the posterior surface of the tongue. They contain the majority of the taste buds. Foliate papillae are located on the posterolateral region of the tongue and they are mostly used during infancy and childhood. Filiform papillae are shaped like bristles and do not contain taste buds. They are important for detecting texture and manipulating food. Fungiform papillae are located on the tip and sides of the tongues and contain few taste buds. Within the structure of the papillae are **taste buds** which are recessed into a **taste pore** and are shaped like an onion. Taste buds contain a variety of cells. **Basal cells** are undifferentiated stem cells located near the base of the taste bud that undergo continuous regeneration to replace the other cells of the taste buds. **Transitional cells** are scattered throughout the taste buds and support the other cells. Specialized **gustatory receptor cells** have microvilli called **taste hairs** and can absorb the chemicals contained within foods that are ingested. These cells release neurotransmitters based on the amount of the chemical in the food. These cells are not neurons but they are in contact with the dendrites of sensory neurons.

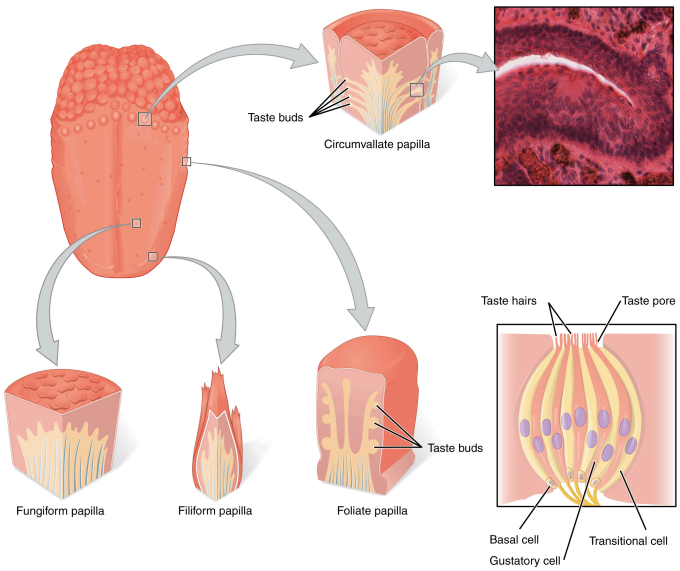

Figure 13.2.2: The Tongue. The tongue is covered with small bumps, called papillae, which contain taste buds that are sensitive to chemicals in ingested food or drink. Different types of papillae are found in different regions of the tongue. From anterior to posterior we find filiform papillae, fungiform papillae, foliate papillae, and circumvallate papillae. Taste buds within the papillae have a recessed taste pore and contain three types of cells: specialized gustatory receptor cells, basal cells and transitional cells. LM × 1600. (Image Credit: "The Tongue" by OpenStax is licensed under CC BY 4.0/Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Once the gustatory cells are activated by the taste molecules, they release neurotransmitters onto the dendrites of sensory neurons. These neurons are part of the facial (CN VII) and glossopharyngeal (CN IX) cranial nerves, as well as a component within the vagus nerve (CN X) dedicated to the gag reflex. The facial nerve connects to taste buds in the anterior third of the tongue. The glossopharyngeal nerve connects to taste buds in the posterior two thirds of the tongue. The vagus nerve connects to taste buds in the extreme posterior of the tongue, verging on the pharynx, which are more sensitive to noxious stimuli such as bitterness. Gustatory information is then transmitted through these cranial nerves to the brain, through the **thalamus**, which acts as a relay station, and finally into the **primary gustatory cortex** of the **insula**. It is here that this information is processed and perception is initiated.

Novel studies have shown that gustatory cells are not only present on the tongue but also in the guts. In humans, sweet, umami and bitter taste cells are also present in the intestines and used to "taste" the ingested food and regulate its variations.

Olfaction (Smell)

Like taste, the sense of smell, or **olfaction**, is also responsive to chemical stimuli. Inhaled air containing **odorant molecules** (smells) enters the nasal cavity and passes by the nasal conchae. The **olfactory receptor neurons (ORNs)** are located in a small region within the superior nasal cavity (Figure 13.2.3). This region is referred to as the **olfactory epithelium** and also contains **supporting cells** and **basal cells** (not shown), with similar functions as the homonyms in the taste buds. Each olfactory receptor neuron has dendrites that extend from the apical surface of the epithelium into the mucus lining the cavity. **Olfactory glands** within the basal lamina at the interface between the olfactory epithelium and the superior connective tissue produce the mucus that lines the olfactory epithelium, The olfactory sensory neurons present nonmotile cilia called **olfactory cilia** (or hairs) that contain the chemoreceptor for a specific odorant molecule. As airborne molecules are inhaled through the nose, they pass over the olfactory epithelial region and dissolve into the mucus. These odorant molecules bind to proteins that keep them dissolved in the mucus and help transport them to the olfactory dendrites. The odorant–protein complex binds to a receptor protein within the cell membrane of an olfactory dendrite, producing an electrical change in the olfactory neurons.

The axon of an olfactory neuron extends from the basal surface of the epithelium towards the cribriform plate of the ethmoid bone forming the **olfactory nerve (CN I)**. The olfactory fibers go through an olfactory foramen in the cribriform plate and converge to form spherical structures called **glomeruli** in the **olfactory bulb**, which resides on the ventral surface of the frontal lobe. Within the glomeruli, the olfactory receptor neurons synapse with mitral cells which in turn extend their axons to form the **olfactory tract**. From there, the axons split to travel to several brain regions. Some travel to the cerebrum, specifically to the **primary olfactory cortex** that is located in the inferior and medial areas of the temporal lobe. Others project to structures within the limbic system and hypothalamus, where smells become associated with long-term memory and emotional responses. This is how certain smells

trigger emotional memories, such as the smell of food associated with one's birthplace. Smell is the one sensory modality that does not synapse in the thalamus before connecting to the cerebral cortex. This intimate connection between the olfactory system and the cerebral cortex is one reason why smell can be a potent trigger of memories and emotion.

The olfactory system can recognize seven primary odors (musky, putrid, pungent, camphoraceous, ethereal, floral, pepperminty) as well as thousands of odorant molecules that produce various scents. The nasal epithelium, including the olfactory cells, can be harmed by airborne toxic chemicals. Therefore, the olfactory neurons are one of the few types of neurons that undergo mitosis and is able to replace old cells. Olfactory neurons are regularly replaced within the nasal epithelium, after which the axons of the new neurons must find their appropriate connections in the olfactory bulb. These new axons grow along the axons that are already in place in the cranial nerve.

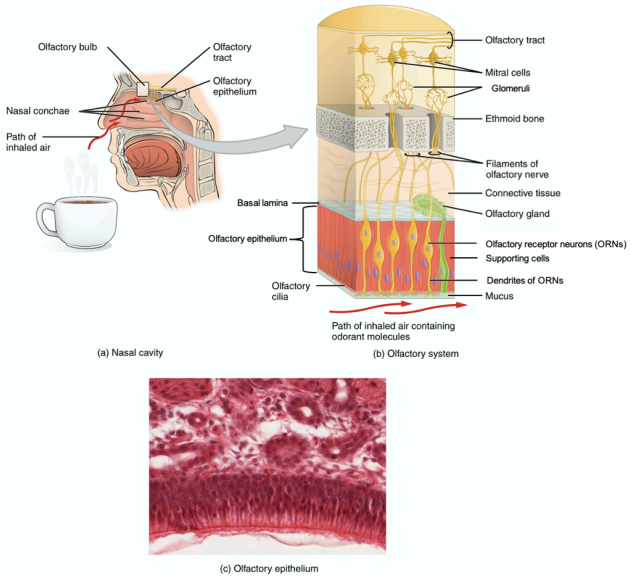

Figure 13.2.3: The Olfactory System. In (a), inhaled air passes by the nasal conchae to reach the olfactory epithelium in the superior nasal cavity. In (b), the olfactory epithelium is composed of olfactory receptor neurons and supporting cells. The dendrites of olfactory receptors neurons contain olfactory cilia that are embedded in the mucus lining the nasal cavity. The mucus is produced by olfactory glands located at the basal lamina. Axons of olfactory receptor neurons extend into the connective tissue and through the cribriform plate of the ethmoid bone, to synapse onto mitral cells in the glomeruli of the olfactory bulb. Axons of mitral cells extend towards the brain to form the olfactory tract. In (c), an histological slide (tissue source: simian) shows the olfactory epithelium. LM × 812. (Image Credit: "Olfactory System" by Chiara Mazzasette is licensed under CC BY 4.0 / A derivative from the original work)

DISORDERS OF THE...

Olfactory System: Anosmia

Blunt force trauma to the face, such as that common in many car accidents, can lead to the loss of the olfactory nerve, and subsequently, loss of the sense of smell. This condition is known as anosmia. When the frontal lobe of the brain moves relative to the ethmoid bone, the olfactory tract axons may be sheared apart. Professional fighters often experience anosmia because of repeated trauma to face and head. In addition, certain pharmaceuticals, such as antibiotics, can cause anosmia by killing all the olfactory neurons at once. If no axons are in place within the olfactory nerve, then the axons from newly formed olfactory neurons have no guide to lead them to their connections within the olfactory bulb. There are temporary causes of anosmia, as well, such as those caused by inflammatory responses related to respiratory infections or allergies.

Loss of the sense of smell can result in food tasting bland. A person with an impaired sense of smell may require additional spice and seasoning levels for food to be tasted. Anosmia may also be related to some presentations of mild depression, because the loss of enjoyment of food may lead to a general sense of despair.

The ability of olfactory neurons to replace themselves decreases with age, leading to age-related anosmia. This explains why some elderly people salt their food more than younger people do. However, this increased sodium intake can increase blood volume and blood pressure, increasing the risk of cardiovascular diseases in the elderly.

Concept Review

The cells that transduce sensory stimuli into the electrochemical signals of the nervous system are classified on the basis of structural or functional aspects of the cells. The structural classifications are either based on the anatomy of the cell that is interacting with the stimulus (free nerve endings, encapsulated endings, or specialized receptor cell), or where the cell is located relative to the stimulus (interoceptor, exteroceptor, proprioceptor). Thirdly, the functional classification is based on how the cell transduces the stimulus into a neural signal. Chemoreceptors respond to chemical stimuli and are the basis for olfaction and gustation. Related to chemoreceptors are osmoreceptors and nociceptors for fluid balance and pain reception, respectively. Mechanoreceptors respond to mechanical stimuli and are the basis for most aspects of somatosensation, as well as being the basis of audition and equilibrium in the inner ear. Thermoreceptors are sensitive to temperature changes, and photoreceptors are sensitive to light energy.

The senses are somatosensation (sensations associated with the skin and body), gustation (taste), olfaction (smell), audition (hearing), equilibrium (balance), and vision. With the exception of somatosensation, this list represents the special senses, or those systems of the body that are associated with specific organs such as the tongue or eye. The general senses can be divided into somatosensation, which is commonly considered touch, but includes tactile, pressure, vibration, temperature, and pain perception. The general senses also include the visceral senses, which are separate from the somatic nervous system function in that they do not normally rise to the level of conscious perception. The special senses are all primarily part of the somatic nervous system in that they are consciously perceived through cerebral processes, though some special senses contribute to autonomic function.

Somatosensation belongs to the general senses, which are those sensory structures that are distributed throughout the body and in the walls of various organs. Gustation and olfaction belong to the special senses. Gustation transduction is achieved by raised bumps on the tongue called papillae that contain taste buds, which in turn contain specialized gustatory receptor cells for chemical stimuli (”tastes”). Olfactory receptor neurons (unipolar) located in olfactory epithelium respond to chemical stimuli (“odorants”) of the nasal cavity. Their dendrites extend from the apical surface of the epithelium into the mucus lining the cavity and have receptors for odorants. Axons extend into the cribriform plate of the ethmoid bone to reach the olfactory bulb, forming the olfactory nerve (CN I). Once the olfactory nerve crosses the CNS, it becomes the olfactory tract and sends axons to several brain regions. The axons do not synapse onto the thalamus (unlike the other special senses).

Review Questions

Q. What type of receptor cell is responsible for transducing pain stimuli?

A. mechanoreceptor

B. nociceptor

C. osmoreceptor

D. photoreceptor

Answer

B

Q. Which of these cranial nerves is part of the gustatory system?

A. olfactory

B. trochlear

C. trigeminal

D. facial

Answer

D

Glossary

basal cell
undifferentiated stem cells located in the taste buds and olfactory epithelium

chemoreceptor
sensory receptor cell that is sensitive to chemical stimuli, such as in taste, smell, or pain

encapsulated ending
configuration of a sensory receptor neuron with dendrites surrounded by specialized structures to aid in transduction of a particular type of sensation, such as the lamellated corpuscles in the deep dermis and subcutaneous tissue

exteroceptor
sensory receptor that is positioned to interpret stimuli from the external environment, such as photoreceptors in the eye or somatosensory receptors in the skin

free nerve ending
configuration of a sensory receptor neuron with dendrites in the connective tissue of the organ, such as in the dermis of the skin, that are most often sensitive to chemical, thermal, and mechanical stimuli

general sense
any sensory system that is distributed throughout the body and incorporated into organs of multiple other systems, such as the walls of the digestive organs or the skin

glomeruli
spherical structures located in the olfactory bulb

gustation
sense of taste

gustatory receptor cells
sensory cells in the taste bud that transduce the chemical stimuli of gustation

insula
small region of the cerebral cortex located deep within the lateral sulcus

interoceptor
sensory receptor that is positioned to interpret stimuli from internal organs, such as stretch receptors in the wall of blood vessels

kinesthesia
sense of body movement based on sensations in skeletal muscles, tendons, joints, and the skin

mechanoreceptor
receptor cell that transduces mechanical stimuli into an electrochemical signal

nociceptor
receptor cell that senses pain stimuli

odorant molecules
volatile chemicals that bind to receptor proteins in olfactory neurons to stimulate the sense of smell

olfaction
sense of smell

olfactory bulb
central target of the first cranial nerve; located on the ventral surface of the frontal lobe in the cerebrum

olfactory cilia
hairlike structures arising from the dendrites of an olfactory receptor neuron

olfactory epithelium
region of the nasal epithelium where olfactory neurons are located

olfactory gland
gland of the olfactory epithelium that secretes mucus into the nasal cavity

olfactory nerve
first cranial nerve; responsible for the sense of smell

olfactory receptor neuron
receptor cell of the olfactory system, sensitive to the chemical stimuli of smell, the axons of which compose the first cranial nerve

olfactory tract
central bundle of axons deriving from the mitral cells of the olfactory bulb

osmoreceptor
receptor cell that senses differences in the concentrations of bodily fluids on the basis of osmotic pressure

papilla
for gustation, a bump-like projection on the surface of the tongue that contains taste buds

photoreceptor
receptor cell specialized to respond to light stimuli

primary gustatory cortex
region of the cerebral cortex within the insula responsible for the perception of taste

primary olfactory cortex
region of the cerebral cortex within the temporal lobe responsible for the perception of smell

proprioception
sense of position of the body in space based on sensations in skeletal muscles, tendons, joints, and the skin

proprioceptor
receptor cell that senses changes in the position and kinesthetic aspects of the body

receptor cell
cell that transduces environmental stimuli into neural signals

sensory modality
a particular system for interpreting and perceiving environmental stimuli by the nervous system

somatosensation
general sense associated with modalities lumped together as touch

special sense
any sensory system associated with a specific organ structure, namely smell, taste, sight, hearing, and balance

submodality
specific sense within a broader major sense such as sweet as a part of the sense of taste, or color as a part of vision

supporting cells
cells that support the olfactory receptor neurons

taste buds
structures within a papilla on the tongue that contain gustatory receptor cells

taste hairs
Hairlike projections of gustatory cells of taste buds

taste pore
opening of a taste bud

thalamus
major region of the diencephalon that is responsible for relaying information between the cerebrum and the hindbrain, spinal cord, and periphery

thermoreceptor
sensory receptor specialized for temperature stimuli

transduction
process of changing an environmental stimulus into the electrochemical signals of the nervous system

transitional cells
cells that support the gustatory receptor cells

umami
taste submodality for sensitivity to the concentration of amino acids; also called the savory sense

visceral sense
sense associated with the internal organs

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13.3: Hearing, Balance and Vision

By the end of this section, you will be able to:

- Describe the gross and microscopic structures responsible for the special senses of hearing, balance, and vision
- List the supporting structures around the eye and describe the lacrimal apparatus

Audition (Hearing)

Hearing, or **audition**, is the transduction of sound waves into a neural signal that is made possible by the structures of the ear (Figure 13.3.1). The large, fleshy structure on the lateral aspect of the head is known as the **auricle**. Some sources will also refer to this structure as the pinna, though that term is more appropriate for a structure that can be moved, such as the external ear of a cat. The C-shaped curves of the auricle direct sound waves toward the **auditory canal**, also called **ear canal**. The canal enters the skull through the external auditory meatus of the temporal bone. At the end of the auditory canal is the **tympanic membrane**, or ear drum, which vibrates after it is struck by sound waves. The auricle, ear canal, and tympanic membrane are often referred to as the **external ear**. The **middle ear** consists of a space spanned by three small bones called the **ossicles**. The three ossicles are the **malleus**, **incus**, and **stapes**, which are Latin names that roughly translate to hammer, anvil, and stirrup. The malleus is attached to the tympanic membrane and articulates with the incus. The incus, in turn, articulates with the stapes. The stapes is then attached to the **inner ear**, where the sound waves will be transduced into a neural signal. The middle ear is connected to the pharynx through the **Eustachian (or auditory) tube**, which helps equilibrate air pressure across the tympanic membrane. The tube is normally closed but will pop open when the muscles of the pharynx contract during swallowing or yawning. This helps to equalize the pressure on both sides of the ear drum with change in altitude, such as driving up the mountain or in a plane.

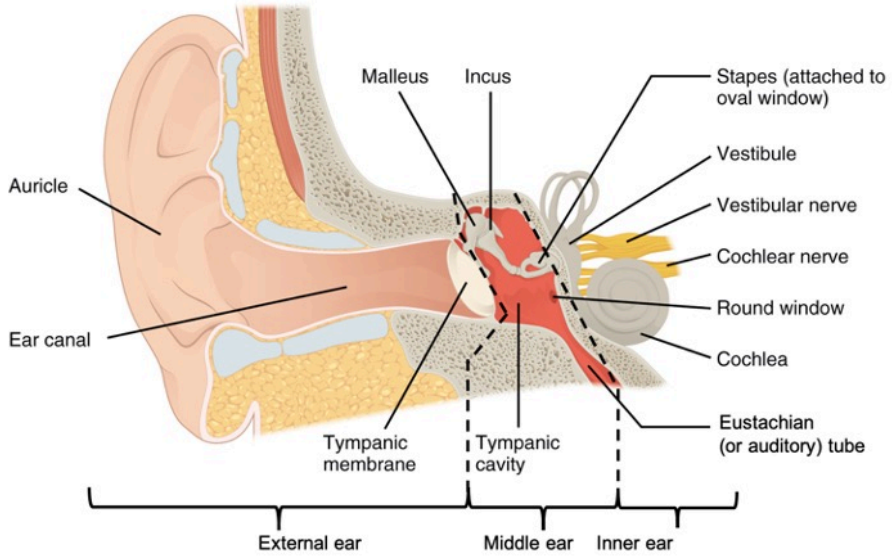

Figure 13.3.1: Structures of the Ear. The external ear contains the auricle, ear canal, and tympanic membrane. The middle ear contains the ossicles and is connected to the pharynx by the Eustachian (or auditory) tube. The inner ear contains the cochlea and vestibule, which are responsible for audition and equilibrium, respectively. (Image credit: "External, Middle and Inner Ear" by Chiara Mazzasette is licensed under CC BY 4.0 / A derivative from the original work)

The inner ear is often described as a **bony labyrinth**, as it is composed of a series of canals embedded within the temporal bone. Within the bony labyrinth are membranes that separate tubes and spaces filled with liquid. This is called the **membranous labyrinth**. The space between the bony labyrinth and membranous labyrinth is filled with a fluid called **perilymph** which is similar to extracellular fluid. Inside the membranous labyrinth there is **endolymph** which has a high potassium and low sodium concentration compared to the perilymph and consequently is conducive to nerve impulses. The inner ear has three separate regions, the **cochlea,** the **vestibule**, and the **semicircular canals**. The cochlea is responsible for hearing while the vestibule and semicircular canals are important for balance. The neural signals from these regions are relayed to the brainstem through

separate fiber bundles. called the **cochlear nerve** and the **vestibular nerve**. However, these two distinct bundles travel together from the inner ear to the brainstem as the **vestibulocochlear nerve (CN VIII)**.

Sound is transduced into neural signals within the cochlear region of the inner ear, which contains the sensory neurons of the **spiral ganglia**. These ganglia are located within the spiral-shaped cochlea of the inner ear. The cochlea is attached to the stapes through the **oval window**. The oval window is located at the beginning of a fluid-filled tube within the cochlea called the **scala vestibuli**. The scala vestibuli extends from the oval window, travelling above the **cochlear duct**, which is the central cavity of the cochlea that contains the sound-transducing neurons. At the uppermost tip of the cochlea, the scala vestibuli curves over the top of the cochlear duct. The fluid-filled tube, now called the **scala tympani**, returns to the base of the cochlea, this time travelling under the cochlear duct. The scala tympani ends at the **round window**, which is covered by a membrane that contains the fluid within the scala.

A cross-sectional view of the cochlea shows that the scala vestibuli and scala tympani run along both sides of the cochlear duct (Figure 13.3.2 and Figure 13.3.3). The cochlear duct contains several **organs of Corti**, which tranduce the wave motion of the two scala into neural signals. The organs of Corti lie on top of the **basilar membrane**, which is the side of the cochlear duct located between the organs of Corti and the scala tympani. Another membrane called the **vestibular membrane** separates the cochlear duct from the scala vestibuli.

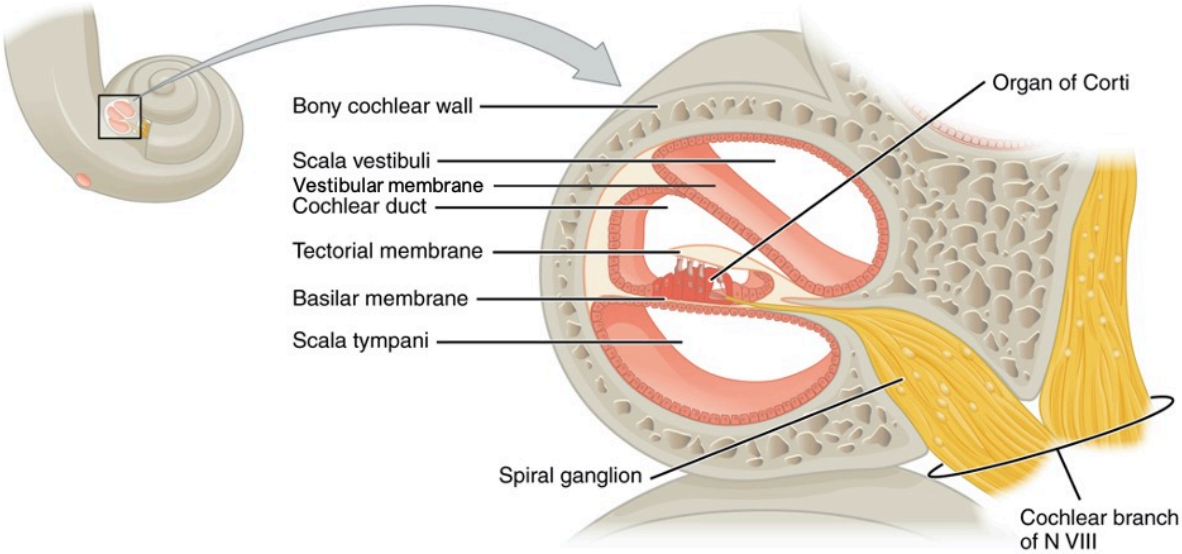

Figure 13.3.2: Cross Section of the Cochlea. The membranous labyrinth separates the cochlea in three major regions. The scala vestibuli and scala tympani lie on either side of the cochlear duct. The roof of the cochlear duct is formed by the vestibular memrbane while the base of it is formed by the basilar membrane. Within the cochlear duct, the organ of Corti sits atop the basilar membrane and its cells extend towards the tectorial membrane. (Image credit: "Cochlea" by Chiara Mazzasette is licensed under CC BY 4.0 / A derivative from the original work)

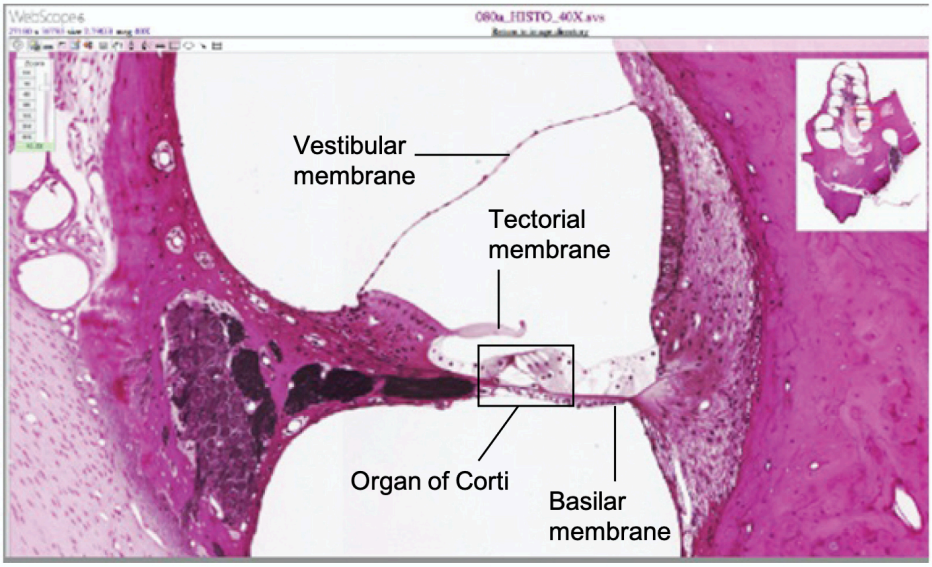

Figure 13.3.3: Histology of the Cochlea. The organ of Corti sits on the basilar membrane and extends towards the tectorial membrane. The vestibular membrane forms the roof of the cochlear duct. LM × 412. (Image credit: "Cochlea Micrograph Labeled" by Chiara Mazzasette is licensed under CC BY 4.0 / A derivative from the original work)

The organs of Corti contain **hair cells**, which are named for the hair-like **stereocilia** extending from the cell's apical surfaces (Figure 13.3.4). The stereocilia are an array of microvilli-like structures arranged from tallest to shortest. Protein fibers tether adjacent hairs together within each array, such that the array will bend in response to movements of the basilar membrane. The stereocilia extend up from the hair cells to the overlying **tectorial membrane**, which is attached medially to the organ of Corti.

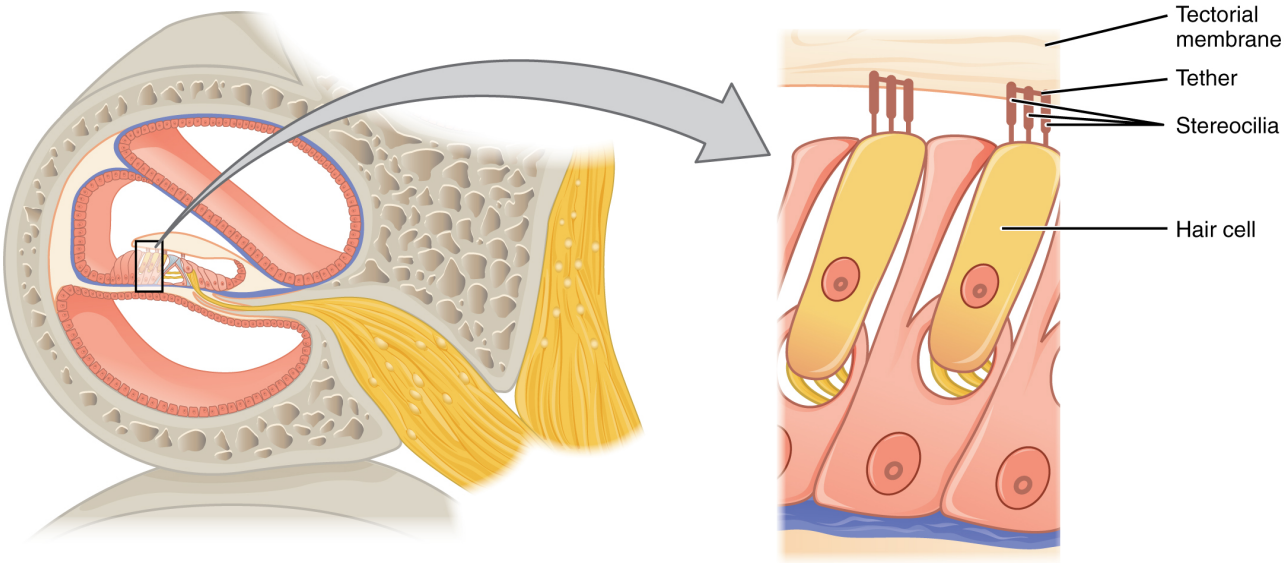

Figure 13.3.4: Hair Cells of the Organ of Corti. The hair cell is a mechanoreceptor with an array of stereocilia emerging from its apical surface. The stereocilia extend towards the tectorial membrane. The stereocilia are tethered together by proteins and bend in response to movements of the basilar membrane. (Image credit: "The Hair Cell" by OpenStax is licensed under CC BY 4.0)

The transmission and transduction of sound require the participation of the majority of the structures of the ear. Each sound wave has a specific frequency, which depends on its pitch, and amplitude, which depends on its loudness. Sound waves are funneled into the ear canal by the auricle and reach the tympanic membrane (Figure 13.3.5). The vibration of the tympanic membrane is amplified across the ossicles. As vibrations of the ossicles travel through the oval window, the fluid of the scala vestibuli and scala tympani moves in a wave-like motion. The frequency of the fluid waves match the frequencies of the sound waves. The membrane covering the round window will bulge out or pucker in with the movement of the fluid within the scala tympani. As the fluid waves move through the scala vestibuli and scala tympani, the basilar membrane moves at a specific spot of the cochlea, depending on the frequency of the waves. Higher frequency waves move the region of the basilar membrane that is close to the

base of the cochlea. Lower frequency waves move the region of the basilar membrane that is near the tip of the cochlea. When the fluid waves from the scala move the basilar membrane, the tectorial membrane slides across the stereocilia. This bends the stereocilia either toward or away from the tallest member of each array of stereocilia. When the stereocilia bend toward the tallest member of their array, tension in the protein tethers opens ion channels in the hair cell membrane. This will electrically change the hair cell membrane, triggering nerve impulses that travel down the afferent nerve fibers attached to the hair cells. When the stereocilia bend toward the shortest member of their array, the tension on the tethers slackens and the ion channels close. The relative movement of different arrays of stereocilia along the length of the basilar membrane allows the brain to perceive frequency, or pitch. The greater force of louder sounds causes an increase in the range of movement of the stereocilia of the hair cells, determining the loudness of a sound. The hair cells then transmit neural signals through the release of neurotransmitters to the **cochlear nerve** which travels within the **vestibulocochlear nerve (CN VIII)**. The nerve carries the auditory information into the brain, through the **thalamus**, and into the **primary auditory cortex** of the temporal lobe.

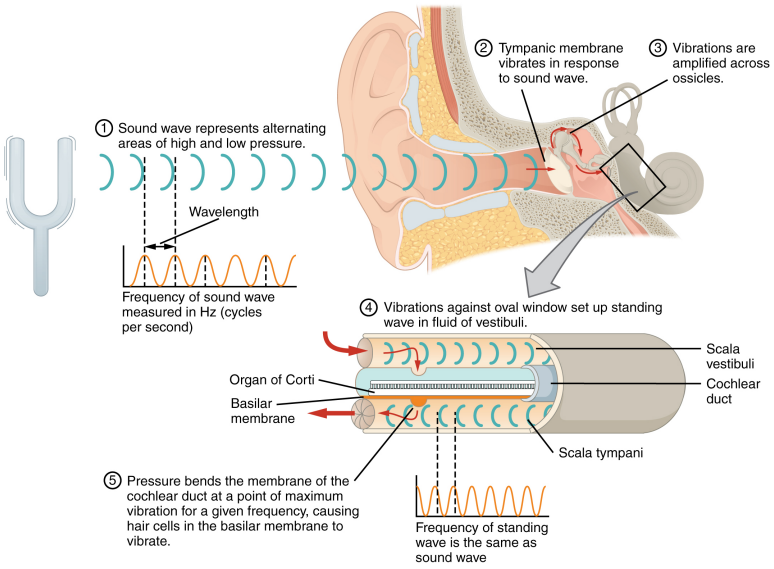

Figure 13.3.5: Transmission of Sound Waves to Cochlea. The transmission is represented in five steps. 1) Sound wave represents alternating areas of high and low pressure, whose frequency can be measured in Hz (cycles per second). 2) Tympanic membrane vibrates in response to sound wave. 3) Vibrations are amplified across the ossicles, in order malleus, incus, and stapes. 4) Vibrations against oval window set up standing wave in fluid of the scala vestibuli and scala tympani. The frequency of the standing wave is the same as the initial sound wave. 5) Pressure bends the membrane of the cochlear duct at a point of maximum vibration for a give frequency, causing hair cells of the Organ of Corti in the basilar membrane to vibrate. The complexity of the pressure waves is determined by the changes in amplitude and frequency of the sound waves entering the ear. (Image credit: "Sound Waves and the Ear" by OpenStax is licensed under CC BY 4.0)

Interactive Link

Cochlea

> View a histological slide of the cochlea at the University of Michigan WebScope to explore the tissue sample in greater detail. The basilar membrane is the thin membrane that extends from the central core of the cochlea to the edge. What is anchored to this membrane so that they can be activated by movement of the fluids within the cochlea?
>
> *Answer available at the end of this section.*

Equilibrium (Balance)

Along with audition, the inner ear is responsible for encoding information about **equilibrium**, the sense of balance. A similar mechanoreceptor—a hair cell with stereocilia—senses head position, head movement, and whether our bodies are in motion. These cells are located in the **vestibule** and **semicircular canals** within the inner ear. Vestibule and semicircular canals compose the **vestibular system**. The vestibule is the central part of the bony labyrinth, and is located posterior to the cochlea and anterior to the semicircular canals. Within the vestibule, the membranous labyrinth forms two chambers, the **utricle** and **saccule**, which contain endolymph. The utricle and saccule are interconnected by a narrow **endolymphatic duct** and their endolymph is confluent with that of the semicircular ducts and cochlear duct. Head position is sensed by the utricle and saccule, whereas head movement is sensed by the semicircular canals.

The utricle and saccule are both largely composed of **macula** tissue (plural = maculae). The macula is composed of hair cells surrounded by **supporting cells**. The stereocilia of the hair cells extend into a viscous gel called the **otolithic membrane** (Figure 13.3.6). On top of the otolithic membrane is a layer of calcium carbonate crystals, called **otoliths**. The otoliths essentially make the otolithic membrane top-heavy. The otolithic membrane moves separately from the macula in response to head movements. Tilting the head causes the otolithic membrane to slide over the macula in the direction of gravity. The moving otolithic membrane, in turn, bends the sterocilia, causing the hair cells to elicit electrical changes. The exact position of the head is interpreted by the brain based on the pattern of hair-cell activation.

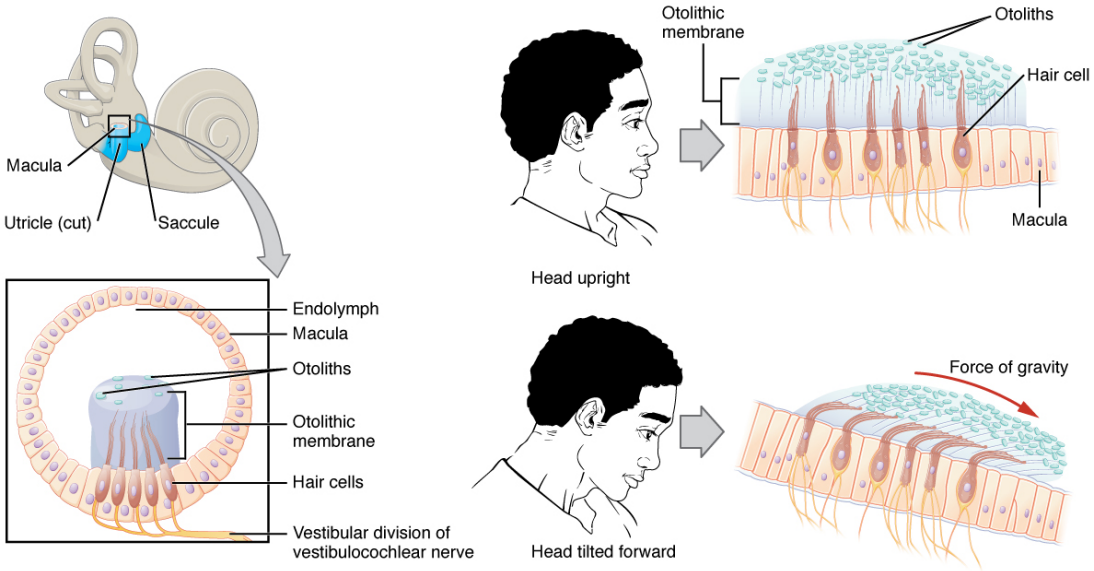

Figure 13.3.6: Linear Acceleration Coding by Maculae. The maculae within the utricle and saccule are specialized structures lined with supporting cells and hair cells and filled with endolymph. The hair cells have stereocilia that are embedded in a gel-like layer called the otolithic membrane for the presence of heavy crystals called otoliths. The maculae sense linear acceleration, such as when gravity acts on the tilting head, or if the head starts moving in a straight line. The difference in inertia between the hair cell stereocilia and the otolithic membrane in which they are embedded leads to a shearing force that causes the stereocilia to bend in the direction of that linear acceleration. (Image credit: "Maculae and Equilibrium" by OpenStax is licensed under CC BY 3.0)

The semicircular canals are three ring-like extensions of the vestibule. One is oriented in the horizontal plane, whereas the other two are oriented in the vertical plane. The anterior and posterior vertical canals are oriented at approximately 45 degrees relative to the sagittal plane (Figure 13.3.7). The base of each semicircular canal, where it meets with the vestibule, connects to an enlarged region known as the **ampulla**. The ampulla contains the hair cells that respond to rotational movement, such as turning the head while saying “no.” The stereocilia of these hair cells extend into the **cupula**, a gelatinous membrane that attaches to the top of the ampulla. As the head rotates in a plane parallel to the semicircular canal, the fluid lags, deflecting the cupula in

the direction opposite to the head movement. The semicircular canals contain several ampullae, with some oriented horizontally and others oriented vertically. By comparing the relative movements of both the horizontal and vertical ampullae, the vestibular system can detect the direction of most head movements within three-dimensional (3-D) space.

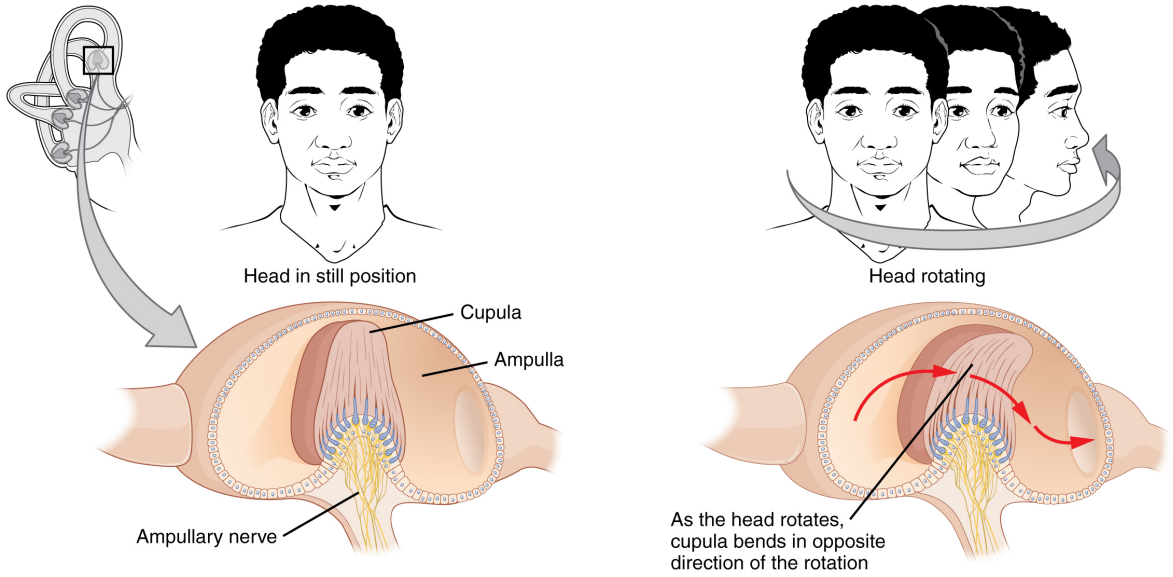

Figure 13.3.7: Rotational Coding by Semicircular Canals. Rotational movement of the head is encoded by the hair cells contained in ampullae at the base of the semicircular canals. The ampulla is filled with endolymph and contains hair cells that have stereocilia embedded in a gelatinous substance called the cupula. As one of the canals moves in an arc with the head, the endolymph moves in the opposite direction, causing the cupula and stereocilia to bend. The movement of two canals within a plane results in information about the direction in which the head is moving, and activation of all six canals can give a very precise indication of head movement in three dimensions. (Image credit: "Equilibrium and Semicircular Canals" by OpenStax is licensed under CC BY 3.0)

The neural signals generated in the vestibule and semicircular canals are transmitted through the **vestibular nerve** which travels within the **vestibulocochlear nerve (CN VIII)**. The nerve carries the equilibrium information into the brain, through the **thalamus**, and to **cerebral nuclei**, **brainstem** and **cerebellum**.

Vision

Vision is the special sense of sight that is based on the transduction of light stimuli received through the eyes. The eyes are located within either orbit in the skull. Supportive structures protect the eye, prevent objects from entering the eye, keep its surface lubricated and moist and provide superficial covering.

The bony orbits surround the eyeballs, protecting them and anchoring the soft tissues of the eye (Figure 13.3.8). The eyelids, with lashes at their leading edges, help to protect the eye from abrasions by blocking particles that may land on the surface of the eye. Each eyelid contains a thin covering of skin, a fibrous core and tarsal muscles and glands. The **tarsal muscles** is composed of smooth muscle innervated by the sympathetic nervous system and helps maintaining the elevation of the superior eyelid. The **tarsal glands** are sebaceous glands that produce an oily substance which prevents the eyelids from attaching together and prevents the overflow of tears from the open eye. The inner lid is a thin membrane known as the **palpebral conjunctiva**. The palpebral conjunctiva connects the eyelids to the eyeball. At the connection with the eyeball, a thin layer called the **ocular conjunctiva** forms a continuous layer on the external and anterior surface of the eye. The most anterior part of the eye is called the **cornea** and the ocular conjunctiva is absent here. Underneath the ocular conjunctiva lies a white layer called the **sclera**. The conjunctiva contains blood vessels and nerves that support the avascular sclera and detect foreign particles entering the eye. Bacteria and viruses can infect the conjunctiva, which then becomes red and swollen, as in pink eye (another name for pink eye is conjunctivitis).

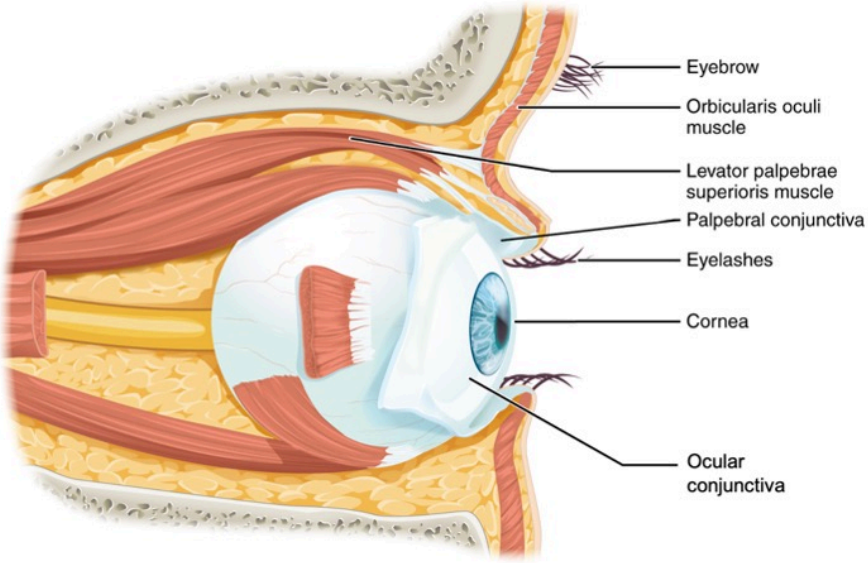

Figure 13.3.8: Protection and Support of the Eye. The eye is located within the orbit and surrounded by soft tissues such as muscles and the conjunctiva that protect and support its function. (Image credit: "Eye in the Orbit Labeled" by Chiara Mazzasette is licensed under CC BY 4.0 / A derivative from the original work)

The lacrimal apparatus associated with each eye is responsible for the production and drainage of lacrimal fluid (tears). The lacrimal fluid helps protect the eye by reducing friction of the eyelids, continuously cleaning the anterior surface of the eye, and preventing bacterial infection through the action of lysozyme. Tears are produced by the **lacrimal gland**, located within the superolateral depression of each orbit (Figure 13.3.9). Tears produced by this gland are dispersed on the external surface of the eye by the movement of the eyelids and then flow towards the medial surface of the eye. The **superior and inferior lacrimal puncta** (plural of "punctum") are small openings to drain the lacrimal fluid into channels called the **superior and inferior lacrimal canaliculi**. From there, the lacrimal fluid enters the **lacrimal sac** and drains into the **nasolacrimal duct** that delivers it into the nasal cavity where it mixes with the mucus.

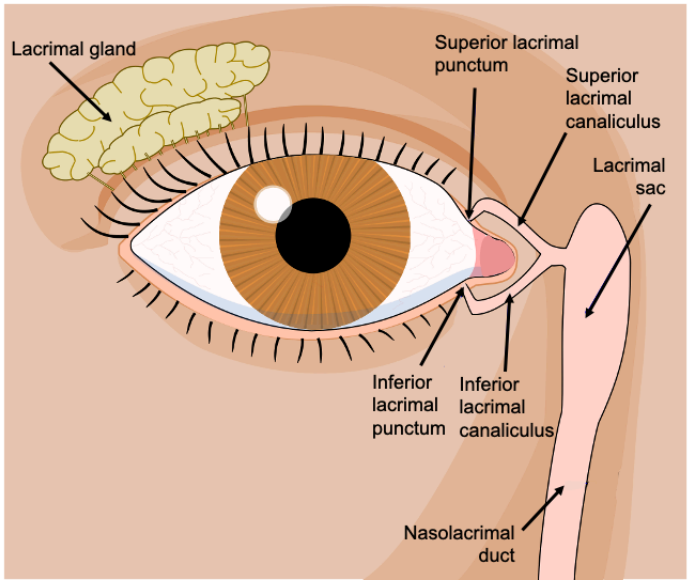

Figure 13.3.9: Lacrimal Apparatus. The lacrimal system produces lacrimal fluid that cleanses and moisturizes the anterior surface of the eye. Tears are produced by the lacrimal gland and dispersed on the external surface of the eye by the movement of the eyelids. The superior and inferior medial lacrimal puncta are small openings to drain the lacrimal fluid into channels called the superior and inferior lacrimal canaliculi. From there, the lacrimal fluid enters the lacrimal sac and drains into the nasolacrimal duct that delivers it into the nasal cavity where it mixes with the mucus. (Image credit: "Lacrimal Apparatus" by Chiara Mazzasette is licensed under CC BY-SA 4.0 / A derivative from the original work)

Movement of the eye within the orbit is accomplished by the contraction of six **extraocular muscles** that originate from the

bones of the orbit and insert into the surface of the eyeball (Figure 13.3.10). Four of the muscles are arranged at opposite sides of a cross around the eye and are named for those locations. They are the **superior rectus**, **medial rectus**, **inferior rectus**, and **lateral rectus** and originate at the **common tendinous ring**. When each of these muscles contract, the eye to moves toward the contracting muscle. For example, when the superior rectus contracts, the eye rotates to look up. The **superior oblique** originates at the posterior orbit, near the origin of the four rectus muscles. However, the tendon of the superior oblique muscles threads through a pulley-like piece of cartilage known as the **trochlea**. The tendon inserts obliquely into the superior surface of the eye. The angle of the tendon through the trochlea means that contraction of the superior oblique abducts, depresses, and internally rotates (intorsion) the eye. The **inferior oblique** muscle originates from the floor of the orbit and inserts into the inferolateral surface of the eye. When it contracts, it abducts, elevates, and externally rotates (extorsion) the eye. Rotation of the eye by the two oblique muscles is necessary because the eye is not perfectly aligned on the sagittal plane. When the eye looks up or down, the eye must also rotate slightly to compensate for the superior rectus pulling at approximately a 20-degree angle, rather than straight up. The same is true for the inferior rectus, which is compensated by contraction of the inferior oblique. A seventh muscle in the orbit is the **levator palpebrae superioris**, which is responsible for elevating and retracting the upper eyelid, a movement that usually occurs in concert with elevation of the eye by the superior rectus (see Figure 13.3.10).

The extraocular muscles are innervated by three cranial nerves. The lateral rectus, which causes abduction of the eye, is innervated by the **abducens nerve (CN VI)**. The superior oblique is innervated by the **trochlear nerve (CN IV)**. All of the other muscles are innervated by the **oculomotor nerve (CN III)**, as is the levator palpebrae superioris. The motor nuclei of these cranial nerves connect to the brainstem, which coordinates eye movements.

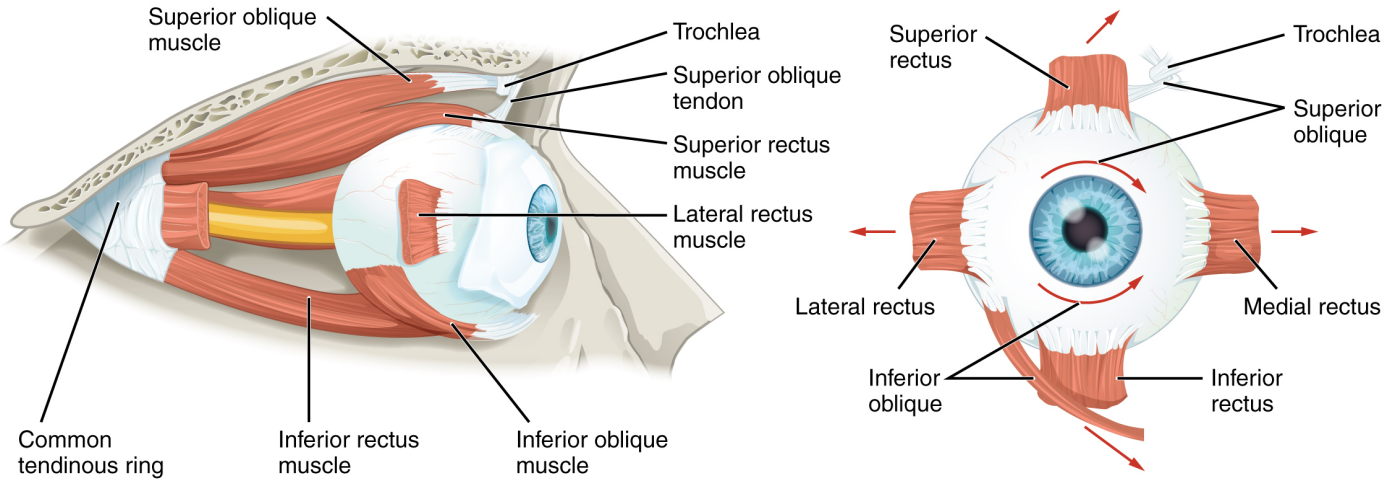

Figure 13.3.10: Extraocular Muscles. The extraocular muscles move the eye within the orbit. A lateral view of the right eye shows the common tendinous ring, where the four rectus muscles originate from. The superior oblique muscle originate from the posterior orbit and its tendon threads through the trochlea to insert into the superior surface of the eye. The inferior oblique muscle originate from the inferior portion of the orbit and inserts into the inferolateral surface of the eye. An anterior view of the right eye shows the movements of the extraocular muscles. (Image credit: "Extraocular Muscles" by OpenStax is licensed under CC BY 3.0)

The eye itself is a hollow sphere composed of three layers of tissue. The outermost layer is the **fibrous tunic**, which includes the white sclera posteriorly and clear cornea anteriorly. The sclera accounts for five sixths of the surface of the eye, most of which is not visible, though humans are unique compared with many other species in having so much of the “white of the eye” visible (Figure 13.3.11). The transparent cornea covers the anterior tip of the eye and allows light to enter the eye. The middle layer of the eye is the **vascular tunic**, which is mostly composed of the choroid, ciliary body, and iris. The **choroid** is a layer of highly vascularized connective tissue that provides a blood supply to the eyeball. The choroid is posterior to the **ciliary body**, a muscular structure that is attached to the **lens** by **suspensory ligaments**. These two structures pull the lens, allowing it to focus light on the back of the eye. Overlaying the ciliary body, and visible in the anterior eye, is the **iris**—the colored part of the eye. The innermost layer of the eye is the **neural tunic**, or **retina**, which contains the nervous tissue responsible for photoreception. The retina consists of two layers: a pigmented layer and a neural layer. The **pigmented layer** is a layer of pigmented cells that absorb light after it passes through the retina and provides vital metabolic support for the photoreceptors of the retina. The **neural layer** consists of photoreceptors and blood vessels that supply the neural layer.

The eye is also divided into two cavities: the **anterior cavity** and the **posterior cavity**. The anterior cavity is the space between the cornea and lens, including the iris and ciliary body. It can be further divided into **anterior and posterior chambers** by the

iris. These chambers are filled with a watery fluid called the **aqueous humor**. The posterior cavity is the space behind the lens that extends to the posterior side of the interior eyeball, where the retina is located. The posterior cavity is filled with a more viscous fluid called the **vitreous humor**. Aqueous humor is continually produced at the **ciliary processes** of the ciliary body. The aqueous humor passes through the pupil into the anterior chamber and drains into the **scleral venous sinus** at the edge of the cornea.

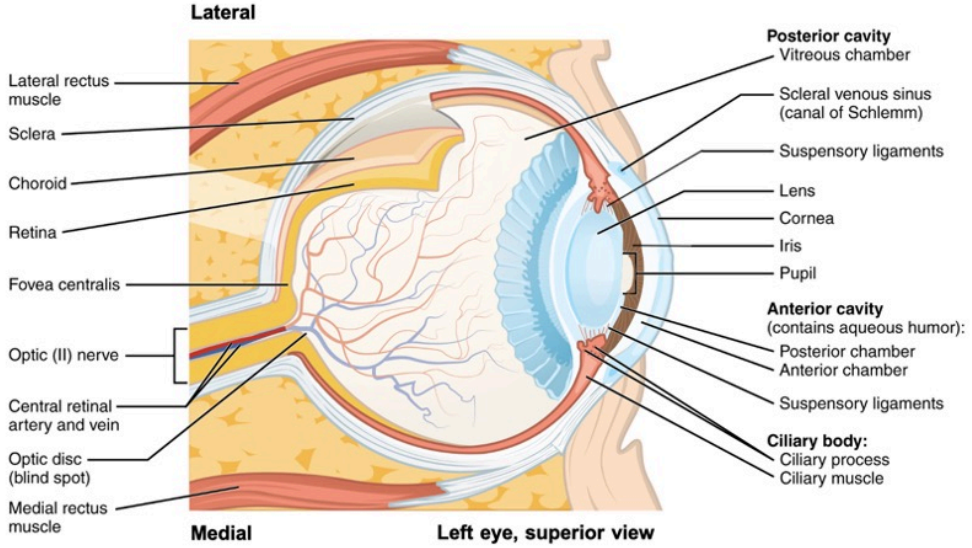

Figure 13.3.11: Structure of the Eye. A superior view of the left eye shows the tissues and chambers composing the eye. The sphere of the eye can be divided into anterior and posterior cavities. The anterior cavity is the space between the cornea and the lens. It contains aqueous humor and is divided in anterior and posterior chambers by the iris, which forms the pupil. The posterior cavity is the space posterior to the lens and is filled with vitreous humor. The wall of the eye is composed of three layers: the fibrous tunic, vascular tunic, and neural tunic. The fibrous tunic is composed of the sclera and cornea. The vascular tunic is composed of the choroid, ciliary body and iris. The neural tunic is composed of the pigmented and neural layers. (Image credit: "Structures of the Eye Labeled" by Chiara Mazzasette is licensed under CC BY 4.0 / A derivative from the original work)

The iris is composed of pigmented layers that give the eye its color and two layers of smooth muscle that opens or closes the **pupil**, which is the hole at the center of the eye that allows light to enter. The layers of smooth muscle are organized circularly into the **sphincter pupillae** and radially into the **dilator pupillae** (Figure 13.3.12). The sphincter pupillae constricts the pupil, while the dilator pupillae dilates the pupil. The iris constricts the pupil in response to bright light and dilates the pupil in response to dim light.

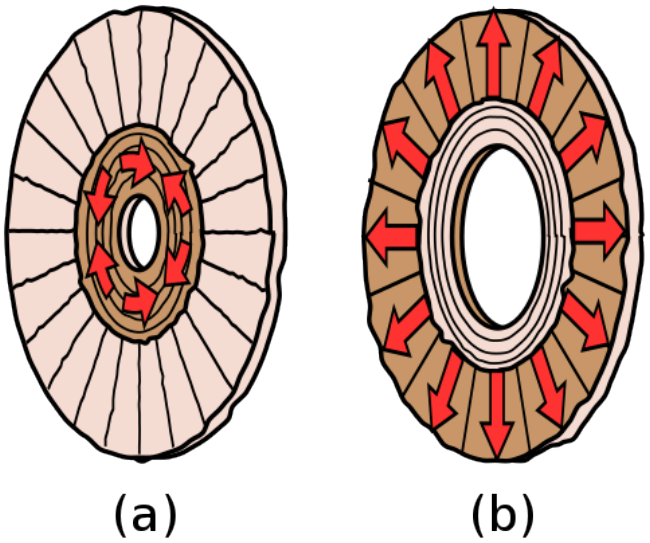

Figure 13.3.12: Iris muscles. Illustrations showing the two smooth muscle layers of the iris In (a), the sphincter pupillae is the inner circular muscular layer surrounding the pupil (hole in the center) and is responsible for constricting it. In (b), the dilator pupillae is the outer longitudinal muscular layer and is responsible for dilating the pupil. (Image credit: "Iris Muscles" by MikeRun is licensed under CC BY-SA 4.0)

The retina is composed of several layers and contains specialized cells for the initial processing of visual stimuli. The photoreceptors change their membrane electrical properties when stimulated by light energy. Light falling on the retina causes chemical changes to pigment molecules in the photoreceptors. There are two types of photoreceptors called rods and cones. **Cones** in human eyes are specialized in perceiving three different primary colors: red, green, and blue. **Rods** are sensitive to vision in low light conditions, for example in a darkened room. The change in electrical properties of these photoreceptors alters the amount of neurotransmitter that the photoreceptor cells release onto **bipolar cells** (see Figure 13.3.13). It is the bipolar cell in the retina that connects a photoreceptor to a **retinal ganglion cell (RGC)**. There, **amacrine cells** and **horizontal cells** additionally contribute to retinal processing before an action potential is produced by the RGC. The axons of RGCs, which lie at the innermost layer of the retina, collect at the **optic disc** and leave the eye as the **optic nerve**. Because these axons pass through the retina, there are no photoreceptors at the very back of the eye, where the optic nerve begins. This creates a "blind spot" in the retina, and a corresponding blind spot in our visual field. The visual information of the optic nerve will be transmitted through the **thalamus** and sent to the **primary visual cortex** of the occipital lobe.

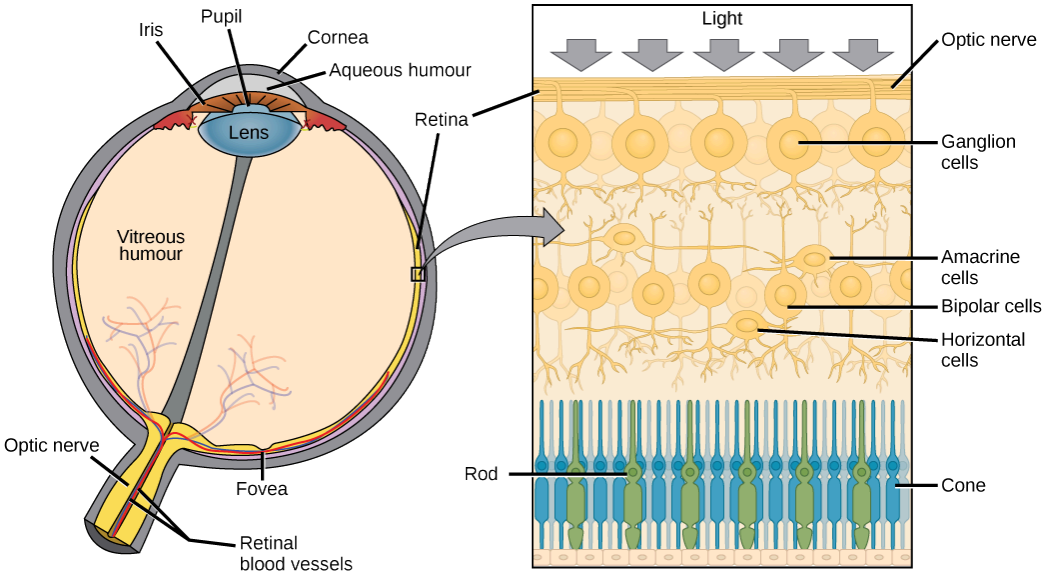

Figure 13.3.13: Retina. The retina is composed of several layers of cells that perceive changes in light and color. First, the light goes through the axons of ganglion cells that collect at the optic disc and leave the eye as the optic nerve. Ganglion cells synapse with bipolar cells. Amacrine and horizontal cells are scattered along the layer of bipolar cells. Bipolar cells synapse with the photoreceptors, composed of rods and cones. (Image credit: "Figure 36 05 02" by OpenStax is licensed under CC BY 4.0)

Note that the photoreceptors in the retina (rods and cones) are located behind the axons, RGCs, bipolar cells, and retinal blood vessels. A significant amount of light is absorbed by these structures before the light reaches the photoreceptor cells. However, at the exact center of the retina is a small region known as the **macula lutea** at which center there is a depression called the **fovea** (Figure 13.3.14). In these regions, the retina lacks the supporting cells and blood vessels, and only contains cones. Therefore, **visual acuity**, or the sharpness of vision, is greatest at the fovea. As one moves in either direction from this central point of the retina, visual acuity drops significantly. In addition, each photoreceptor cell of the fovea is connected to a single RGC. Therefore, this RGC does not have to integrate inputs from multiple photoreceptors, which reduces the accuracy of visual transduction. Toward the edges of the retina, several photoreceptors converge on RGCs (through the bipolar cells) up to a ratio of 50 to 1. The difference in visual acuity between the fovea and peripheral retina is easily evidenced by looking directly at a word in the middle of this paragraph. The visual stimulus in the middle of the field of view falls on the fovea and is in the sharpest focus. Without moving your eyes off that word, notice that words at the beginning or end of the paragraph are not in focus. The images in your peripheral vision are focused by the peripheral retina, and have vague, blurry edges and words that are not as clearly identified. As a result, a large part of the neural function of the eyes is concerned with moving the eyes and head so that important visual stimuli are centered on the fovea.

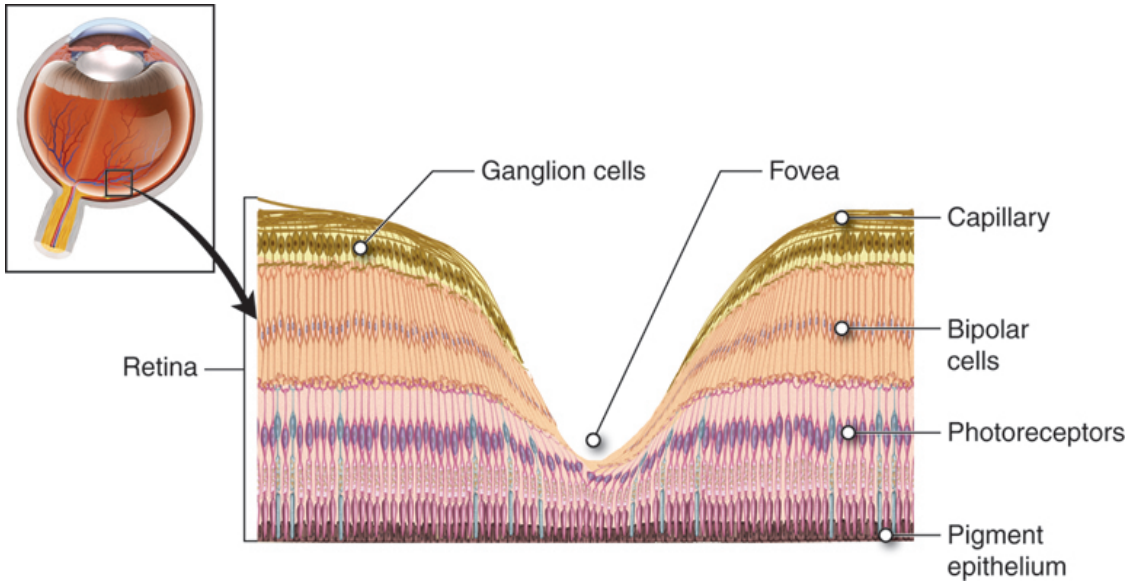

Figure 13.3.14: Fovea. At the exact center of the retina is a region called the macula lutea where there is a depression called fovea. At the fovea there are no blood vessels, ganglion cells or bipolar cells to interrupt light reaching the receptor cells and only cones are present. Because more light passes to the receptor cells at the fovea, it is in this region that visual acuity is the greatest. (Image credit: "Anatomy of the fovea - English labels" by Cenveo is licensed under CC BY 4.0)

Concept Review

Hearing and balance belong to the special senses and its specialized organ is the ear. The ear is divided in three regions: external, middle and inner ear. In the external ear, the auricle is the fleshy structure that convey sounds into the auditory canal. At the end of the canal is the tympanic membrane that vibrates and transforms sound waves into mechanical waves. The middle ear consists of a space spanned by three small bones called ossicles (malleus, incus, and stapes) that conduct the mechanical waves. The middle ear is connected to the pharynx through the Eustachian (or auditory) tube, which helps equilibrate air pressure across the tympanic membrane. The inner ear is made of a bony labyrinth lined with a membranous labyrinth that separate tubes and spaces. The space between the two labyrinths is filled with a fluid called perilymph. Inside the membranous labyrinth the space is filled with endolymph. The inner ear is responsible for transforming mechanical waves into electrical signals, which are then sent to the brain through the vestibulocochlear nerve (CN VIII).

The cochlea is a spiral-shaped tube, divided into three compartments: the scala vestibuli, scala tympani and cochlear duct. All compartments are filled with endolymph. The scala vestibuli starts at the oval window, curves over the top of the cochlear duct and becomes the scala tympani, that returns to the base of the cochlea, travelling under the cochlear duct and ends at the round window. As vibrations of the ossicles travel through the oval window, the fluid of the scala vestibuli and scala tympani moves in a wave-like motion. The cochlear duct contains several organs of Corti, which tranduce the wave motion of the two scala into neural signals. The organs of Corti lie on top of the basilar membrane, which is the side of the cochlear duct located between the organs of Corti and the scala tympani. The organs of Corti contain hair cells, which are named for the hair-like stereocilia

extending from the cell's apical surfaces. The stereocilia extend up from the hair cells to the overlying tectorial membrane, which is attached medially to the organ of Corti. When the pressure waves from the scala move the basilar membrane, the tectorial membrane slides across the stereocilia. This bends the stereocilia either toward or away from the tallest member of each array, which causes an electrical signal to be generated.

The vestibule and the semicircular canals are responsible for the sense of equilibrium. The vestibule is composed of the utricle and saccule. Hair cells are located in maculae of the utricle and saccule. The stereocilia of the hair cells extend into a viscous gel called the otolithic membrane, on top of which is a layer of calcium carbonate crystals, called otoliths. The vestibule senses the linear acceleration of the head and gravity. When the head moves, the otoliths move and the otolithic membrane bends the stereocilia of the hair cells. Hair cells are also located in ampullae at the base of the three semicircular canals. One is oriented in the horizontal plane, whereas the other two are oriented in the vertical plane. The stereocilia of these hair cells extend into the cupula, a membrane that attaches to the top of the ampulla. The semicircular canals sense the head rotation. As the head rotates in a plane parallel to the semicircular canal, the fluid lags, deflecting the cupula in the direction opposite to the head movement, and bending the stereocilia of the hair cells.

Vision belongs to the special senses and its specialized organ is the eye. The bony orbits, eyelids, tarsal glands and lacrimal apparatus protect the eyes. The inner eyelid is a thin membrane known as the palpebral conjunctiva. The conjunctiva connects the eyelids to the eyeball. At the connection with the eyeball, a thin layer called the ocular conjunctiva forms a continuous layer on the external and anterior surface of the eye (except for the corneal region), superior to the white part of the eye, the sclera. The conjunctiva contains blood vessels and nerves that support the avascular sclera and detect foreign particles entering the eye.

The lacrimal apparatus is responsible for the production and drainage of lacrimal fluid (tears). Tears reduce friction of the eyelids, continuously clean the anterior surface of the eye, and prevent bacterial infection through the action of lysozyme. Tears are produced by the lacrimal gland, located within the superolateral depression of each orbit. The superior and inferior lacrimal puncta are small openings to drain the lacrimal fluid into channels called the superior and inferior lacrimal canaliculi. From there, the lacrimal fluid enters the lacrimal sac and drains into the nasolacrimal duct that delivers it into the nasal cavity where it mixes with the mucus.

There are six extraocular muscles innervated by the abducens nerve (CN VI), trochlear nerve (CN IV) and oculomotor nerve (CN III). The superior rectus elevates the eye, the medial rectus adducts the eye, the inferior rectus depresses the eye, the lateral rectus abducts the eye. The superior oblique abducts, depresses, and internally rotates (intorsion) the eye. The inferior oblique abducts, elevates, and externally rotates (extorsion) the eye.

The eye walls are made by three layers of tissue called tunics. The fibrous tunic includes the white sclera and the clear cornea. The vascular tunic composed of the choroid, ciliary body attached to the lens by suspensory ligaments and iris (colored part of the eye). The iris is composed of pigmented layers and two layers of smooth muscle called the sphincter pupillae and dilator pupillae, that open and close the pupil. The neural tunic (or retina) includes a pigmented layer and a neural layer that contains the photoreceptors. The eye is divided in two cavities: the anterior cavity between the cornea and lens, filled with aqueous humor, and the posterior cavity behind the lens, filled with vitreous humor. The retina is composed of several layers of cells, connected to each other, that support vision transduction. The photoreceptors are rods for light vision and cones for color vision. Retinal ganglion cells (RGCs) have axons that collect at the optic disc and leave the eye as the optic nerve (CN II). At the exact center of the retina is a small area known as the macula lutea with a depression in the middle called the fovea. At the fovea, the retina lacks the supporting cells and blood vessels, and only contains cones. Therefore, visual acuity, or the sharpness of vision, is greatest at the fovea.

Review Questions

Q. Axons from which neuron in the retina make up the optic nerve?

A. amacrine cells

B. photoreceptors

C. bipolar cells

D. retinal ganglion cells

Answer

D

Q. What type of receptor cell is involved in the sensations of sound and balance?

A. photoreceptor

B. chemoreceptor

C. mechanoreceptor

D. nociceptor

Answer

C

Glossary

abducens nerve
sixth cranial nerve; responsible for contraction of one of the extraocular muscles

amacrine cell
type of cell in the retina that connects to the bipolar cells near the outer synaptic layer and provides the basis for early image processing within the retina

ampulla
in the ear, the structure at the base of a semicircular canal that contains the hair cells and cupula for transduction of rotational movement of the head

anterior cavity
space of the eye between the cornea and the lens

anterior chamber
space within the anterior cavity of the eye that is anterior to the iris

aqueous humor
watery fluid that fills the anterior chamber containing the cornea, iris, ciliary body, and lens of the eye

audition
sense of hearing

auditory canal
passageway of the external ear that leads to the tympanic membrane; also known as ear canal

auditory tube
tube that connects the nasopharynx to the middle ear; also known as Eustachian tube

auricle
fleshy external structure of the ear

basilar membrane
in the ear, the floor of the cochlear duct on which the organ of Corti sits

bipolar cell
cell type in the retina that connects the photoreceptors to the RGCs

bony labyrinth
complex cavities in the inner ear made by bones

brainstem
region of the adult brain that includes the midbrain, pons, and medulla oblongata and develops from the mesencephalon, metencephalon, and myelencephalon of the embryonic brain

cerebellum
region of the adult brain connected primarily to the pons that developed from the metencephalon (along with the pons) and is largely responsible for comparing information from the cerebrum with sensory feedback from the periphery through the spinal cord

cerebral nuclei
deep gray matter of the cerebrum

choroid
highly vascular tissue in the wall of the eye that supplies the outer retina with blood

ciliary body
smooth muscle structure on the interior surface of the iris that controls the shape of the lens through the zonule fibers

ciliary process
vascular fold of the inner ciliary body that produce aqueous humor

cochlea
auditory portion of the inner ear containing structures to transduce sound stimuli

cochlear duct
space within the auditory portion of the inner ear that contains the organ of Corti and is adjacent to the scala tympani and scala vestibuli on either side

cochlear nerve
branch of the vestibulocochlear nerve projecting from the cochlea

common tendinous ring
ring of fibrous tissue surrounding the optic nerve at its entrance at the apex of the orbit

cone photoreceptor
one of the two types of retinal receptor cell that is specialized for color vision through the use of three photopigments distributed through three separate populations of cells

cornea
fibrous covering of the anterior region of the eye that is transparent so that light can pass through it

cupula
specialized structure within the base of a semicircular canal that bends the stereocilia of hair cells when the head rotates by way of the relative movement of the enclosed fluid

dilator pupillae
outer smooth muscle of the iris whose contraction increases the size of the pupil

ear canal
passageway of the external ear that leads to the tympanic membrane; also known as auditory canal

endolymph
fluid in the membranous labyrinth of the ear

endolymphatic duct
canal filled with endolymph connecting the utricle and saccule

equilibrium
sense of balance that includes sensations of position and movement of the head

Eustachian tube
tube that connects the nasopharynx to the middle ear; also known as auditory tube

external ear
structures on the lateral surface of the head, including the auricle and the ear canal back to the tympanic membrane

extraocular muscle
one of six muscles originating out of the bones of the orbit and inserting into the surface of the eye which are responsible for moving the eye

fibrous tunic
outer layer of the eye primarily composed of connective tissue known as the sclera and cornea

fovea
exact center of the retina at which visual stimuli are focused for maximal acuity, where the retina is thinnest, at which there is nothing but photoreceptors

hair cells
mechanoreceptor cells found in the inner ear that transduce stimuli for the senses of hearing and balance

horizontal cell
lateral interconnecting neurons of the retina

incus
(also, anvil) ossicle of the middle ear that connects the malleus to the stapes

inferior oblique
extraocular muscle responsible for lateral rotation of the eye

inferior rectus
extraocular muscle responsible for looking down

inner ear
structure within the temporal bone that contains the sensory apparati of hearing and balance

iris
colored portion of the anterior eye that surrounds the pupil

lacrimal canaliculus
duct in the medial corner of the orbit that drains tears into the nasal cavity

lacrimal gland
gland lateral to the orbit that produces tears to wash across the surface of the eye

lacrimal punctum
opening of the lacrimal canaliculus

lacrimal sac
superior end of the nasolacrimal duct

lateral rectus
extraocular muscle responsible for abduction of the eye

lens
component of the eye that focuses light on the retina

levator palpebrae superioris
muscle that causes elevation of the upper eyelid, controlled by fibers in the oculomotor nerve

macula
enlargement at the base of a semicircular canal at which transduction of equilibrium stimuli takes place within the

ampulla

macula lutea
area surrounding the fovea near the center of the retina in the eye, which is the region of sharpest vision

malleus
(also, hammer) ossicle that is directly attached to the tympanic membrane

medial rectus
extraocular muscle responsible for adduction of the eye

membranous labyrinth
membranes of the the inner ear that line the bony labyrinth

middle ear
space within the temporal bone between the ear canal and bony labyrinth where the ossicles amplify sound waves from the tympanic membrane to the oval window

nasolacrimal duct
tube that connects the lacrimal sac to the nasal cavity

neural layer
one of the two layers of the neural tunic of the eye

neural tunic
layer of the eye that contains nervous tissue, namely the retina

ocular conjunctiva
part of the conjunctiva which covers the outer surface of the eye

oculomotor nerve
third cranial nerve; responsible for contraction of four of the extraocular muscles, the muscle in the upper eyelid, and pupillary constriction

optic disc
spot on the retina at which RGC axons leave the eye and blood vessels of the inner retina pass

optic nerve
second cranial nerve, which is responsible visual sensation

organ of Corti
structure in the cochlea in which hair cells transduce movements from sound waves into electrochemical signals

ossicles
three small bones in the middle ear

otolith
layer of calcium carbonate crystals located on top of the otolithic membrane

otolithic membrane
gelatinous substance in the utricle and saccule of the inner ear that contains calcium carbonate crystals and into which the stereocilia of hair cells are embedded

oval window
membrane at the base of the cochlea where the stapes attaches, marking the beginning of the scala vestibuli

palpebral conjunctiva
membrane attached to the inner surface of the eyelids that covers the anterior surface of the cornea

perilymph
fluid between the membranous labyrinth of the ear and the bony labyrinth

pigmented layer
one of the two layers of the neural tunic of the eye

posterior cavity
space of the eye posterior to the lens

posterior chamber
space within the anterior cavity of the eye that is posterior to the iris

primary auditory cortex
region of the cerebral cortex within the temporal lobe responsible for the perception of sounds

primary visual cortex
region of the cerebral cortex within the occipital lobe responsible for the perception of vision

pupil
open hole at the center of the iris that light passes through into the eye

retina
nervous tissue of the eye at which phototransduction takes place

retinal ganglion cell (RGC)
neuron of the retina that projects along the second cranial nerve

rod photoreceptor
one of the two types of retinal receptor cell that is specialized for low-light vision

round window
membrane that marks the end of the scala tympani

saccule
structure of the inner ear responsible for transducing linear acceleration in the vertical plane

scala tympani
portion of the cochlea that extends from the apex to the round window

scala vestibuli
portion of the cochlea that extends from the oval window to the apex

sclera
white of the eye

scleral venous sinus
circular channel in the eye that collects aqueous humor from the anterior chamber

semicircular canals
structures within the inner ear responsible for transducing rotational movement information

sphincter pupillae
inner smooth muscle of the iris whose contraction decreases the size of the pupil

spiral ganglion
location of neuronal cell bodies that transmit auditory information along the eighth cranial nerve

stapes
(also, stirrup) ossicle of the middle ear that is attached to the inner ear

stereocilia
array of apical membrane extensions in a hair cell that transduce movements when they are bent

superior oblique
extraocular muscle responsible for medial rotation of the eye

superior rectus
extraocular muscle responsible for looking up

supporting cells
cells that support the hair cells in the macula

suspensory ligaments
fibers that connect the ciliary body of the eye with the lens, holding it in place

tarsal gland
gland within the eyelid that produces an oily substance

tarsal muscle
smooth muscle that helps to raise the upper eyelid

tectorial membrane
component of the organ of Corti that lays over the hair cells, into which the stereocilia are embedded

thalamus
major region of the diencephalon that is responsible for relaying information between the cerebrum and the hindbrain, spinal cord, and periphery

trochlea
cartilaginous structure that acts like a pulley for the superior oblique muscle

trochlear nerve
fourth cranial nerve; responsible for contraction of one of the extraocular muscles

tympanic membrane
ear drum

utricle
structure of the inner ear responsible for transducing linear acceleration in the horizontal plane

vascular tunic
middle layer of the eye primarily composed of connective tissue with a rich blood supply

vestibular membrane
membrane separating the cochlear duct and scala vestibuli

vestibular nerve
branch of the vestibulocochlear nerve projecting from the vestibule

vestibular system
system composed of the vestibule and semicircular canals to sense equilibrium

vestibule
in the ear, the portion of the inner ear responsible for the sense of equilibrium

vestibulocochlear nerve
eighth cranial nerve; responsible for the sensations of hearing and balance

vision
special sense of sight based on transduction of light stimuli

visual acuity
property of vision related to the sharpness of focus, which varies in relation to retinal position

vitreous humor
viscous fluid that fills the posterior chamber of the eye

Contributors and Attributions

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Answers

Interactive Link

The hair cells are located in the organ of Corti, which is located on the basilar membrane. The stereocilia of those cells would normally be attached to the tectorial membrane (though they are detached in the micrograph because of processing of the tissue).

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13.4: Integration of Somatic Functions

By the end of this section, you will be able to:

- Describe the pathways that sensory systems follow into the central nervous system
- Differentiate between the two major ascending pathways in the spinal cord
- Describe the pathway of somatosensory input from the face and compare it to the ascending pathways in the spinal cord
- Explain topographical representations of sensory information

Sensory Nerves

Once any sensory cell transduces a stimulus into a nerve impulse, that impulse has to travel along axons to reach the CNS. In many of the special senses, the axons leaving the sensory receptors have a **topographical** arrangement, meaning that the location of the sensory receptor relates to the location of the axon in the nerve. For example, in the retina, axons from RGCs in the fovea are located at the center of the optic nerve, where they are surrounded by axons from the more peripheral RGCs.

Spinal Nerves

Generally, **spinal nerves** contain afferent axons from sensory receptors in the periphery, such as from the skin, mixed with efferent axons travelling to the muscles or other effector organs. As the spinal nerve nears the spinal cord, it splits into dorsal and ventral roots. The dorsal root contains only the axons of sensory neurons, whereas the ventral roots contain only the axons of the motor neurons. Some of the branches will synapse with local neurons in the dorsal root ganglion, posterior (dorsal) horn, or even the anterior (ventral) horn, at the level of the spinal cord where they enter. Other branches will travel a short distance up or down the spine to interact with neurons at other levels of the spinal cord. A branch may also turn into the posterior (dorsal) column of the white matter to connect with the brain. Typically, spinal nerve systems that connect to the brain are **contralateral**, in that the right side of the body is connected to the left side of the brain and the left side of the body to the right side of the brain.

Cranial Nerves

Cranial nerves convey specific sensory information from the head and neck directly to the brain. For sensations below the neck, the right side of the body is connected to the left side of the brain and the left side of the body to the right side of the brain. Whereas spinal information is contralateral, cranial nerve systems are mostly **ipsilateral**, meaning that a cranial nerve on the right side of the head is connected to the right side of the brain. Some cranial nerves contain only sensory axons, such as the olfactory, optic, and vestibulocochlear nerves. Other cranial nerves contain both sensory and motor axons, including the trigeminal, facial, glossopharyngeal, and vagus nerves (however, the vagus nerve is not associated with the somatic nervous system). The general senses of somatosensation for the face travel through the trigeminal system.

There are few cranial nerves that are not ipsilateral: optic nerve (CN II), trochlear nerve (CN IV), facial nerve (CN VII), hypoglossal nerves (CN XII). Of these, the optic nerve and facial nerve carry sensory information, while the others carry motor information only.

The connections of the **optic nerve** are more complicated than those of other cranial nerves. Instead of the connections being between each eye and the brain, visual information is segregated between the left and right sides of the visual field. In addition, some of the information from one side of the visual field projects to the opposite side of the brain. Within each eye, the axons projecting from the medial side of the retina cross at the **optic chiasm** and create new bundles called the **optic tract** which synapse onto the **thalamus** and extend to **occipital lobes**. For example, the axons from the medial retina of the left eye cross over to the right side of the brain at the optic chiasm. However, within each eye, the axons projecting from the lateral side of the retina do not cross. For example, the axons from the lateral retina of the right eye project back to the right side of the brain. Therefore the left field of view of each eye is processed on the right side of the brain, whereas the right field of view of each eye is processed on the left side of the brain (Figure 13.4.1).

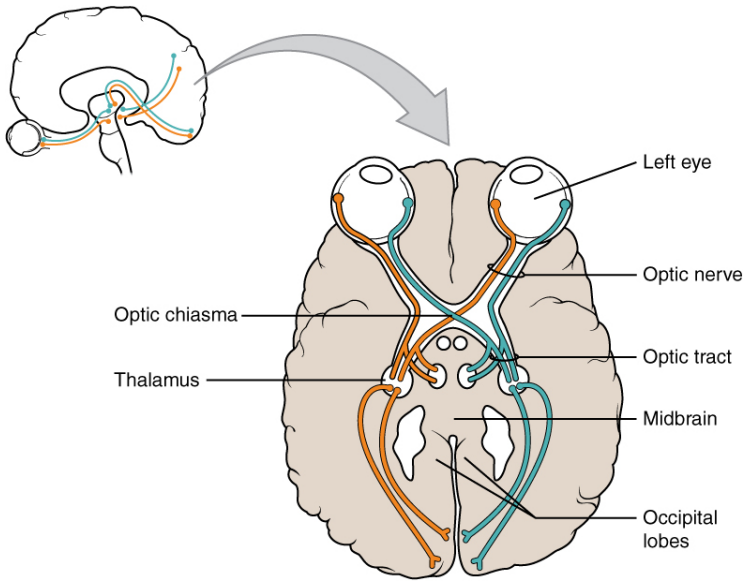

Figure 13.4.1: Segregation of Visual Field Information. Optic nerves carry visual information to the brain. Axons within the optic nerves project both contralaterally and ipsilaterally, depending on the visual field. Contralateral visual field information from the lateral retina projects to the ipsilateral brain, whereas ipsilateral visual field information has to cross at the optic chiasm to reach the opposite side of the brain. (Image credit: "1204 Optic Nerve vs Optic Tract" by OpenStax is licensed under CC BY 4.0)

DISORDERS OF THE...

Vision: Bilateral hemianopia

A unique clinical presentation that relates to this anatomic arrangement is the loss of lateral peripheral vision, known as bilateral hemianopia. This is different from "tunnel vision" because the superior and inferior peripheral fields are not lost. Visual field deficits can be disturbing for a patient, but in this case, the cause is not within the visual system itself. A growth of the pituitary gland presses against the optic chiasm and interferes with signal transmission. However, the axons projecting to the same side of the brain are unaffected. Therefore, the patient loses the outermost areas of their field of vision and cannot see objects to their right and left.

Sensory Pathways

Specific regions of the CNS coordinate different somatic processes using sensory inputs and motor outputs of peripheral nerves. A simple case is a reflex caused by a synapse between a dorsal sensory neuron axon and a motor neuron in the ventral horn. More complex arrangements are possible to integrate peripheral sensory information with higher processes. The important regions of the CNS that play a role in somatic processes can be separated into the spinal cord, brainstem, diencephalon, and cerebrum (cortex and subcortical structures).

Spinal Cord and Brainstem

A sensory pathway that carries peripheral sensations to the brain is referred to as an **ascending pathway**, or ascending tract. Various sensory modalities follow specific pathways through the CNS. Tactile and other somatosensory stimuli activate receptors in the skin, muscles, tendons, and joints throughout the entire body. However, the somatosensory pathways are divided into two separate systems on the basis of the location of the receptor neurons. Somatosensory stimuli from below the neck pass along the sensory pathways of the spinal cord, whereas somatosensory stimuli from the head and neck travel through the cranial nerves—specifically, the trigeminal system.

The **dorsal column system** (sometimes referred to as the dorsal column–medial lemniscus) and the **spinothalamic tract** are two major pathways that bring sensory information to the brain (Figure 13.4.2). The sensory pathways in each of these systems are composed of three successive neurons.

The dorsal column system begins with the axon of a dorsal root ganglion neuron entering the dorsal root and joining the dorsal column white matter in the spinal cord. As axons of this pathway enter the dorsal column, they take on a positional arrangement so that axons from lower levels of the body position themselves medially, whereas axons from upper levels of the body position themselves laterally. The dorsal column is separated into two component tracts, the **fasciculus gracilis** that contains axons from the legs and lower body, and the **fasciculus cuneatus** that contains axons from the upper body and arms.

The axons in the dorsal column terminate in the nuclei of the medulla, where each synapses with the second neuron in their respective pathway. The **nucleus gracilis** is the target of fibers in the fasciculus gracilis, whereas the **nucleus cuneatus** is the target of fibers in the fasciculus cuneatus. The second neuron in the system projects from one of the two nuclei and then **decussates**, or crosses the midline, in the medulla. These axons then continue to ascend the brainstem as a bundle called the **medial lemniscus**. These axons terminate in the thalamus, where each synapses with the third neuron in their respective pathway. The third neuron in the system projects its axons to the postcentral gyrus of the cerebral cortex, where somatosensory stimuli are initially processed and the conscious perception of the stimulus occurs.

The spinothalamic tract also begins with neurons in a dorsal root ganglion. These neurons extend their axons to the dorsal horn, where they synapse with the second neuron in their respective pathway. The name “spinothalamic” comes from this second neuron, which has its cell body in the spinal cord gray matter and connects to the thalamus. Axons from these second neurons then decussate within the spinal cord and ascend to the brain and enter the thalamus, where each synapses with the third neuron in its respective pathway. The neurons in the thalamus then project their axons to the spinothalamic tract, which synapses in the postcentral gyrus of the cerebral cortex.

These two systems are similar in that they both begin with dorsal root ganglion cells, as with most general sensory information. The dorsal column system is primarily responsible for touch sensations and proprioception, whereas the spinothalamic tract pathway is primarily responsible for pain and temperature sensations. Another similarity is that the second neurons in both of these pathways project across the midline to the other side of the brain or spinal cord, so that sensation is perceived contralaterally. In the dorsal column system, this decussation takes place in the brainstem; in the spinothalamic pathway, it takes place in the spinal cord at the same spinal cord level at which the information entered. The third neurons in the two pathways are essentially the same. In both, the second neuron synapses in the thalamus, and the thalamic neuron projects to the somatosensory cortex.

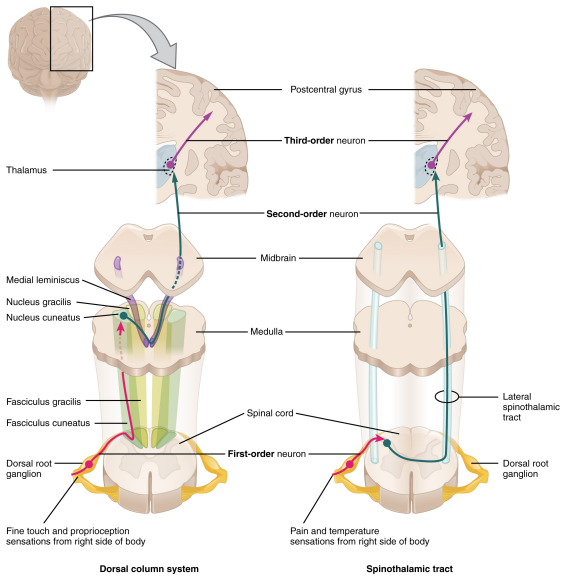

Figure 13.4.2: Ascending Sensory Pathways of the Spinal Cord. The dorsal column system and spinothalamic tract are the major ascending pathways that connect the periphery with the brain. The dorsal column system carries information of fine touch and proprioception from the periphery to dorsal root ganglia and posterior columns of the spinal cord. Axons ascend the spinal cord through the fasciculus cuneatus and gracilis and synapse in the nucleus cuneatus and gracilis of the medulla. From there, ascending fibers cross at the midline and reach the midbrain and thalamus, which in turn send the information to the postcentral gyrus. The spinothalamic tract carries information about pain and temperature from the periphery to the dorsal root ganglia and posterior horn of the spinal cord. Then, axons cross at the midline at the level of the spinal cord and ascend through the medulla and midbrain to synapse onto the thalamus, which in turn send the information to the postcentral gyrus. (Image credit: "Ascending Pathways of Spinal Cord" by OpenStax is licensed under CC BY 3.0)

The trigeminal pathway carries somatosensory information from the face, head, mouth, and nasal cavity. As with the previously

discussed nerve tracts, the sensory pathways of the trigeminal pathway each involve three successive neurons. First, axons from the trigeminal ganglion enter the brainstem at the level of the pons. These axons project to one of three locations. The **spinal trigeminal nucleus** of the medulla receives information similar to that carried by spinothalamic tract, such as pain and temperature sensations. Other axons go to either the **chief sensory nucleus** in the pons or the **mesencephalic nuclei** in the midbrain. These nuclei receive information like that carried by the dorsal column system, such as touch, pressure, vibration, and proprioception. Axons from the second neuron decussate and ascend to the thalamus along the trigeminothalamic tract. In the thalamus, each axon synapses with the third neuron in its respective pathway. Axons from the third neuron then project from the thalamus to the primary somatosensory cortex of the cerebrum.

The sensory pathway for gustation travels along the facial and glossopharyngeal cranial nerves, which synapse with neurons of the **solitary nucleus** in the brainstem. Axons from the solitary nucleus then project to the **ventral posterior nucleus** of the thalamus. Finally, axons from the ventral posterior nucleus project to the gustatory cortex of the cerebral cortex, where taste is processed and consciously perceived.

The sensory pathway for audition travels along the vestibulocochlear nerve, which synapses with neurons in the **cochlear nuclei** of the superior medulla. Within the brainstem, input from either ear is combined to extract location information from the auditory stimuli. Whereas the initial auditory stimuli received at the cochlea strictly represent the frequency—or pitch—of the stimuli, the locations of sounds can be determined by comparing information arriving at both ears. Auditory processing continues on to a nucleus in the midbrain called the **inferior colliculus**. Axons from the inferior colliculus project to two locations, the thalamus and the **superior colliculus**. The **medial geniculate nucleus** of the thalamus receives the auditory information and then projects that information to the auditory cortex in the temporal lobe of the cerebral cortex. The superior colliculus receives input from the visual and somatosensory systems, as well as the ears, to initiate stimulation of the muscles that turn the head and neck toward the auditory stimulus.

Balance is coordinated through the vestibular system, the nerves of which are composed of axons from the vestibular ganglion that carries information from the utricle, saccule, and semicircular canals. The system contributes to controlling head and neck movements in response to vestibular signals. An important function of the vestibular system is coordinating eye and head movements to maintain visual attention. Most of the axons terminate in the **vestibular nuclei** of the medulla. Some axons project from the vestibular ganglion directly to the cerebellum, with no intervening synapse in the vestibular nuclei. The cerebellum is primarily responsible for initiating movements on the basis of equilibrium information. Neurons in the vestibular nuclei project their axons to targets in the brainstem. One target is the reticular formation, which influences respiratory and cardiovascular functions in relation to body movements. A second target of the axons of neurons in the vestibular nuclei is the spinal cord, which initiates the spinal reflexes involved with posture and balance. To assist the visual system, fibers of the vestibular nuclei project to the oculomotor, trochlear, and abducens nuclei to influence signals sent along the cranial nerves.

The sensory pathway for vision starts with the optic tract. The optic tract has three major targets, two in the diencephalon and one in the midbrain. The connection between the eyes and diencephalon is demonstrated during development, in which the neural tissue of the retina differentiates from that of the diencephalon by the growth of the secondary vesicles. The connections of the retina into the CNS are a holdover from this developmental association. The majority of the connections of the optic tract are to the thalamus—specifically, the **lateral geniculate nucleus**. Axons from this nucleus then project to the visual cortex of the cerebrum, located in the occipital lobe. Another target of the optic tract is the superior colliculus. In addition, a very small number of retinal ganglion cells (RGCs) axons project from the optic chiasm to the **suprachiasmatic nucleus** of the hypothalamus. These RGCs are photosensitive, in that they respond to the presence or absence of light. Unlike the photoreceptors, however, these photosensitive RGCs cannot be used to perceive images. By simply responding to the absence or presence of light, these RGCs can send information about day length. The perceived proportion of sunlight to darkness establishes the **circadian rhythm** of our bodies, allowing certain physiological events to occur at approximately the same time every day.

Diencephalon

The diencephalon is beneath the cerebrum and includes the thalamus and hypothalamus. In the somatic nervous system, the **thalamus** is an important relay for communication between the cerebrum and the rest of the nervous system. The **hypothalamus** has both somatic and autonomic functions. In addition, the hypothalamus communicates with the limbic system, which controls emotions and memory functions.

Sensory input to the thalamus comes from most of the special senses and ascending somatosensory tracts. Each sensory system is relayed through a particular nucleus in the thalamus. The thalamus is a required transfer point for most sensory tracts that reach the cerebral cortex, where conscious sensory perception begins. The one exception to this rule is the olfactory system. The olfactory tract axons from the olfactory bulb project directly to the cerebral cortex, along with the limbic system and hypothalamus.

The thalamus is a collection of several nuclei that can be categorized into three anatomical groups. White matter running through the thalamus defines the three major regions of the thalamus, which are an **anterior nucleus**, a **medial nucleus**, and a **lateral group of nuclei**. The anterior nucleus serves as a relay between the hypothalamus and the emotion and memory-producing limbic system. The medial nuclei serve as a relay for information from the limbic system and basal ganglia to the cerebral cortex. This allows memory creation during learning, but also determines alertness. The special and somatic senses connect to the lateral nuclei, where their information is relayed to the appropriate sensory cortex of the cerebrum.

Cerebrum

As described earlier, many of the sensory axons are positioned in the same way as their corresponding receptor cells in the body. This allows identification of the position of a stimulus on the basis of which receptor cells are sending information. The cerebral cortex also maintains this **sensory topography** in the particular areas of the cortex that correspond to the position of the receptor cells. This mapping is often depicted using a sensory homunculus.

Likewise, the topographic relationship between the retina and the visual cortex is maintained throughout the visual pathway. The visual field is projected onto the two retinae, as described above, with sorting at the optic chiasm. The right peripheral visual field falls on the medial portion of the right retina and the lateral portion of the left retina. The right medial retina then projects across the midline through the optic chiasm. This results in the right visual field being processed in the left visual cortex. Likewise, the left visual field is processed in the right visual cortex. Though the chiasm is helping to sort right and left visual information, superior and inferior visual information is maintained topographically in the visual pathway. Light from the superior visual field falls on the inferior retina, and light from the inferior visual field falls on the superior retina. This topography is maintained such that the superior region of the visual cortex processes the inferior visual field and vice versa. Therefore, the visual field information is inverted and reversed as it enters the visual cortex—up is down, and left is right (Figure 13.4.3). However, the cortex processes the visual information such that the final conscious perception of the visual field is correct. The topographic relationship is evident in that information from the foveal region of the retina is processed in the center of the primary visual cortex. Information from the peripheral regions of the retina are correspondingly processed toward the edges of the visual cortex. Similar to the exaggerations in the sensory homunculus of the somatosensory cortex, the foveal-processing area of the visual cortex is disproportionately larger than the areas processing peripheral vision.

In an experiment performed in the 1960s, subjects wore prism glasses so that the visual field was inverted before reaching the eye. On the first day of the experiment, subjects would duck when walking up to a table, thinking it was suspended from the ceiling. However, after a few days of acclimation, the subjects behaved as if everything were represented correctly. Therefore, the visual cortex is somewhat flexible in adapting to the information it receives from our eyes.

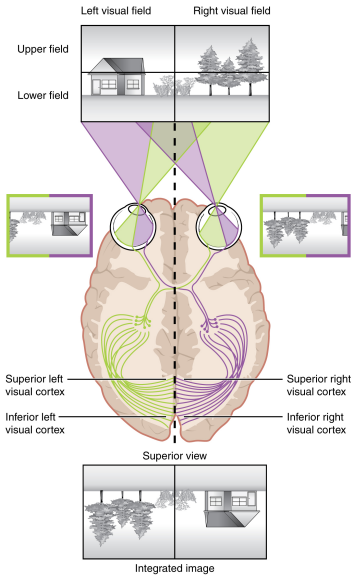

Figure 13.4.3: Topographic Mapping of the Retina onto the Visual Cortex. The visual field projects onto the retina through the lenses and falls on the retinae as an inverted, and reversed image where left is right and superior is inferior, and viceversa. The topography of this image is maintained as the visual information travels through the visual pathway to the visual cortex of the occipital lobe, resulting into an integrated image being inverted and reversed. (Image credit: "1422 Topographical Image on Retina" by OpenStax is licensed under CC BY 3.0)

The cortex has been described as having specific regions that are responsible for processing specific information; there is the visual cortex, somatosensory cortex, gustatory cortex, etc. However, our experience of these senses is not divided. Instead, we experience what can be referred to as a seamless percept. Our perceptions of the various sensory modalities—though distinct in their content—are integrated by the brain so that we experience the world as a continuous whole.

In the cerebral cortex, sensory processing begins at the **primary sensory cortex**, then proceeds to an **association area**, and finally, into a **multimodal integration area**. For example, the visual pathway projects from the retinae through the thalamus to the primary visual cortex in the occipital lobe. This area is primarily in the medial wall within the longitudinal fissure. Here, visual stimuli begin to be recognized as basic shapes. Edges of objects are recognized and built into more complex shapes. Also, inputs from both eyes are compared to extract depth information. Because of the overlapping field of view between the two eyes, the brain can begin to estimate the distance of stimuli based on **binocular depth cues**.

Concept Review

The nerves that convey sensory information from the periphery to the CNS are either spinal nerves, connected to the spinal cord, or cranial nerves, connected to the brain. Spinal nerves have mixed populations of fibers; some are motor fibers and some are sensory. The sensory fibers connect to the spinal cord through the dorsal root, which is attached to the dorsal root ganglion. Sensory information from the body that is conveyed through spinal nerves will project to the opposite side of the brain to be processed by the cerebral cortex. The cranial nerves can be strictly sensory fibers, such as the olfactory, optic, and vestibulocochlear nerves, or mixed sensory and motor nerves, such as the trigeminal, facial, glossopharyngeal, and vagus nerves. The cranial nerves are connected to the same side of the brain from which the sensory information originates.

Sensory input to the brain enters through pathways that travel through either the spinal cord (for somatosensory input from the body) or the brainstem (for everything else, except the visual and olfactory systems) to reach the diencephalon. In the diencephalon, sensory pathways reach the thalamus. This is necessary for all sensory systems to reach the cerebral cortex, except for the olfactory system that is directly connected to the frontal and temporal lobes.

The two major tracts in the spinal cord, originating from sensory neurons in the dorsal root ganglia, are the dorsal column system and the spinothalamic tract. The major differences between the two are in the type of information that is relayed to the brain and where the tracts decussate. The dorsal column system primarily carries information about touch and proprioception and crosses the midline in the medulla. The spinothalamic tract is primarily responsible for pain and temperature sensation and crosses the midline in the spinal cord at the level at which it enters. The trigeminal nerve adds similar sensation information from the head to these pathways.

The auditory pathway passes through multiple nuclei in the brainstem in which additional information is extracted from the basic frequency stimuli processed by the cochlea. Sound localization is made possible through the activity of these brainstem structures. The vestibular system enters the brainstem and influences activity in the cerebellum, spinal cord, and cerebral cortex.

The visual pathway segregates information from the two eyes so that one half of the visual field projects to the other side of the brain. Within visual cortical areas, the perception of the stimuli and their location is passed along two streams, one ventral and one dorsal. The ventral visual stream connects to structures in the temporal lobe that are important for long-term memory formation. The dorsal visual stream interacts with the somatosensory cortex in the parietal lobe, and together they can influence the activity in the frontal lobe to generate movements of the body in relation to visual information.

Review Questions

Q. Which of these sensory modalities does *not* pass through the ventral posterior thalamus?

A. gustatory

B. proprioception

C. audition

D. nociception

Answer

C

Q. Which nucleus in the medulla is connected to the inferior colliculus?

A. solitary nucleus

B. vestibular nucleus

C. chief sensory nucleus

D. cochlear nucleus

Answer

D

Q. Visual stimuli in the upper-left visual field will be processed in what region of the primary visual cortex?

A. inferior right

B. inferior left

C. superior right

D. superior left

Answer

A

Q. Which of the following is a direct target of the vestibular ganglion?

A. superior colliculus

B. cerebellum

C. thalamus

D. optic chiasm

Answer

B

Critical Thinking Questions

Q. Following a motorcycle accident, the victim loses the ability to move the right leg but has normal control over the left one, suggesting a hemisection somewhere in the thoracic region of the spinal cord. What sensory deficits would be expected in terms of touch versus pain? Explain your answer.

> A. The right leg would feel painful stimuli, but not touch, because the spinothalamic tract decussates at the level of entry, which would be below the injury, whereas the dorsal column system does not decussate until reaching the brainstem, which would be above the injury and thus those fibers would be damaged.

Q. A pituitary tumor can cause perceptual losses in the lateral visual field. The pituitary gland is located directly inferior to the hypothalamus. Why would this happen?

A. As the tumor enlarges, it would press against the optic chiasm, and fibers from the medial retina would be disrupted. These fibers carry information about the lateral visual field because the visual scene is reversed as the light passes through the pupil and lens.

Glossary

anterior nucleus
collection of nuclei of the anterior region of the thalamus

ascending pathway
fiber structure that relays sensory information from the periphery through the spinal cord and brainstem to other structures of the brain

association area
region of cortex connected to a primary sensory cortical area that further processes the information to generate more complex sensory perceptions

binocular depth cues
indications of the distance of visual stimuli on the basis of slight differences in the images projected onto either retina

chief sensory nucleus
component of the trigeminal nuclei that is found in the pons

circadian rhythm
internal perception of the daily cycle of light and dark based on retinal activity related to sunlight

cochlear nuclei
nuclei that receive first-order auditory input from the organ of Corti in the cochlea of the inner ear

contralateral
word meaning “on the opposite side,” as in axons that cross the midline in a fiber tract

decussate
to cross the midline, as in fibers that project from one side of the body to the other

dorsal column system
ascending tract of the spinal cord associated with fine touch and proprioceptive sensations

fasciculus cuneatus
lateral division of the dorsal column system composed of fibers from sensory neurons in the upper body

fasciculus gracilis
medial division of the dorsal column system composed of fibers from sensory neurons in the lower body

hypothalamus
major region of the diencephalon that is responsible for coordinating autonomic and endocrine control of homeostasis

inferior colliculus
last structure in the auditory brainstem pathway that projects to the thalamus and superior colliculus

ipsilateral
word meaning on the same side, as in axons that do not cross the midline in a fiber tract

lateral geniculate nucleus
thalamic target of the RGCs that projects to the visual cortex

lateral group of nuclei
collection of nuclei of the lateral region of the thalamus

medial geniculate nucleus
thalamic target of the auditory brainstem that projects to the auditory cortex

medial lemniscus
fiber tract of the dorsal column system that extends from the nuclei gracilis and cuneatus to the thalamus, and decussates

medial nucleus
collection of nuclei of the medial region of the thalamus

mesencephalic nucleus
component of the trigeminal nuclei that is found in the midbrain

multimodal integration area
region of the cerebral cortex in which information from more than one sensory modality is processed to arrive at higher level cortical functions such as memory, learning, or cognition

nucleus cuneatus
medullary nucleus at which first-order neurons of the dorsal column system synapse specifically from the upper body and arms

nucleus gracilis
medullary nucleus at which first-order neurons of the dorsal column system synapse specifically from the lower body and legs

optic chiasm
decussation point in the visual system at which medial retina fibers cross to the other side of the brain

optic tract
name for the fiber structure containing axons from the retina posterior to the optic chiasm representing their CNS location

primary sensory cortex
region of the cerebral cortex that initially receives sensory input from an ascending pathway from the thalamus and begins the processing that will result in conscious perception of that modality

solitary nucleus
medullar nucleus that receives taste information from the facial and glossopharyngeal nerves

spinal nerve
one of 31 nerves connected to the spinal cord

spinal trigeminal nucleus
component of the trigeminal nuclei that is found in the medulla

spinothalamic tract
ascending tract of the spinal cord associated with pain and temperature sensations

superior colliculus
structure in the midbrain that combines visual, auditory, and somatosensory input to coordinate spatial and topographic representations of the three sensory systems

suprachiasmatic nucleus
hypothalamic target of the retina that helps to establish the circadian rhythm of the body on the basis of the presence or absence of daylight

thalamus
major region of the diencephalon that is responsible for relaying information between the cerebrum and the hindbrain, spinal cord, and periphery

topographical
relating to positional information

ventral posterior nucleus
nucleus in the thalamus that is the target of gustatory sensations and projects to the cerebral cortex

vestibular nuclei
targets of the vestibular component of the eighth cranial nerve

Contributors and Attributions

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13.5: Somatic Motor Responses

By the end of this section, you will be able to:

- List the cortical components of motor processing
- Describe the pathway of descending motor commands from the cortex to the skeletal muscles
- Compare different descending pathways, both by structure and function
- List the structures and steps involved in a reflex arc
- Describe several reflex arcs and their functional roles

The defining characteristic of the somatic nervous system is that it controls skeletal muscles. Somatic senses inform the nervous system about the external environment, but the response to that is through voluntary muscle movement. The term “voluntary” suggests that there is a conscious decision to make a movement. However, some aspects of the somatic system use voluntary muscles without conscious control. One example is the ability of our breathing to switch to unconscious control while we are focused on another task. However, the muscles that are responsible for the basic process of breathing are also utilized for speech, which is entirely voluntary.

Cortical Responses

The information on sensory stimuli registered through receptor cells is relayed to the CNS along ascending pathways. In the cerebral cortex, the initial processing of sensory perception can lead to the incorporation of sensory perceptions into memory, but more importantly, it leads to a response. The completion of cortical processing through the primary, associative, and integrative sensory areas initiates a similar progression of motor processing, usually in different cortical areas.

Prefrontal Cortex

Whereas the sensory cortical areas are located in the occipital, temporal, and parietal lobes, motor functions are largely controlled by the frontal lobe. The most anterior regions of the frontal lobe—the prefrontal areas—are important for **executive functions**, which are cognitive functions that lead to goal-directed behaviors. These higher cognitive processes include **working memory** that can help organize and represent information that is not in the immediate environment. The prefrontal lobe is responsible for aspects of attention, such as inhibiting distracting thoughts and actions so that a person can focus on a goal and direct behavior toward achieving that goal. The functions of the prefrontal cortex are integral to the personality of an individual, because it is largely responsible for what a person intends to do and how they accomplish those plans.

Secondary Motor Cortices

In generating motor responses, the executive functions of the prefrontal cortex will need to initiate actual movements. One way to define the prefrontal area is any region of the frontal lobe that does not elicit movement when electrically stimulated. These are primarily in the anterior part of the frontal lobe. The regions of the frontal lobe that remain are the regions of the cortex that produce movement. The prefrontal areas project into the secondary motor cortices, which include the **premotor cortex** and the **supplemental motor area**. The premotor area aids in controlling movements of the core muscles to maintain posture during movement, whereas the supplemental motor area is hypothesized to be responsible for planning and coordinating movement. The supplemental motor area also manages sequential movements that are based on prior experience (that is, learned movements). Neurons in these areas are most active leading up to the initiation of movement. For example, these areas might prepare the body for the movements necessary to drive a car in anticipation of a traffic light changing.

Adjacent to these two regions are two specialized motor planning centers. The **frontal eye fields** are responsible for moving the eyes in response to visual stimuli. There are direct connections between the frontal eye fields and the superior colliculus. Also, anterior to the premotor cortex and primary motor cortex is **Broca’s area**. This area is responsible for controlling movements of the structures of speech production.

Primary Motor Cortex

The primary motor cortex is located in the precentral gyrus of the frontal lobe. The primary motor cortex receives input from several areas that aid in planning movement, and its principle output stimulates spinal cord neurons to stimulate skeletal muscle contraction. The primary motor cortex is arranged in a similar fashion to the primary somatosensory cortex, in that it has a topographical map of the body, creating a motor homunculus. The neurons responsible for musculature in the feet and lower legs are in the medial wall of the precentral gyrus, with the thighs, trunk, and shoulder at the crest of the longitudinal fissure. The hand and face are in the lateral face of the gyrus. Also, the relative space allotted for the different regions is exaggerated in muscles that have greater enervation. The greatest amount of cortical space is given to muscles that perform fine, agile movements, such as the muscles of the fingers and the lower face. The "power muscles" that perform coarser movements, such as the buttock and back muscles, occupy much less space on the motor cortex.

Descending Pathways

The motor output from the cortex descends into the brainstem and to the spinal cord to control the musculature through motor neurons. Neurons located in the primary motor cortex, named **Betz cells**, are large cortical neurons that synapse with lower motor neurons in the spinal cord or the brainstem. The two descending pathways traveled by the axons of Betz cells are the **corticospinal tract** and the **corticobulbar tract**. Both tracts are named for their origin in the cortex and their targets—either the spinal cord or the brainstem (the term "bulbar" refers to the brainstem as the bulb, or enlargement, at the top of the spinal cord).

These two descending pathways are responsible for the conscious or voluntary movements of skeletal muscles. Any motor command from the primary motor cortex is sent down the axons of the Betz cells to activate upper motor neurons in either the cranial motor nuclei or in the ventral horn of the spinal cord. The axons of the corticobulbar tract are ipsilateral, meaning they project from the cortex to the cranial motor nucleus on the same side of the nervous system. The corticobulbar tract controls the movement of muscles in the face, head and neck. Conversely, the axons of the corticospinal tract are largely contralateral, meaning that they cross the midline of the brainstem or spinal cord and synapse on the opposite side of the body. The corticospinal tract controls movement of muscles of limbs and trunk. Therefore, the right motor cortex of the cerebrum controls muscles on the left arm, for example, and vice versa.

The corticospinal tract descends from the cortex through the deep white matter of the cerebrum. It then passes between the caudate nucleus and putamen of the basal nuclei as a bundle called the **internal capsule**. The tract then passes through the midbrain as the **cerebral peduncles**, after which it burrows through the pons. Upon entering the medulla, the tracts make up the large white matter tract referred to as the **pyramids** (Figure 13.5.1). The defining landmark of the medullary-spinal border is the **pyramidal decussation**, which is where most of the fibers in the corticospinal tract cross over to the opposite side of the brain. At this point, the tract separates into two parts, which have control over different domains of the musculature.

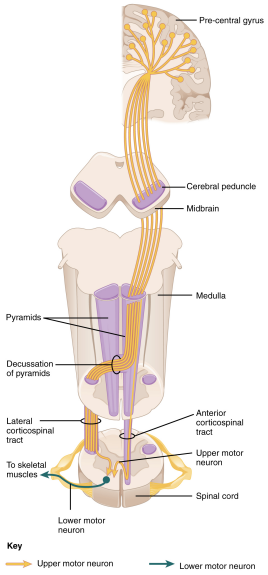

Figure 13.5.1: Corticospinal Tract. The major descending tract that controls skeletal muscle movements is the corticospinal tract. It is composed of two neurons, the upper motor neuron and the lower motor neuron. The upper motor neuron has its cell body in the primary motor cortex located in the precentral gyrus of the frontal lobe. Its axon descend through the cerebral peduncle of the midbrain and crosses the midline at the medulla through the decussation of pyramids. Traveling down through the anterior and lateral corticospinal tracts, it then synapses on the lower motor neuron, which is in the ventral horn of the spinal cord and projects to the skeletal muscle in the periphery. (Image credit: "Corticospinal Pathway" by OpenStax is licensed under CC BY 3.0)

Appendicular Control

The **lateral corticospinal tract** is composed of the fibers that cross the midline at the pyramidal decussation (see Figure 13.5.1). The axons cross over from the anterior position of the pyramids in the medulla to the lateral column of the spinal cord. These axons are responsible for controlling appendicular muscles.

This influence over the appendicular muscles means that the lateral corticospinal tract is responsible for moving the muscles of the arms and legs. The lower cervical spinal cord and the lumbar spinal cord both have wider ventral horns, representing the greater number of muscles controlled by these motor neurons. The **cervical enlargement** is particularly large because there is greater control over the fine musculature of the upper limbs, particularly of the fingers. The **lumbar enlargement** is not as significant in appearance because there is less fine motor control of the lower limbs.

Axial Control

The **anterior corticospinal tract** is responsible for controlling the muscles of the body trunk (see Figure 13.5.1). These axons do not decussate in the medulla. Instead, they remain in an anterior position as they descend the brainstem and enter the spinal cord. These axons then travel to the spinal cord level at which they synapse with a lower motor neuron. Upon reaching the appropriate level, the axons decussate, entering the ventral horn on the opposite side of the spinal cord from which they entered. In the ventral horn, these axons synapse with their corresponding lower motor neurons. The lower motor neurons are located in the medial regions of the ventral horn, because they control the axial muscles of the trunk.

Because movements of the body trunk involve both sides of the body, the anterior corticospinal tract is not entirely contralateral. Some collateral branches of the tract will project into the ipsilateral ventral horn to control synergistic muscles on that side of the body, or to inhibit antagonistic muscles through interneurons within the ventral horn. Through the influence of both sides of the body, the anterior corticospinal tract can coordinate postural muscles in broad movements of the body. These coordinating axons in the anterior corticospinal tract are often considered bilateral, as they are both ipsilateral and contralateral.

Extrapyramidal System

Other descending connections between the brain and the spinal cord are called the **extrapyramidal system**. The name comes from the fact that this system is outside the corticospinal pathway, which includes the pyramids in the medulla. A few pathways

originating from the brainstem contribute to this system.

The **tectospinal tract** projects from the midbrain to the spinal cord and is important for postural movements that are driven by the superior colliculus (Figure 13.5.2). The name of the tract comes from an alternate name for the superior colliculus, which is the tectum. The **reticulospinal tract** connects the reticular system, a diffuse region of gray matter in the brainstem, with the spinal cord. This tract influences trunk and proximal limb muscles related to posture and locomotion. The reticulospinal tract also contributes to muscle tone and influences autonomic functions. The **vestibulospinal tract** connects the brainstem nuclei of the vestibular system with the spinal cord. This allows posture, movement, and balance to be modulated on the basis of equilibrium information provided by the vestibular system. The pathways of the extrapyramidal system are influenced by subcortical structures. For example, connections between the secondary motor cortices and the extrapyramidal system modulate spine and cranium movements. The basal nuclei, which are important for regulating movement initiated by the CNS, influence the extrapyramidal system as well as its thalamic feedback to the motor cortex.

Figure 13.5.2 summarizes both ascending and descending pathways.

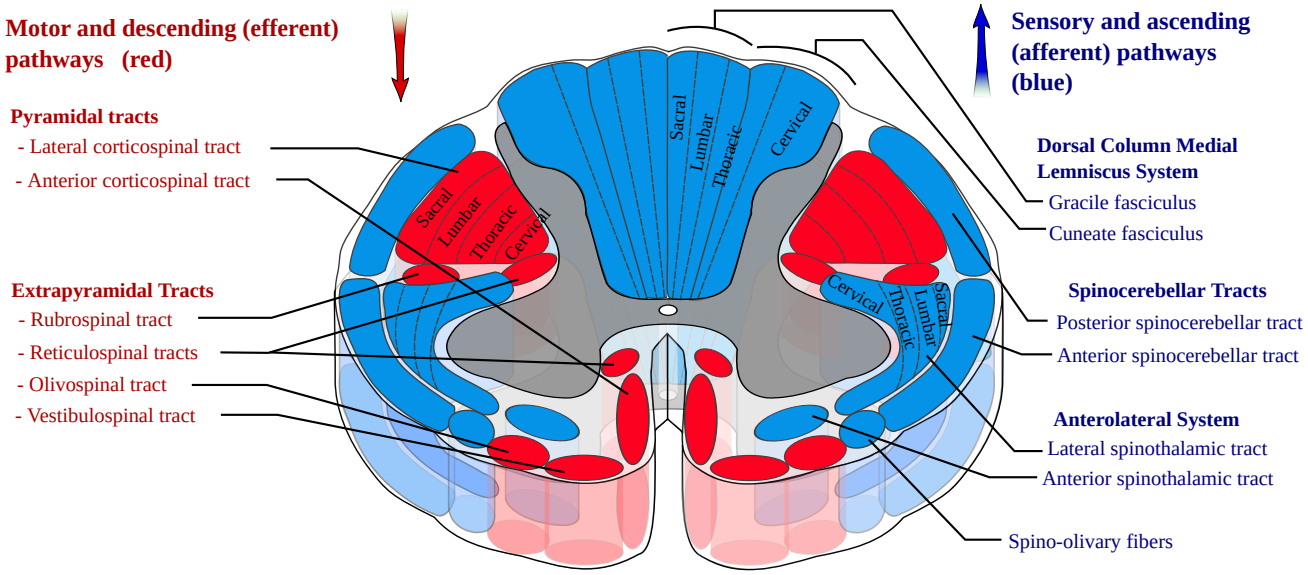

Figure 13.5.2: Ascending and Descending Tracts. A cross section of the spinal cord shows the sensory ascending tracts (in blue) and motor descending tracts (in red). Ascending sensory pathways include the dorsal column medial lemniscus system, the spinocerebellar tracts and anterolateral system. Descending motor pathways include pyramidal tracts and extrapyramidal tracts. (Image credit: "Spinal Cord Tracts - English" by Polarlys and Mikael Häggström is licensed under CC BY-SA 3.0)

Ventral Horn Output

The somatic nervous system provides output strictly to skeletal muscles. The lower motor neurons, which are responsible for the contraction of these muscles, are found in the ventral horn of the spinal cord. These large, multipolar neurons have a corona of dendrites surrounding the cell body and an axon that extends out of the ventral horn. This axon travels through the ventral nerve root to join the emerging spinal nerve. The axon is relatively long because it needs to reach muscles in the periphery of the body. The diameters of cell bodies may be on the order of hundreds of micrometers to support the long axon; some axons are a meter in length, such as the lumbar motor neurons that innervate muscles in the first digits of the feet.

The axons will also branch to innervate multiple muscle fibers. Together, the motor neuron and all the muscle fibers that it controls make up a motor unit. Motor units vary in size. Some may contain up to 1000 muscle fibers, such as in the quadriceps, or they may only have 10 fibers, such as in an extraocular muscle. The number of muscle fibers that are part of a motor unit corresponds to the precision of control of that muscle. Also, muscles that have finer motor control have more motor units connecting to them, and this requires a larger topographical field in the primary motor cortex.

Somatic Reflexes

This chapter began by introducing reflexes as an example of the basic elements of the somatic nervous system. Simple somatic

reflexes do not include the higher centers discussed for conscious or voluntary aspects of movement. Reflexes can be spinal or cranial, depending on the nerves and central components that are involved.

The example described at the beginning of the chapter involved heat and pain sensations from a hot stove causing withdrawal of the arm through a connection in the spinal cord that leads to contraction of the biceps brachii (Figure 13.5.3). The description of this **withdrawal reflex** was simplified, for the sake of the introduction, to emphasize the parts of the somatic nervous system. But to consider reflexes fully, more attention needs to be given to this example.

As you withdraw your hand from the stove, you do not want to slow that reflex down. Consequently, as the biceps brachii contracts, the antagonistic triceps brachii needs to relax. In the hot-stove withdrawal reflex, this occurs through an interneuron in the spinal cord. The interneuron's cell body is located in the dorsal horn of the spinal cord. The interneuron receives a synapse from the axon of the sensory neuron that detects that the hand is being burned. In response to this stimulation from the sensory neuron, the interneuron then inhibits the motor neuron that controls the triceps brachii. Without the antagonistic contraction, withdrawal from the hot stove is faster and keeps further tissue damage from occurring.

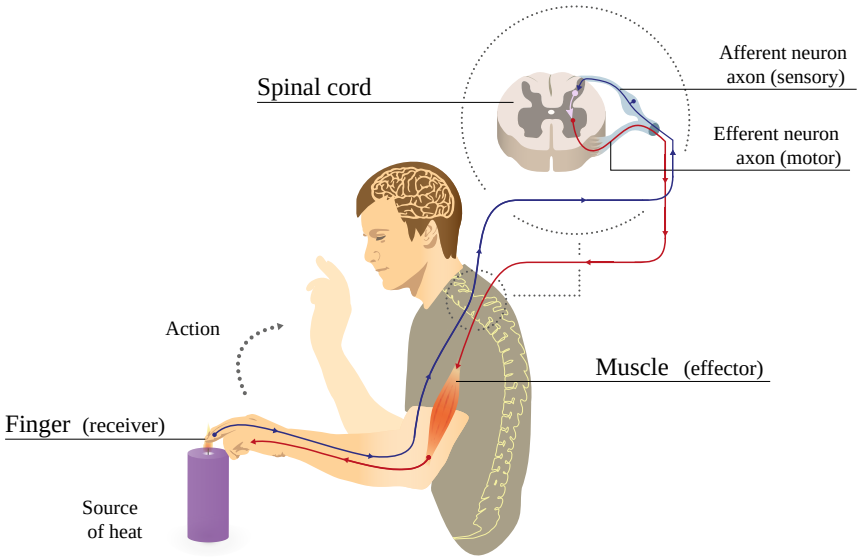

Figure 13.5.3: Withdrawal Reflex Arc. Nerve impulse of a stimulus is sensed by two or more neurons in the skin of the fingers. The spinal cord receives sensory impulses of the body and, through an interneuron, sends impulses to the arm muscle through spinal nerves. After receiving the order, the muscle runs the command, in this case to remove the finger from the stimulus. (Image credit: "Imgnotraçat arc reflex eng" by MartaAguayo is licensed under CC BY-SA 3.0)

Another type of reflex is a **stretch reflex** shown in Figure 13.5.4. In this reflex, when a skeletal muscle is stretched, a muscle spindle receptor is activated. The axon from this receptor structure will cause direct contraction of the muscle. A collateral of the muscle spindle fiber will also inhibit the motor neuron of the antagonist muscles. A common example of this reflex is the knee jerk that is elicited by a rubber hammer struck against the patellar ligament in a physical exam. The muscle is quickly stretched, resulting in activation of the muscle spindle that sends a signal into the spinal cord through the dorsal root. The fiber synapses directly on the ventral horn motor neuron that activates the muscle, causing contraction. The reflexes are physiologically useful for stability. If a muscle is stretched, it reflexively contracts to return the muscle to compensate for the change in length. In the context of the neurological exam, reflexes indicate that the lower motor neuron is functioning properly.

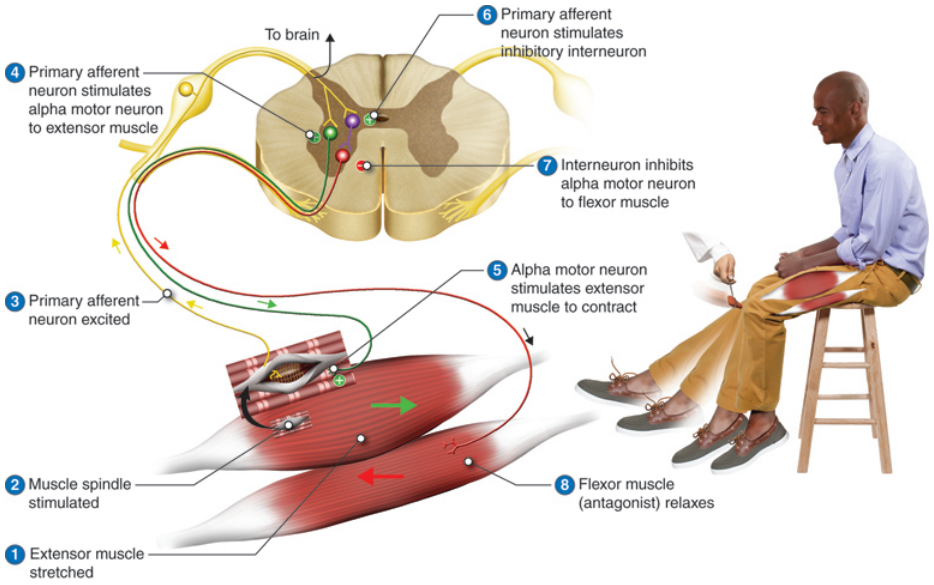

Figure 13.5.4: Stretch Reflex. When an extensor muscle is stretched (1), muscle spindles are stimulated (2) and send information to the spinal cord through a primary afferent neuron (3). The primary afferent neurons synapses on alpha motor neuron of the same extensor muscle (4) causing it to contract (5). At the same time, the primary afferent neuron stimulates an inhibitory interneuron (6) which inhibits the alpha motor neuron to the flexor muscle, preventing its contraction (7). Consequently, the flexor muscle (antagonist) relaxes. (Image credit: "Stretch Reflex" by Cenveo is licensed under CC BY 3.0)

A specialized reflex to protect the surface of the eye is the **corneal reflex**, or the eye blink reflex. When the cornea is stimulated by a tactile stimulus, or even by bright light in a related reflex, blinking is initiated. The sensory component travels through the trigeminal nerve, which carries somatosensory information from the face, or through the optic nerve, if the stimulus is bright light. The motor response travels through the facial nerve and innervates the orbicularis oculi on the same side. This reflex is commonly tested during a physical exam using an air puff or a gentle touch of a cotton-tipped applicator.

Concept Review

The motor components of the somatic nervous system begin with the frontal lobe of the brain, where the prefrontal cortex is responsible for higher functions such as working memory. The integrative and associate functions of the prefrontal lobe feed into the secondary motor areas, which help plan movements. The premotor cortex and supplemental motor area then feed into the primary motor cortex that initiates movements. Large Betz cells project through the corticobulbar and corticospinal tracts to synapse on lower motor neurons in the brainstem and ventral horn of the spinal cord, respectively. These connections are responsible for generating movements of skeletal muscles.

The extrapyramidal system includes projections from the brainstem and higher centers that influence movement, mostly to maintain balance and posture, as well as to maintain muscle tone. The superior colliculus and red nucleus in the midbrain, the vestibular nuclei in the medulla, and the reticular formation throughout the brainstem each have tracts projecting to the spinal cord in this system. Descending input from the secondary motor cortices, basal nuclei, and cerebellum connect to the origins of these tracts in the brainstem.

All of these motor pathways project to the spinal cord to synapse with motor neurons in the ventral horn of the spinal cord. These lower motor neurons are the cells that connect to skeletal muscle and cause contractions. These neurons project through the spinal nerves to connect to the muscles at neuromuscular junctions. One motor neuron connects to multiple muscle fibers within a target muscle. The number of fibers that are innervated by a single motor neuron varies on the basis of the precision necessary for that muscle and the amount of force necessary for that motor unit. The quadriceps, for example, have many fibers controlled by single motor neurons for powerful contractions that do not need to be precise. The extraocular muscles have only a small number of fibers controlled by each motor neuron because moving the eyes does not require much force, but needs to be very precise.

Reflexes are the simplest circuits within the somatic nervous system. A withdrawal reflex from a painful stimulus only requires the sensory fiber that enters the spinal cord and the motor neuron that projects to a muscle. Antagonist and postural muscles can be coordinated with the withdrawal, making the connections more complex. The simple, single neuronal connection is the basis of

somatic reflexes. The corneal reflex is contraction of the orbicularis oculi muscle to blink the eyelid when something touches the surface of the eye. Stretch reflexes maintain a constant length of muscles by causing a contraction of a muscle to compensate for a stretch that can be sensed by a specialized receptor called a muscle spindle.

Review Questions

Q. Which region of the frontal lobe is responsible for initiating movement by directly connecting to cranial and spinal motor neurons?

A. prefrontal cortex

B. supplemental motor area

C. premotor cortex

D. primary motor cortex

Answer

D

Q. Which extrapyramidal tract incorporates equilibrium sensations with motor commands to aid in posture and movement?

A. tectospinal tract

B. vestibulospinal tract

C. reticulospinal tract

D. corticospinal tract

Answer

B

Q. Which region of gray matter in the spinal cord contains motor neurons that innervate skeletal muscles?

A. ventral horn

B. dorsal horn

C. lateral horn

D. lateral column

Answer

A

Glossary

anterior corticospinal tract
division of the corticospinal pathway that travels through the ventral (anterior) column of the spinal cord and controls axial musculature through the medial motor neurons in the ventral (anterior) horn

Betz cells
output cells of the primary motor cortex that cause musculature to move through synapses on cranial and spinal motor neurons

Broca's area
region of the frontal lobe associated with the motor commands necessary for speech production

cerebral peduncles
segments of the descending motor pathway that make up the white matter of the ventral midbrain

cervical enlargement
region of the ventral (anterior) horn of the spinal cord that has a larger population of motor neurons for the greater number of and finer control of muscles of the upper limb

corneal reflex
protective response to stimulation of the cornea causing contraction of the orbicularis oculi muscle resulting in blinking of the eye

corticobulbar tract
connection between the cortex and the brainstem responsible for generating movement

corticospinal tract
connection between the cortex and the spinal cord responsible for generating movement

executive functions
cognitive processes of the prefrontal cortex that lead to directing goal-directed behavior, which is a precursor to executing motor commands

extrapyramidal system
pathways between the brain and spinal cord that are separate from the corticospinal tract and are responsible for modulating the movements generated through that primary pathway

frontal eye fields
area of the prefrontal cortex responsible for moving the eyes to attend to visual stimuli

internal capsule
segment of the descending motor pathway that passes between the caudate nucleus and the putamen

lateral corticospinal tract
division of the corticospinal pathway that travels through the lateral column of the spinal cord and controls appendicular musculature through the lateral motor neurons in the ventral (anterior) horn

lumbar enlargement
region of the ventral (anterior) horn of the spinal cord that has a larger population of motor neurons for the greater number of muscles of the lower limb

premotor cortex
cortical area anterior to the primary motor cortex that is responsible for planning movements

pyramidal decussation
location at which corticospinal tract fibers cross the midline and segregate into the anterior and lateral divisions of the pathway

pyramids
segment of the descending motor pathway that travels in the anterior position of the medulla

reticulospinal tract
extrapyramidal connections between the brainstem and spinal cord that modulate movement, contribute to posture, and regulate muscle tone

stretch reflex
response to activation of the muscle spindle stretch receptor that causes contraction of the muscle to maintain a constant length

supplemental motor area
cortical area anterior to the primary motor cortex that is responsible for planning movements

tectospinal tract
extrapyramidal connections between the superior colliculus and spinal cord

vestibulospinal tract
extrapyramidal connections between the vestibular nuclei in the brainstem and spinal cord that modulate movement and contribute to balance on the basis of the sense of equilibrium

withdrawal reflex
automatic withdrawal of an extremity (e.g. a hand) from a painful stimulus

working memory
function of the prefrontal cortex to maintain a representation of information that is not in the immediate environment

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14: AUTONOMIC NERVOUS SYSTEM

The autonomic nervous system (ANS) controls cardiac and smooth muscle, as well as glandular tissue, to maintain homeostasis when the body is at rest or in an emergency.. It is associated with unconscious responses to regulate heart rate, blood pressure, body temperature, sweating and digestion. It can be divided into two divisions: the sympathetic divisions maintains homeostasis in conditions of "fight-or-flight" while the parasympathetic division maintains homeostasis when the body is at rest. In this chapter, you will look at the structures of the two divisions of the ANS, their reflexes and the control on the ANS exercised by the central nervous system.

14.1: Introduction to the Autonomic Nervous System

14.2: Divisions of the Autonomic Nervous System

14.3: Autonomic Synapses, Effects and Reflexes

14.4: Central Control Autonomic Function

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14.1: Introduction to the Autonomic Nervous System

Chapter Learning Objectives

After studying this chapter, you will be able to:

- Describe the components of the autonomic nervous system
- Differentiate between the structures of the sympathetic and parasympathetic divisions in the autonomic nervous system
- Name the components of a visceral reflex specific to the autonomic division to which it belongs
- Describe how the central nervous system coordinates and contributes to autonomic functions

The autonomic nervous system is often associated with the “fight-or-flight response,” which refers to the preparation of the body to either run away from a threat or to stand and fight in the face of that threat. To suggest what this means, consider the (very unlikely) situation of seeing a lioness hunting out on the savannah. Though this is not a common threat that humans deal with in the modern world, it represents the type of environment in which the human species thrived and adapted. The reactions modern humans have in the modern world are based on these prehistoric situations. If your boss is walking down the hallway on Friday afternoon looking for “volunteers” to come in on the weekend, your response is the same as the prehistoric human seeing the lioness running across the savannah: fight or flight. Most likely, your response to your boss—not to mention the lioness—would be flight. Run away! The autonomic system is responsible for the physiological response to make that possible, and hopefully successful. Adrenaline starts to flood your circulatory system. Your heart rate increases. Sweat glands become active. The bronchi of the lungs dilate to allow more air exchange. Pupils dilate to increase visual information. Blood pressure increases in general, and blood vessels dilate in skeletal muscles. Time to run. Similar physiological responses would occur in preparation for fighting off the threat.

This response should sound a bit familiar. The autonomic nervous system is tied into emotional responses as well, and the fight-or-flight response probably sounds like a panic attack. In the modern world, these sorts of reactions are associated with anxiety as much as with response to a threat. It is engrained in the nervous system to respond like this. In fact, the adaptations of the autonomic nervous system probably predate the human species and are likely to be common to all mammals, and perhaps shared by many animals. That lioness might herself be threatened in some other situation. However, the autonomic nervous system is not just about responding to threats. Besides the fight-or-flight response, there are the responses referred to as “rest and digest.” If a lioness is successful in her hunting, then she is going to rest from the exertion. Her heart rate will slow. Breathing will return to normal. The digestive system has a big job to do. Much of the function of the autonomic system is based on the connections within an autonomic, or visceral, reflex.

Figure 14.1.1: Fight or Flight? Though the threats that modern humans face are not large predators, the autonomic nervous system is adapted to this type of stimulus. The modern world presents stimuli that trigger the same response. (Image credit: "Lioness on the hunt" by Vernon Swanepoel is licensed under CC BY 2.0)

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14.2: Divisions of the Autonomic Nervous System

By the end of this section, you will be able to:

- Compare and contrast the somatic and autonomic nervous systems
- Describe the functional differences between the sympathetic and parasympathetic divisions
- Outline the anatomical differences between the two divisions of the ANS
- Describe the preganglionic neurons, ganglia, nerves and pathways of the two divisions of the ANS

Comparison between the Somatic and Autonomic Nervous System

The nervous system can be divided into two functional parts: the **somatic nervous system (SNS)** and the **autonomic nervous system (ANS)**. The major difference between these two systems is based on whether you are conscious of its process. The somatic nervous system consciously detects sensory stimuli from the special senses, skin and proprioceptors. The autonomic nervous system reflexively responds to visceral sensory stimuli, such as levels of carbon dioxide concentration in the blood or stretch caused by blood pressure, that you are not consciously aware of. Moreover, the motor efferent branches of these two systems innervate different **target effectors**. While the somatic motor neurons innervate and cause contraction of skeletal muscles, autonomic motor neurons innervate and control cardiac and smooth muscle, as well as glandular tissue. Thus, the motor response of the somatic nervous system is voluntary while the one of the autonomic nervous system is involuntary.

Another major difference between these two systems lies within the number of lower motor neurons that are involved in the response. In the somatic nervous system, a single lower somatic motor neuron of the brainstem or spinal cord extends from the CNS towards a skeletal muscle through a cranial or spinal nerve, respectively. These somatic motor neurons have large myelinated axons that release acetylcholine (ACh) at neuromuscular junctions. In comparison, the autonomic nervous system is composed of a chain of two lower motor neurons. The cell body of the first of the two ANS motor neurons is located in the brainstem or spinal cord and is called a **preganglionic neuron**. The axon of the preganglionic neuron extends outside of the CNS through cranial or spinal nerves forming a **preganglionic fiber**. This fiber projects to an **autonomic ganglion** of the peripheral nervous system. Preganglionic neurons have small myelinated axons that release acetylcholine (ACh) to excite a second motor neuron. The second motor neuron is called a **ganglionic neuron**. The cell body of the ganglionic neuron resides within the autonomic ganglion and its axon extends to an effector (cardiac muscle, smooth muscle, or gland) forming a **postganglionic fiber**. Ganglionic neurons have small unmyelinated axons that release either acetylcholine (ACh) or norepinephrine (NE) to either excite or inhibit an effector, depending on the type of receptors present on the effector. Since preganglionic and postganglionic axons are small or unmyelinated, the propagation of autonomic electrical impulses is slower compared to the somatic motor axons.

Divisions of the Autonomic Nervous System

The autonomic nervous system regulates many of the internal organs through a balance of two aspects, or divisions. The two divisions of the autonomic nervous system are the **sympathetic division** and the **parasympathetic division**. From a functional point of view, the sympathetic system is associated with the **fight-or-flight response**, while the parasympathetic activity is referred to by the epithet **rest-and-digest**. Homeostasis is the balance between the two divisions since one system complements the other. For example, the parasympathetic division will be more active when you need to conserve energy and replenish nutrient stores. The sympathetic division will activate when during exercise, stress or emergency situations. Many autonomic target effectors have dual innervation by both divisions of the autonomic nervous system, which determines their activity. For example, the heart receives connections from both the sympathetic and parasympathetic divisions: one causes heart rate to increase, whereas the other causes heart rate to decrease. From an anatomical point of view, both divisions use preganglionic and ganglionic neurons to innervate cardiac muscle, smooth muscle and glands. However, the location of preganglionic neurons within the CNS is different between the two divisions. Moreover, the location of the ganglia as well as the length of preganglionic and postganglionic axons differ in the two divisions. In the following sections, you will examine the functional and anatomical features of the sympathetic and parasympathetic divisions.

Sympathetic Division

To respond to a threat—to fight or to run away—the sympathetic system causes diverse effects as many different effector organs are activated together for a common purpose. More oxygen needs to be inhaled and delivered to skeletal muscle. The respiratory, cardiovascular, and musculoskeletal systems are all activated together. Additionally, sweating keeps the excess heat that comes from muscle contraction from causing the body to overheat. The digestive system shuts down so that blood is not absorbing nutrients when it should be delivering oxygen to skeletal muscles. To coordinate all these responses, the connections in the sympathetic system diverge from a limited region of the central nervous system (CNS) to a wide array of ganglia that project to the many effector organs simultaneously. The complex set of structures that compose the output of the sympathetic system make it possible for these disparate effectors to come together in a coordinated, systemic change.

The sympathetic division of the autonomic nervous system influences various organ systems of the body through connections emerging from the first thoracic (T1) and second lumbar (L2) spinal segments (Figure 14.2.1). It is referred to as the **thoracolumbar system** to reflect this anatomical basis. Sympathetic preganglionic neurons are located in the lateral horns of any of these spinal regions and project to ganglia adjacent to the vertebral column through the ventral roots of the spinal cord.

Sympathetic Neurons, Ganglia and Nerves

The majority of ganglia of the sympathetic system belong to a network of **sympathetic chain (or trunk) ganglia** that runs lateral to the vertebral column and anterior to the paired spinal nerves (Figure 14.2.1). For this reason, these ganglia can also be called **paravertebral ganglia**. The ganglia appear as a series of clusters of neurons linked by ascending and descending axonal bridges called **sympathetic trunks**. There are typically 23 ganglia in the sympathetic chain on either side of the spinal column. Three correspond to the cervical region, 12 are in the thoracic region, four are in the lumbar region, and four correspond to the sacral region. The thoracic and lumbar sympathetic preganglionic fibers travel sequentially through ventral roots, spinal nerves and bundles of myelinated axons called **white rami communicantes** (singular = ramus communicans) to reach the correspondent paravertebral ganglia (Figure 14.2.2). Here preganglionic sympathetic fibers either synapse with ganglionic neurons or often pass on through the sympathetic chain ganglion into one of its emerging nerves to synapse with ganglionic neurons elsewhere. Postganglionic fibers then travel through additional nerves to their destination in one of the organs. Many of the fibers from the postganglionic neurons in the sympathetic chain ganglia pass back into the spinal nerves through **gray rami communicantes** composed of unmyelinated axons and carry sympathetic information through the spinal nerves.

The cervical and sacral paravertebral ganglia are not connected to the spinal cord directly through the spinal nerves, but through sympathetic trunks. Among the cervical ganglia, the **superior cervical ganglion** contains ganglionic neurons that innervate structures of the head and neck such the dilator pupillae and superior tarsal muscles of the eye, the lacrimal gland, mucous membranes of the nose, palate and mouth, and salivary glands. The **middle and inferior cervical ganglia** contain ganglionic neurons that innervate neck and thoracic organs such as the larynx, trachea, pharynx, smooth muscle of arteries and heart.

Preganglionic sympathetic axons extending from T5-L2 do not synapse in a sympathetic chain ganglion and instead continue through the chain anteriorly towards the abdominal and pelvic organs (Figure 14.2.1). These axons form **splanchnic nerves** and typically terminate in three autonomic ganglia called **prevertebral (or collateral) ganglia**. They are referred to as prevertebral because they are anterior to the vertebral column and descending aorta. The prevertebral ganglia are associated with controlling organs in the abdominal cavity, and are also considered part of the enteric nervous system. The **greater splanchnic nerves** originate from T5-T9 spinal nerves and synapse into the prevertebral **celiac ganglia**. Postganglionic axons from these ganglia innervate stomach, abdominal blood vessels, liver, gallbladder, part of the pancreas and small intestine. The **lesser splanchnic nerves** originate from T9-T11 spinal nerves and project to prevertebral **superior mesenteric ganglia**. Postganglionic axons from these ganglia innervate the large intestine. The **least splanchnic nerves** that extend from T12 spinal nerves project to and terminate in the prevertebral renal ganglia (not shown here). Postganglionic axons from these ganglia innervate the remainder of the pancreas and small intestine, the proximal part of the large intestine, the kidneys and proximal ureters. **Lumbar splanchnic nerves** that extend from L1-L2 spinal nerves terminate to the **inferior mesenteric ganglia**. Postganglionic axons from these ganglia project to and innervate the distal part of the large intestine, rectum, kidneys, urinary bladder, gonads and external genitalia. In addition to the above splanchnic nerves, there are also small **sacral splanchnic nerves** that originate from the sacral sympathetic ganglia that are not directly connected to the spinal cord and terminate into urinary and reproductive organs.

The neurons of the sympathetic autonomic ganglia are multipolar in shape, with dendrites radiating out around the cell body where synapses from the spinal cord neurons are made. Because the sympathetic ganglia are adjacent to the vertebral column, preganglionic sympathetic fibers are relatively short, and they are myelinated. Compared with the preganglionic fibers, postganglionic sympathetic fibers are long because of the relatively greater distance from the ganglion to the target effector. These postganglionic fibers are unmyelinated. A diagram that shows the connections of the sympathetic system is somewhat like

a circuit diagram that shows the electrical connections between different receptacles and devices. In Figure 14.2.1, the “circuits” of the sympathetic system are intentionally simplified.

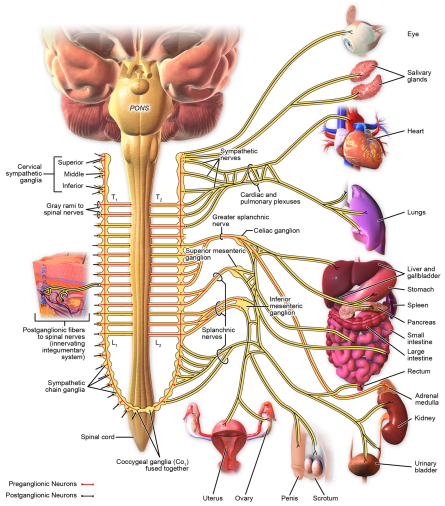


Figure 14.2.1: Sympathetic Innervation. Neurons from the lateral horn of the spinal cord extend their preganglionic nerve fibers (shown in red) to the sympathetic chain ganglia on either side of the vertebral column or to prevertebral (collateral) ganglia that are anterior to the vertebral column in the abdominal cavity. Axons from these ganglionic neurons called postganglionic nerve fibers (shown in black) then project to target effectors throughout the body. (Image credit: "Blausen 0838 Sympathetic Innervation" by BruceBlaus is licensed under CC BY 3.0).

Sympathetic Pathways

A sympathetic preganglionic axon leaving the lateral horn of the thoracolumbar spinal cord enters the sympathetic chain ganglia, where it branches toward 10-20 targets. To continue with the analogy of the circuit diagram, there are four different types of “junctions” that connect the sympathetic preganglionic axons with their effectors. The type of pathway is determined by the location and type of target effector organ being innervated. In all cases, the preganglionic axon extends into the spinal nerve at the same level as its spinal cord segment. Then it can then either (a) synapse in the paravertebral ganglion and carry information through the spinal nerve at the same level (spinal nerve pathway), (b) ascend to a more superior or descend to a more inferior paravertebral ganglion, synapse there and carry information through sympathetic nerves (sympathetic nerve pathway), (c) descend to a prevertebral (collateral) ganglion, synapse there and carry information through a splanchnic nerve (splanchnic nerve pathway) or (d) project directly to the adrenal medulla (adrenal medulla pathway). All of these branches mean that one preganglionic neuron can influence different regions of the sympathetic system very broadly, by acting on widely distributed organs. In the following paragraphs, you will examine these four different pathways. Except for the adrenal medulla pathway, these connections are represented in Figure 14.2.2.

The **spinal nerve pathway** is the most direct connection. The sympathetic preganglionic nerve projects to the sympathetic chain ganglion at the same level as the target effector. The myelinated preganglionic fiber extending from the lateral horns of the spinal cord projects to the sympathetic chain ganglion through the ventral root and spinal nerve. Through the white ramus communicans, the fiber reaches and synapses with the ganglionic neuron in the sympathetic chain ganglion. The postganglionic fiber then projects to the target effector via the gray ramus communicans, which is formed by unmyelinated axons. An example of this type is spinal nerve T1 that synapses with the T1 sympathetic chain ganglion to innervate the skin (Figure 14.2.2.a). Indeed, this pathway generally innervates integumentary structures such as sweat glands, arrector pili muscles, and blood vessels of the skin in the neck, torso and limbs.

The **postganglionic sympathetic nerve pathway** occurs when the target effectors are located superior or inferior to the spinal segment at which the sympathetic preganglionic fiber emerges. With respect to the “wiring” involved, the synapse with the ganglionic neuron occurs at sympathetic chain ganglia superior or inferior to the location of the preganglionic neuron. In order to do this, the preganglionic fiber travels through sympathetic trunks to reach the superior or inferior sympathetic chain ganglion. The postganglionic fiber does not leave the ganglion through the gray ramus communicans. Instead, it extends away from the ganglion through a sympathetic nerve. An example of this is spinal nerve T1 that innervates the eye. The spinal nerve tracks up through the sympathetic trunks until it reaches the superior cervical ganglion, where it synapses with the ganglionic neuron and

projects to the eye through a sympathetic nerve (Figure 14.2.2.b). This pathway innervates viscera of head (sweat glands, arrector pili muscles, blood vessels of the skin; dilator pupillae, tarsal muscle and gland of the eye; salivary glands) and neck, and thoracic organs such as esophagus, heart, lungs, thoracic blood vessels.

Not all axons from the central neurons terminate in the sympathetic chain ganglia. The **splanchnic nerve pathway** include branches from the ventral nerve root that continue through the sympathetic chain ganglion and on to one of the prevertebral (collateral) ganglia as the greater splanchnic nerve or lesser splanchnic nerve. For example, the greater splanchnic nerve at the level of T5 synapses with a prevertebral (collateral) ganglion outside the sympathetic chain before making the connection to the postganglionic nerves that innervate the stomach (Figure 14.2.2.c). This pathway innervates abdominopelvic organs such as stomach, intestines, kidneys, ureters, urinary bladder and reproductive organs.

There is one additional way that preganglionic sympathetic fibers can control their effector organs and it is through the **adrenal medulla pathway**. However, in this pathway the preganglionic fiber does not terminate in a ganglion but instead projects to the **adrenal medulla**, the interior portion of the adrenal gland (Figure 14.2.1). These axons are still referred to as preganglionic fibers, but the target is not a ganglion per se. The cells in the adrenal medulla that are contacted by the preganglionic fibers are called **chromaffin cells**. These cells are neurosecretory cells that develop from the neural crest along with the sympathetic chain ganglia. These cells in the adrenal medulla release epinephrine and norepinephrine into the bloodstream, rather than using axons to communicate with target structures. This hormonal component means that the sympathetic chemical signal can spread throughout the body very quickly and affect many organ systems at once. At the same time, these hormones remain in the bloodstream longer than neurotransmitters, prolonging the sympathetic effects.

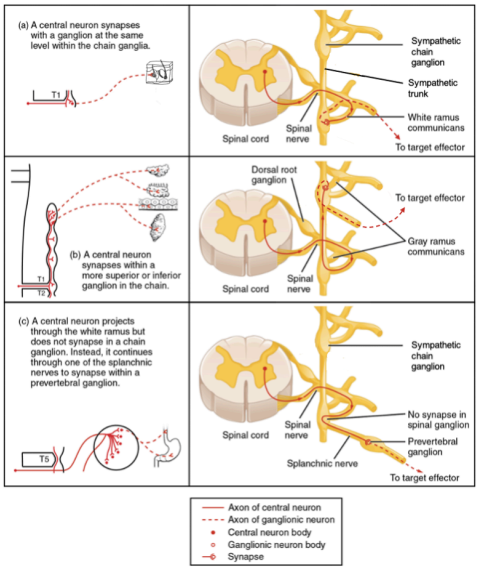


Figure 14.2.2: Sympathetic Pathways. The axon from a central sympathetic neuron in the spinal cord can project to the periphery in a number of different ways. (a) represents the spinal nerve pathway where the preganglionic fiber projects out and synapses onto a ganglionic neuron at the same level which then carries the information out through the spinal nerve. (b) represents the postganglionic sympathetic nerve pathway where a preganglionic branch projects and synapses onto a more superior or inferior ganglion in the chain which then carries the information out through a symapthetic nerve. (c) represents the splanchnic nerve pathway where a preganglionic branch extends through the white ramus communicans, but does not terminate on a ganglionic neuron in the chain. Instead, it projects through one of the splanchnic nerves to a prevertebral (collateral) ganglion. (Image credit: "Sympathetic Pathways" by Chiara Mazzasette is licensed under CC BY 4.0 / A derivative from the original work).

Parasympathetic Division

The parasympathetic division of the autonomic nervous system is named because its central neurons are located away from (para- = “apart from”) the thoracolumbar region of the spinal cord which is dedicated to the sympathetic division. Indeed, the parasympathetic system can also be referred to as the **craniosacral system** because the preganglionic neurons are located in nuclei of the brainstem and the lateral horn of the sacral spinal cord (S2 to S4) ({14{.}2{.}\eatSpaces{3} \endSpaces}\)).

Parasympathetic Neurons, Ganglia and Nerves

The connections, or “circuits,” of the parasympathetic division are similar to the general layout of the sympathetic division with a few specific differences. The parasympathetic preganglionic fibers from the cranial region travel in cranial nerves, whereas parasympathetic preganglionic fibers from the sacral region travel in spinal nerves. The targets of these fibers are **terminal ganglia**, which are located near the target effector, and **intramural ganglia**, which are found within the walls of the target organ. Terminal ganglia receive input from cranial nerves or sacral spinal nerves. The terminal ganglia that receive input from cranial nerves are found in the head and neck, as well as the thoracic and upper abdominal cavities, whereas the terminal ganglia that receive sacral input are in the lower abdominal and pelvic cavities. The postganglionic fiber projects from the terminal ganglia a short distance to the target effector, or to the specific target tissue within the organ.

The cranial nerves associated with the parasympathetic system are the oculomotor nerve (CN III), facial nerve (VII), glossopharyngeal nerve (CN IX) and vagus nerve (CN X). These nerves generate from particular nuclei of the brainstem. Nuclei in the midbrain are part of the oculomotor complex, and parasympathetic axons from those neurons travel in the **oculomotor nerve (CN III)** with the somatic motor fibers that innervate the extraocular muscles. The parasympathetic preganglionic fibers within the oculomotor nerve terminate in the **ciliary ganglion**, which is located in the posterior orbit. The postganglionic parasympathetic fibers then project to the sphincter pupillae and ciliary muscle of the iris to control the size of the pupil and the shape of the lens.

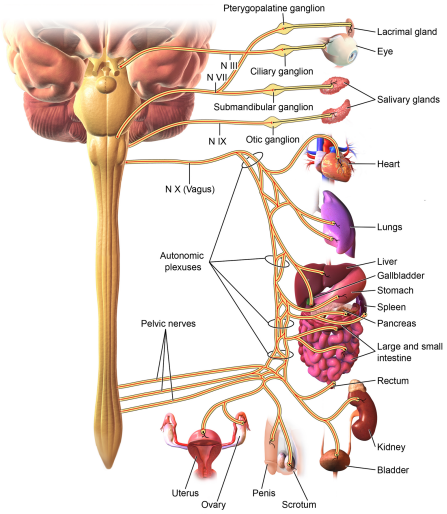
Parasympathetic preganglionic fibers exits the pons and travel through the **facial nerve (CN VII)** to control the secretions of the lacrimal apparatus, nasal epithelium and salivary glands. Two branches exit the facial nerve. The first branch terminates at the **pterygopalatine ganglion**. Postganglionic fibers from this ganglion extend to the lacrimal gland and glands of the nasal cavity, oral cavity, and palate. The second branch terminates at the **submandibular ganglion**. Postganglionic fibers from this ganglion project to submandibular and sublingual salivary glands.

Parasympathetic preganglionic fibers exits the medulla oblongata and travel through the **glossopharyngeal nerve (CN IX)** to the **otic ganglion**. Postganglionic fibers from this ganglion terminate to the parotid salivary glands.

The majority of parasympathetic preganglionic axons travel through the **vagus nerve (CN X)** that innervates thoracic and abdominal organs as well as the gonads (ovaries and testes). Autonomic parasympathetic neurons in the medulla oblongata project through the vagus nerve to the terminal and intramural ganglia of target effectors such as heart, airways, esophagus, stomach, liver, gallbladder, pancreas, small and large intestine, kidneys, ureters, and gonads.

The remaining parasympathetic preganglionic axons originate from neurons of the lateral horns of the S2-S4 segments of the spinal cord. These axons form the **pelvic splanchnic nerves** that project to terminal or intramural ganglia of abdominal and pelvic organs. The main target effectors are the distal portion of the large intestine, rectum, urinary bladder, and most of reproductive organs.

Comparing the relative lengths of axons in the parasympathetic system, the preganglionic fibers are long and the postganglionic fibers are short because the ganglia are close to—and sometimes within—the target effectors. Parasympathetic preganglionic axons tend to have fewer than 4 branches. The lack of divergent branches in parasympathetic preganglionic axons prevents a systemic response and facilitates discrete and localized effects on one group of organs at a time.



Parasympathetic Innervation

Figure 14.2.3: Parasympathetic Innervation. Neurons from brain-stem nuclei, or from the lateral horn of the sacral spinal cord, extend their preganglionic nerve fibers (shown in red) to terminal ganglia near the effector organs or to intramural ganglia within the walls of the effector organs. Postganglionic axons (shown in black) from these ganglionic neurons then project the short distance to target effectors (Image credit: "Blausen 0703 Parasympathetic Innervation" by BruceBlaus is licensed under CC BY 3.0).

Everyday Connections

Fight or Flight? What About Fright and Freeze?

The original usage of the epithet “fight or flight” comes from a scientist named Walter Cannon who worked at Harvard in 1915. The concept of homeostasis and the functioning of the sympathetic system had been introduced in France in the previous century. Cannon expanded the idea, and introduced the idea that an animal responds to a threat by preparing to stand and fight or run away. The nature of this response was thoroughly explained in a book on the physiology of pain, hunger, fear, and rage.

When students learn about the sympathetic system and the fight-or-flight response, they often stop and wonder about other responses. If you were faced with a lioness running toward you as pictured at the beginning of this chapter, would you run or would you stand your ground? Some people would say that they would freeze and not know what to do. So isn’t there really more to what the autonomic system does than fight, flight, rest, or digest. What about fear and paralysis in the face of a threat?

The common epithet of “fight or flight” is being enlarged to be “fight, flight, or fright” or even “fight, flight, fright, or freeze.” Cannon’s original contribution was a catchy phrase to express some of what the nervous system does in response to a threat, but it is incomplete. The sympathetic system is responsible for the physiological responses to emotional states. The name “sympathetic” can be said to mean that (sym- = “together”; -pathos = “pain,” “suffering,” or “emotion”).

Concept Review

The nervous system can be divided into two functional parts: the somatic nervous system (SNS) and the autonomic nervous system (ANS). The differences between these two systems lie on multiple features: the conscious level of their processes, their targets, the number of lower motor neurons involved and the neurotransmitters used. The autonomic nervous system reflexively responds to visceral sensory stimuli, such as levels of carbon dioxide concentration in the blood or stretch caused by blood pressure, that you are not consciously aware of and involuntarily controls cardiac and smooth muscle, as well as glandular tissue. The autonomic nervous system has a chain of two lower autonomic motor neurons. The first neuron is called a preganglionic neuron and resides in the brainstem or lateral horns of the spinal cord. This neuron releases ACh to a second neuron called a ganglionic neuron that is located in ganglia. The axons of ganglionic neurons are called postganglionic fibers. These nerves extend to target effectors and release either ACh or norepinephrine (NE).

The primary responsibilities of the autonomic nervous system are to regulate homeostatic mechanisms in the body. The way we respond to the world around us, to manage the internal environment on the basis of the external environment, is divided between two parts of the autonomic nervous system. The sympathetic division responds to threats and produces a readiness to confront the threat or to run away: the fight-or-flight response. The parasympathetic division plays the opposite role. When the external environment does not present any immediate danger, a restful mode descends on the body, and the digestive system is more active.

The sympathetic output of the nervous system originates out of the lateral horn of the thoracolumbar spinal cord. An axon from one of these central neurons projects by way of the ventral spinal nerve root, spinal nerve and white rami communicantes to a sympathetic chain (paravertebral) ganglion. The preganglionic fibers can synapse on ganglionic neurons here or extend to one of the prevertebral (collateral) ganglia via the splanchnic nerves (splanchnic nerve pathway). Postganglionic fibers of sympathetic chain ganglia can either return to the spinal nerve through the gray rami communicantes (spinal nerve pathway) or extend away from the ganglion through a sympathetic nerve (postganglionic sympathetic pathway). The sympathetic system also has a specialized preganglionic connection to the adrenal medulla that causes epinephrine and norepinephrine to be released into the bloodstream rather than exciting a neuron that contacts an organ directly (adrenal medulla pathway).

The parasympathetic output is based in the brainstem and sacral spinal cord. Neurons from particular nuclei in the brainstem carry parasympathetic information through four cranial nerves: oculomotor nerve (CN III), facial nerve (VII), glossopharyngeal nerve (CN IX) and vagus nerve (CN X). In the sacral spinal cord, preganglionic neurons of the lateral horn project out through pelvic splanchnic nerves. Cranial and sacral preganglionic fibers extend to terminal and intramural ganglia located close to or within the wall of target effectors. The postganglionic fibers of the ganglionic neurons then contact the target tissues within the organ to induce rest-and-digest responses. Due to the fact that parasympathetic ganglia are either close to or within the target organ, parasympathetic preganglionic axons are longer and postganglionic axons are shorter, compared to the sympathetic division.

Review Questions

Q. Which of these physiological changes would *not* be considered part of the sympathetic fight-or-flight response?

A. increased heart rate

B. increased sweating

C. dilated pupils

D. increased stomach motility

Answer

D

Q. Which type of fiber could be considered the longest?

A. preganglionic parasympathetic

B. preganglionic sympathetic

C. postganglionic parasympathetic

D. postganglionic sympathetic

Answer

A

Q. Which of these cranial nerves contains preganglionic parasympathetic fibers?

A. optic, CN II

B. facial, CN VII

C. trigeminal, CN V

D. hypoglossal, CN XII

Answer

B

Q. Which of the following is *not* a target of a sympathetic preganglionic fiber?

A. intermural ganglion

B. prevertebral (collateral) ganglion

C. adrenal gland

D. chain ganglion

Answer

A

Critical Thinking Questions

Q. In the context of a lioness hunting on the savannah, why would the sympathetic system *not* activate the digestive system?

A. Whereas energy is needed for running away from the threat, blood needs to be sent to the skeletal muscles for oxygen supply. The additional fuel, in the form of carbohydrates, probably wouldn't improve the ability to escape the threat as much as the diversion of oxygen-rich blood would hinder it.

Glossary

acetylcholine
neurotransmitter that binds at a motor end-plate to trigger contraction

adrenal medulla
interior portion of the adrenal (or suprarenal) gland that releases epinephrine and norepinephrine into the bloodstream as hormones

adrenal medulla pathway
sympathetic pathway where preganglionic fibers innervate directly the adrenal medulla

autonomic ganglion
localized collection of autonomic neurons in the peripheral nervous system

autonomic nervous system (ANS)
functional division of the nervous system that is responsible for homeostatic reflexes that coordinate control of cardiac and smooth muscle, as well as glandular tissue

celiac ganglion
one of the prevertebral (collateral) ganglia of the sympathetic system that projects to the digestive system

chromaffin cells
neuroendocrine cells of the adrenal medulla that release epinephrine and norepinephrine into the bloodstream as part of sympathetic system activity

ciliary ganglion
one of the terminal ganglia of the parasympathetic system, located in the posterior orbit, axons from which project to the iris

collateral ganglia
ganglia outside of the sympathetic chain that are targets of sympathetic preganglionic fibers, which are the celiac, inferior mesenteric, and superior mesenteric ganglia; sometimes referred to as prevertebral ganglia

craniosacral system
alternate name for the parasympathetic division of the autonomic nervous system that is based on the anatomical location of central neurons in brain-stem nuclei and the lateral horn of the sacral spinal cord; also referred to as craniosacral outflow

epinephrine
signaling molecule released from the adrenal medulla into the bloodstream as part of the sympathetic response

facial nerve (CN VII)
seventh cranial nerve; responsible for contraction of the facial muscles and for part of the sense of taste, as well as causing saliva production

fight-or-flight response
set of responses induced by sympathetic activity that lead to either fleeing a threat or standing up to it, which in the modern world is often associated with anxious feelings

ganglionic neuron
specifically refers to the cell body of a neuron in the autonomic system that is located in a ganglion

glossopharyngeal nerve (CN IX)
ninth cranial nerve; responsible for contraction of muscles in the tongue and throat and for part of the sense of taste, as well as causing saliva production

gray rami communicantes
(singular = ramus communicans) unmyelinated structures that provide a short connection from a sympathetic chain ganglion to the spinal nerve that contains the postganglionic sympathetic fiber

greater splanchnic nerve
nerve that contains fibers from T5-T9 central sympathetic neurons that do not synapse in the chain ganglia but project onto the celiac ganglion

inferior cervical ganglion
the most inferior of the three paravertebral ganglia of the cervical portion of the sympathetic trunk

inferior mesenteric ganglion
one of the collateral ganglia of the sympathetic system that projects to the digestive system

intramural ganglia
terminal ganglia of the parasympathetic system that are found within the walls of the target effector

least splanchnic nerve
nerve that contains fibers from T12 central sympathetic neurons that do not synapse in the chain ganglia but project onto the renal ganglion

lesser splanchnic nerve
nerve that contains fibers from T9-T11 central sympathetic neurons that do not synapse in the chain ganglia but project onto the superior mesenteric ganglion

lumbar splanchnic nerve
nerve that contains fibers from L1-L2 central sympathetic neurons that project to the inferior mesenteric ganglion

middle cervical ganglion
the middle of the three paravertebral ganglia of the cervical portion of the sympathetic trunk

norepinephrine
signaling molecule released as a neurotransmitter by most postganglionic sympathetic fibers as part of the sympathetic response, or as a hormone into the bloodstream from the adrenal medulla

oculomotor nerve (CN III)
third cranial nerve; responsible for contraction of four of the extraocular muscles, the muscle in the upper eyelid, and pupillary constriction

otic ganglion
one of the terminal ganglia of the parasympathetic system, located anterior to the ear, that innervates the parotid salivary gland for salivation

parasympathetic division
division of the autonomic nervous system responsible for restful and digestive functions

paravertebral ganglia
autonomic ganglia superior to the sympathetic chain ganglia

pelvic splanchnic nerves
nerves that contains fibers from S2-S4 parasympathetic neurons that innervate terminal or intramural ganglia of pelvic organs

postganglionic fiber
axon from a ganglionic neuron in the autonomic nervous system that projects to and synapses with the target effector

postganglionic sympathetic nerve pathway
connection between a sympathetic preganglionic neuron and its effector through a synapse onto ganglionic neurons at the level of the sympathetic chain ganglion and extension of postganglionic fibers through a sympathetic nerve

preganglionic fiber
axon from a central neuron in the autonomic nervous system that projects to and synapses with a ganglionic neuron; sometimes referred to as a preganglionic neuron

preganglionic neuron
autonomic central neuron located in the brainstem or lateral horn of the spinal cord

prevertebral ganglia
autonomic ganglia that are anterior to the vertebral column and functionally related to the sympathetic chain ganglia; sometimes referred to as collateral ganglia

pterygopalatine ganglion
one of the terminal ganglia of the parasympathetic system, located near the junction of the maxilla and palatine bones, that innervates the lacrimal gland and glands of oral and nasal cavities and palate

rest-and-digest response
set of functions associated with the parasympathetic system that lead to restful actions and digestion

sacral splanchnic nerves
nerves that contain fibers from S1-S2 central sympathetic neurons that do not synapse in the chain ganglia but project to urinary and reproductive organs

somatic nervous system (SNS)
functional division of the nervous system that is concerned with conscious perception, voluntary movement, and skeletal muscle reflexes

spinal nerve pathway
connection between a sympathetic preganglionic neuron and its effector through a synapse onto ganglionic neurons at the level of the sympathetic chain ganglion and extension of postganglionic fibers through gray rami communicantes and spinal nerves

splanchnic nerve pathway
connection between a sympathetic preganglionic neuron and its effector through a synapse onto ganglionic neurons at the level of a prevertebral ganglion and extension of postganglionic fibers to the target effector

splanchnic nerves
paired, autonomic nerves that carry sympathetic fibers, except for the pelvic splanchnic nerves which carry parasympathetic fibers.

submandibular ganglion
one of the terminal ganglia of the parasympathetic system, located near the angle of the mandible, that innervates the submandibular and sublingual salivary glands for salivation

superior cervical ganglion
one of the paravertebral ganglia of the sympathetic system that projects to the head

superior mesenteric ganglion
one of the prevertebral (collateral) ganglia of the sympathetic system that projects to the digestive system

sympathetic chain (trunk) ganglia
series of ganglia adjacent to the vertebral column that receive input from central sympathetic neurons

sympathetic division
division of the autonomic nervous system associated with the fight-or-flight response

sympathetic trunks
sympathetic fibers connecting adjacent sympathetic chain ganglia

target effector
organ, tissue, or gland that will respond to the control of an autonomic or somatic or endocrine signal

terminal ganglia
ganglia of the parasympathetic division of the autonomic system, which are located near or within the target effector, the latter also known as intramural ganglia

thoracolumbar system
alternate name for the sympathetic division of the autonomic nervous system that is based on the anatomical location of central neurons in the lateral horn of the thoracic and upper lumbar spinal cord

vagus nerve (CN X)
tenth cranial nerve; responsible for the autonomic control of organs in the thoracic and upper abdominal cavities

white rami communicantes
(singular = ramus communicans) myelinated structures that provide a short connection from a sympathetic chain ganglion to the spinal nerve that contains the preganglionic sympathetic fiber

Contributors and Attributions

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14.3: Autonomic Synapses, Effects and Reflexes

By the end of this section, you will be able to:

- Describe the synapses, signaling molecules and receptors involved in communication within the two divisions of the autonomic nervous system
- Determine the effect of the autonomic nervous system on the regulation of the various organ systems
- Explain autonomic tone and dual innervation
- Compare the structure of somatic and autonomic reflexes and differentiate between short and long reflexes

Autonomic Synapses

Where an autonomic neuron connects with a target, there is a synapse. What are referred to here as synapses may not fit the strictest definition of synapse. The structure of postganglionic connections are not the typical synaptic end bulb that is found at the neuromuscular junction, but rather are chains of swellings along the length of a postganglionic fiber. This place of connection is called a **varicosity** and is typical of the autonomic nervous system (ANS) (Figure 14.3.1). Each postganglionic axon has a high number of these endings resembling a string of beads. At each varicosity, synaptic vesicles containing **neurotransmitters** are present and ready to merge with the plasma membrane of the axon to release the neurotransmitters. On the target organ (smooth muscle, cardiac muscle or glands) **neurotransmitter receptors** are present.

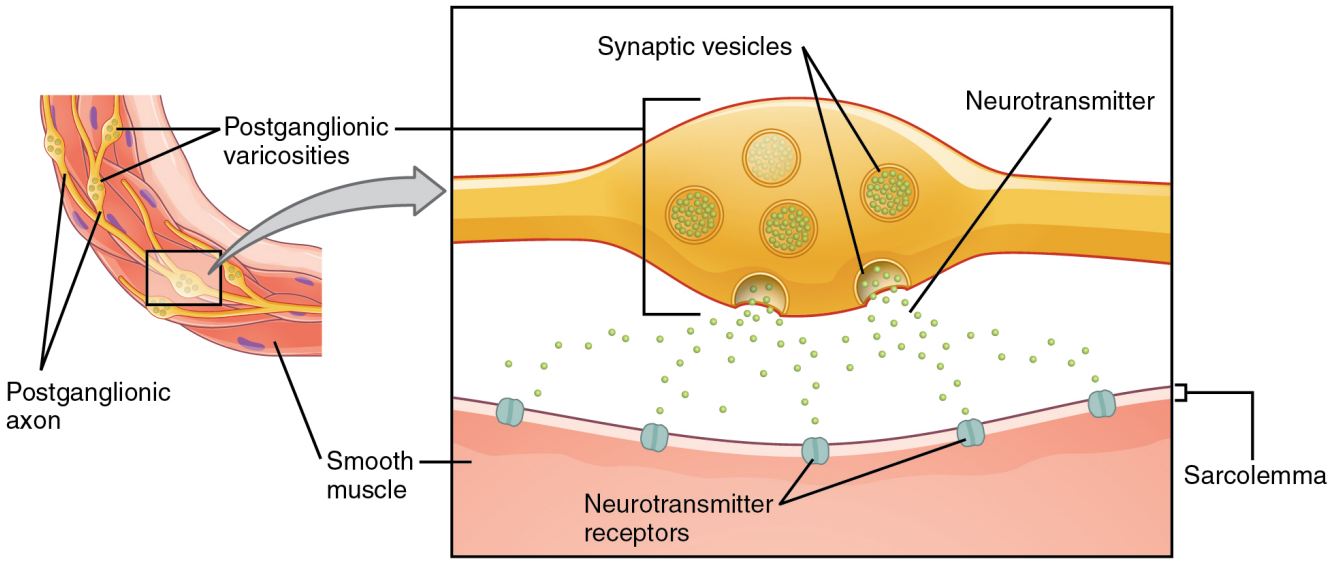

Figure 14.3.1: Autonomic Varicosities. The connection between autonomic postganglionic fibers and target effectors is called a varicosity. Multiple varicosities are present along the length of postganglionic axons forming an extended network of connections on the target effector. Inside the varicosity, synaptic vesicles containing the neurotransmitters are ready to merge with the plasma membrane and release their content. In this picture, the target effector is smooth muscle and receptors for the neurotransmitters are present on its sarcolemma. (Image credit: "Autonomic Varicosities" by OpenStax is licensed under CC BY 3.0)

Autonomic Neurotransmitters

Signaling molecules can belong to two broad groups. Neurotransmitters are released at synapses, whereas hormones are released into the bloodstream. However, the same molecule (for example epinephrine) can be released by neurons within the brain as a neurotransmitter or by the adrenal medulla into the bloodstream as a hormone, blurring the lines between these definitions. The main signaling molecules of the autonomic nervous system are **acetylcholine** (ACh) and **norepinephrine** (NE, also called noradrenaline). The adrenal medulla which is a modified sympathetic ganglion releases **epinephrine** (or adrenaline). These molecules will bind to specific receptors on the target cells. Cells that release acetylcholine are called **cholinergic**, while cells that

release norepinephrine or epinephrine are called **adrenergic**. Acetylcholine can bind to both **nicotinic receptors** and **muscarinic receptors**. Norepinephrine and epinephrine can bind to **adrenergic receptors**. For each of these classes of receptors, there are multiple subtypes (which we will not discuss in this book) that make the cells respond differently to the binding of the same molecule. Depending on the receptor type and subtype, the molecules released will cause either stimulation or inhibition. Thus, the effects of the autonomic divisions depend on the type of signaling molecule and receptor involved.

All preganglionic fibers, both sympathetic and parasympathetic, are cholinergic and release ACh (Table 14.3.1). All ganglionic neurons (the targets of these preganglionic fibers) have nicotinic receptors in their cell membranes, which leads to the stimulation and firing of an action potential from the ganglionic fibers in both sympathetic and parasympathetic divisions. Most sympathetic postganglionic fibers are adrenergic and release norepinephrine. The adrenal medulla which is part of the sympathetic division is also adrenergic and releases epinephrine. However, parasympathetic postganglionic fibers are cholinergic and release ACh. This pattern assures that effector organs under the control of both sympathetic and parasympathetic systems can respond differently. Target cells can contain various types and subtypes of receptors and their response will vary depending on the type of receptor and on the neurotransmitter released on them.

There is one exception to this pattern in the sympathetic system. The sympathetic postganglionic fibers that contact the blood vessels within skeletal muscle and sweat glands in the integument release ACh instead of norepinephrine. This does not create any problem because there is no parasympathetic input to these organs. Blood vessels of skeletal muscles and sweat glands have muscarinic receptors and vasodilate (increase diameter size) and produce and secrete sweat, respectively, in response to ACh.

At most of the other autonomic targets that are innervate by both divisions of the autonomic system, the effector response is based on which neurotransmitter is released and what receptor is present. For example, regions of the heart that establish heart rate are contacted by postganglionic fibers from both systems. If norepinephrine is released, it binds to an adrenergic receptor which causes the heart rate to increase. If ACh is released, it binds to a muscarinic receptor that causes the heart rate to slow. Without this parasympathetic input, the heart would work at a rate of approximately 100 beats per minute (bpm). The sympathetic system speeds that up, as it would during exercise, to 120–140 bpm, for example. The parasympathetic system slows it down to the resting heart rate of 60–80 bpm.

(Table 14.3.1) Comparison of Sympathetic and Parasympathetic Signaling Molecules

	Sympathetic Division	Parasympathetic Division
Preganglionic axons	release ACh (cholinergic)	release ACh (cholinergic)
Ganglionic neurons	contain nicotinic (ACh) receptors	contain nicotinic (ACh) receptors
Postganglionic axons	release NE (adrenergic); release ACh (cholinergic) only in blood vessels of skeletal muscle and sweat glands	release ACh (cholinergic)
Adrenal medulla	contain muscarinic (ACh) receptors; releases epinephrine (adrenergic)	

Autonomic Effects

Organ systems are balanced between the input from the sympathetic and parasympathetic divisions. When something upsets that balance, the homeostatic mechanisms strive to return it to its regular state. For each organ system, there may be more of a sympathetic or parasympathetic tendency to the resting state, which is known as the **autonomic tone** of the system. For example, the resting heart rate is the result of the parasympathetic system slowing the heart down from its intrinsic rate of 100 bpm, consequently the heart can be said to be in parasympathetic tone.

Many effector organs of the autonomic nervous system have **dual innervation**, meaning that they receive competing inputs from the sympathetic and parasympathetic divisions. These divisions each play a role in effecting change, usually in competing directions. At the level of the target effector, the signal of which system is sending the message is strictly chemical and depending on the division involved and neurotransmitter released, the effects would be diverse. For example, the heart and the eye are examples of organs with dual innervation. The sympathetic system increases heart rate, whereas the parasympathetic system

decreases heart rate. The sympathetic system dilates the pupil of the eye, whereas the parasympathetic system constricts the pupil.

In some organs, opposing effects are achieved without dual innervation. For example, the arrector pili muscles, sweat glands, and blood vessels to skeletal muscles and skin are primarily under sympathetic control. Blood pressure is partially determined by the contraction of smooth muscle in the walls of blood vessels. The parasympathetic system has no significant input to the systemic blood vessels, so the sympathetic system determines their tone. The sympathetic system causes vasoconstriction of blood vessels. However, the increasing metabolic activity of muscles causes (paracrine) vasodilation. This allows for blood flow to increase for those skeletal muscles that will be active in the fight-or-flight response.

Not always the sympathetic and parasympathetic divisions have opposite effects and, in a few cases, the two systems cooperate. The best example of cooperative effects occurs in the male sexual function. In reproductive organs, blood vessels of erectile tissues are innervate with parasympathetic projection, making them an exception. Acetylcholine released by these postganglionic parasympathetic fibers cause the vessels to dilate, leading to the engorgement of the erectile tissue and penile erection. At the same time, the sympathetic nervous system stimulates ejaculation by causing the contractions of the seminal vesicle and prostate gland. This synergistic effect facilitates reproduction.

Table 14.3.2 summarizes the effects on different organs of the sympathetic and parasympathetic divisions.

Table 14.3.2 *Effects of Sympathetic and Parasympathetic Divisions*

Target Effector	Sympathetic Effect	Parasympathetic Effect
Arrector pili muscles	Contraction to cause hair erection	None
Sweat glands	Secretion	None
Salivary glands	Inhibits	Stimulates
Pupils	Dilation	Constriction
Ciliary muscle	None	Contraction for near vision
Heart	Increases heart rate	Decreases heart rate
Blood vessels of the heart (coronary)	Vasoconstriction or vasodilation	Vasodilation
Blood vessels to skeletal muscles	Vasodilation	None
Blood vessels to skin and other organs	Vasoconstriction to increase blood pressure	None
Blood vessels to gastrointestinal (GI) tract	Vasoconstriction	Vasodilation
Bronchi of lungs	Dilation	Constriction
Gastrointestinal (GI) tract gland secretion	Inhibits	Stimulates
Gallbladder	Inhibits	Stimulates
Peristalsis (motility)	Inhibits	Stimulates
Sphincters	Contraction (close)	Relaxation (open)
Urinary bladder	Relaxation	Contraction
Internal urethral sphincter	Contraction (close)	Relaxation (open)
Penis	Stimulates ejaculation	Stimulates erection
Clitoris	None	Stimulates erection

Autonomic Reflexes

The autonomic nervous system regulates organ systems through circuits that resemble the reflexes described in the somatic nervous system. A **somatic reflex**, such as the withdrawal reflex, involves a . An **autonomic reflex**, also called **visceral reflex**, consists of contractions of smooth or cardiac muscle, or secretion by glands that are mediated by a **reflex arc** in response to a stimulus. Examples of autonomic reflexes are the initial release of urine (micturition), alteration of heart rate or blood pressure,

regulation of digestion and modification of the pupil size. Somatic and visceral reflexes present similarities and differences.

One similarity between a somatic reflex and a visceral reflex is the **afferent branch**, that brings information towards the CNS. Sensory neurons receiving input from the periphery—with cell bodies in the sensory ganglia, either of a cranial nerve or a dorsal root ganglion adjacent to the spinal cord—project into the CNS to initiate the reflex.

Many of the inputs to visceral reflexes are from special or somatic senses, but particular senses are associated with the viscera that are not part of the conscious perception of the environment through the somatic nervous system. For example, there is a specific type of mechanoreceptor, called a **baroreceptor**, in the walls of the aorta and carotid sinuses that senses the stretch of those organs when blood volume or pressure increases. You do not have a conscious perception of having high blood pressure, but that is an important afferent branch of the cardiovascular and, particularly, vasomotor reflexes. The sensory neuron is essentially the same as any other general sensory neuron, a unipolar neuron that has a cell body in a sensory ganglion. The baroreceptors from the carotid arteries have axons in the glossopharyngeal nerve, and those from the aorta have axons in the vagus nerve.

Though visceral senses are not primarily a part of conscious perception, those sensations sometimes make it to conscious awareness. If a visceral sense is strong enough, it will be perceived. The sensory homunculus—the representation of the body in the primary somatosensory cortex—only has a small region allotted for the perception of internal stimuli. If you swallow a large bolus of food, for instance, you will probably feel the lump of that food as it pushes through your esophagus, or even if your stomach is distended after a large meal. If you inhale especially cold air, you can feel it as it enters your larynx and trachea. These sensations are not the same as feeling high blood pressure or blood sugar levels.

When particularly strong visceral sensations rise to the level of conscious perception, the sensations are often felt in unexpected places. For example, strong visceral sensations of the heart will be felt as pain in the left shoulder and left arm. This irregular pattern of projection of conscious perception of visceral sensations is called **referred pain**. Depending on the organ system affected, the referred pain will project to different areas of the body (Figure 14.3.2). The location of referred pain is not random, but a definitive explanation of the mechanism has not been established. The most broadly accepted theory for this phenomenon is that the visceral sensory fibers enter into the same level of the spinal cord as the somatosensory fibers of the referred pain location. By this explanation, the visceral sensory fibers from the mediastinal region, where the heart is located, would enter the spinal cord at the same level as the spinal nerves from the shoulder and arm, so the brain misinterprets the sensations from the mediastinal region as being from the axillary and brachial regions.

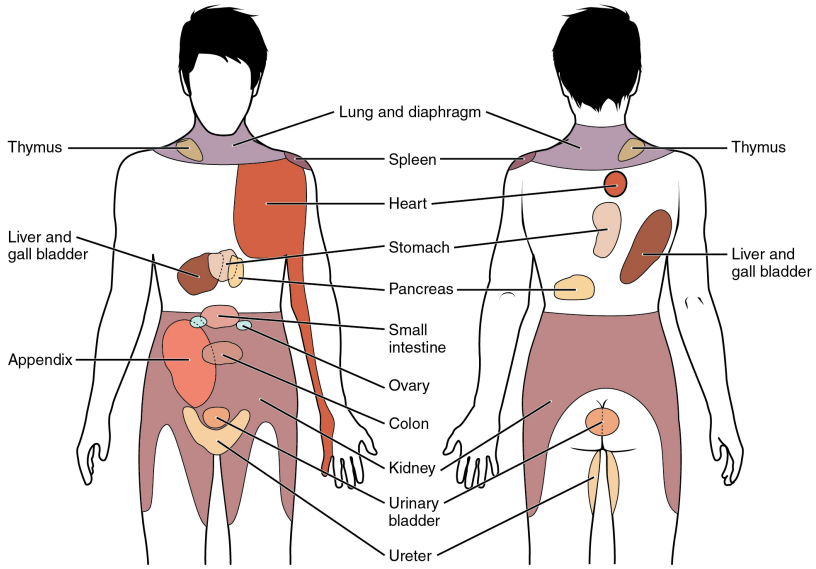

Figure 14.3.2: Referred Pain Chart. Referred pain is the conscious perception of visceral sensations. Represented here is a map that associates the pain perceived in certain regions with the visceral organs. Some sensations are felt locally, whereas others are perceived as affecting areas that are quite distant from the involved organ. (Image credit: "Referred Pain Chart" by OpenStax is licensed under CC BY 3.0)

One difference between a somatic and visceral reflex is in the **efferent branch**. The output of a somatic reflex is the lower motor neuron in the ventral horn of the spinal cord that projects directly to a skeletal muscle to cause its contraction. The output of a visceral reflex is a two-step pathway starting with the preganglionic fiber emerging from a lateral horn neuron in the spinal cord, or a cranial nucleus neuron in the brainstem, to a ganglion—followed by the postganglionic fiber projecting to a target effector

(Figure 14.3.3).

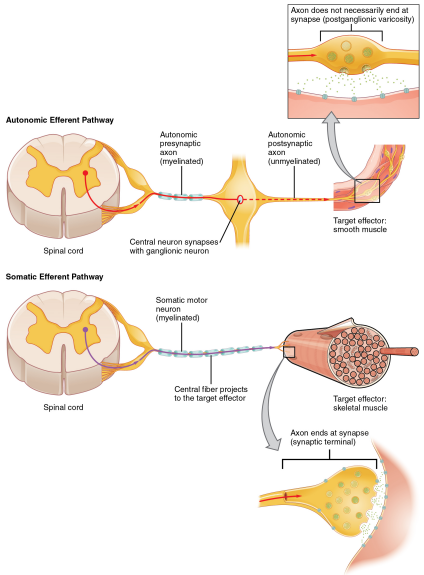

Figure 14.3.3: Comparison of Somatic and Visceral Reflexes. The efferent branches of somatic and visceral reflexes are different. (a) Visceral reflexes involve a projection from the central autonomic neuron to a ganglion through autonomic preganglionic (presynaptic) axons which are myelinated. This is followed by a second projection from the ganglion to the target effector (in this case smooth muscle) through autonomic postganglionic (postsynaptic) axons which are unmyelinated. These axons end in postganglionic varicosities. (b) Somatic reflexes involve a direct connection from the ventral horn of the spinal cord to the skeletal muscle through a myelinated central fiber. This axon ends in a synaptic terminal. (Image credit: "Comparison of Somatic and Visceral Reflexes" by OpenStax is licensed under CC BY 3.0)

Short and Long Reflexes

Somatic reflexes involve sensory neurons that connect sensory receptors to the central nervous system (CNS) and motor neurons that project back out to the skeletal muscles. Visceral reflexes that involve the sympathetic or parasympathetic systems share similar connections. However, there are reflexes that do not need to involve any CNS components. A **long reflex** has afferent branches that enter the spinal cord or brain and involve the efferent branches. A **short reflex** is completely peripheral with sensory neurons synapsing with motor neurons in autonomic ganglia; the CNS is not involved (Figure 14.3.4).

A division of the nervous system that is related to the autonomic nervous system is the enteric nervous system. The word enteric refers to the digestive organs, so this represents the nervous tissue that is part of the digestive system. There are a few myenteric plexuses in which the nervous tissue in the wall of the digestive tract organs can directly influence digestive function. If stretch receptors in the stomach are activated by the filling and distension of the stomach, a short reflex will directly activate the smooth muscle fibers of the stomach wall to increase motility to digest the excessive food in the stomach. No CNS involvement is needed because the stretch receptor is directly activating a neuron in the wall of the stomach that causes the smooth muscle to contract. That neuron, connected to the smooth muscle, is a ganglionic parasympathetic neuron that can be controlled by a fiber found in the vagus nerve.

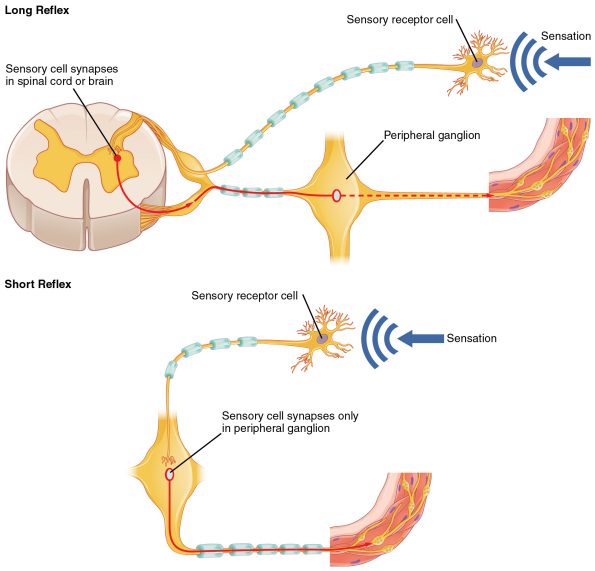

Figure 14.3.4: Autonomic Short and Long Reflexes. Sensory input can stimulate either a short or a long reflex. A sensory neuron can project to the brain or spinal cord or to an autonomic ganglion. The long reflex involves integration in the spinal cord or brain. In this reflex, a sensory signal coming from a sensory receptor cell reaches a central motor neuron, which then extends a preganglionic axon to a peripheral ganglion. The postganglionic axons extend to the organ effector. A short reflex involves the direct stimulation of a ganglionic neuron by the sensory neuron. In this reflex, a sensory receptor cell synapses onto a ganglionic neuron, whose axons extend to the organ effector. (Image credit: "Short and Long Reflexes" by OpenStax is licensed under CC BY 3.0)

DISORDERS OF THE...

Nervous System: Kehr's Sign

Kehr's sign is the presentation of pain in the left shoulder, chest, and neck regions following rupture of the spleen. The spleen is in the upper-left abdominopelvic quadrant, but the pain is more in the shoulder and neck. How can this be? The sympathetic fibers connected to the spleen are from the celiac ganglion, which would be from the mid-thoracic to lower thoracic region whereas parasympathetic fibers are found in the vagus nerve, which connects in the medulla of the brainstem. However, the neck and shoulder would connect to the spinal cord at the mid-cervical level of the spinal cord. These connections do not fit with the expected correspondence of visceral and somatosensory fibers entering at the same level of the spinal cord.

The incorrect assumption would be that the visceral sensations are coming from the spleen directly. In fact, the visceral fibers are coming from the diaphragm. The nerve connecting to the diaphragm takes a special route. The phrenic nerve is connected to the spinal cord at cervical levels 3 to 5. The motor fibers that make up this nerve are responsible for the muscle contractions that drive ventilation. These fibers have left the spinal cord to enter the phrenic nerve, meaning that spinal cord damage below the mid-cervical level is not fatal by making ventilation impossible. Therefore, the visceral fibers from the diaphragm enter the spinal cord at the same level as the somatosensory fibers from the neck and shoulder.

The diaphragm plays a role in Kehr's sign because the spleen is just inferior to the diaphragm in the upper-left quadrant of the abdominopelvic cavity. When the spleen ruptures, blood spills into this region. The accumulating hemorrhage then puts pressure on the diaphragm. The visceral sensation is actually in the diaphragm, so the referred pain is in a region of the body that corresponds to the diaphragm, not the spleen

Concept Review

The synapses in the autonomic system are not always the typical type of connection first described in the neuromuscular junction. Instead of having synaptic end bulbs at the very end of an axonal fiber, they may have swellings called varicosities along the length of a fiber so that it makes a network of connections within the target tissue. All preganglionic fibers are cholinergic and release acetylcholine (ACh). All ganglionic neurons (the targets of these preganglionic fibers) have nicotinic receptors in

their cell membranes. Most sympathetic postganglionic fibers are adrenergic and release norepinephrine. The adrenal medulla which is part of the sympathetic division is also adrenergic and releases epinephrine. Parasympathetic postganglionic fibers are cholinergic and release ACh. Target cells can contain various types and subtypes of receptors and their response will vary depending on the type of receptor and on the neurotransmitter released on them. The sympathetic postganglionic fibers that contact the blood vessels within skeletal muscle and sweat glands in the integument release ACh instead of norepinephrine. This does not create any problem because there is no parasympathetic input to these organs.

For each organ system, there may be more of a sympathetic or parasympathetic tendency to the resting state, which is known as the autonomic tone of the system. Many effector organs of the autonomic nervous system have dual innervation, meaning that they receive competing inputs from the sympathetic and parasympathetic divisions. The sympathetic system increases heart rate, whereas the parasympathetic system decreases heart rate. The sympathetic system dilates the pupil of the eye, whereas the parasympathetic system constricts the pupil. The competing inputs can contribute to the resting tone of the organ system. Heart rate is normally under parasympathetic tone, whereas blood pressure is normally under sympathetic tone. The heart rate is slowed by the autonomic system at rest, whereas blood vessels retain a slight constriction at rest. In a few systems of the body, the competing input from the two divisions is not the norm. The sympathetic tone of blood vessels is caused by the lack of parasympathetic input to the systemic circulatory system. Only certain regions receive parasympathetic input that relaxes the smooth muscle wall of the blood vessels. Sweat glands are another example of organs that only receive input from the sympathetic system. Not always the sympathetic and parasympathetic divisions have opposite effects and, in a few cases, the two systems cooperate.

Autonomic nervous system function is based on the visceral reflex, which is similar to the somatic reflex. Like the somatic reflex, the afferent branch is composed of sensory neurons receiving input from the periphery project into the CNS to initiate the reflex. The cell bodies of these sensory neurons are located in the sensory ganglia, either of a cranial nerve or a dorsal root ganglion adjacent to the spinal cord. However, the efferent branch of a visceral reflex is composed of two neurons. The central neuron projects from the spinal cord or brainstem to synapse on the ganglionic neuron that projects to the effector. The afferent branch of the somatic and visceral reflexes is very similar, as many somatic and special senses activate autonomic responses. However, there are visceral senses that do not form part of conscious perception. If a visceral sensation, such as cardiac pain, is strong enough, it will rise to the level of consciousness. However, the sensory homunculus does not provide a representation of the internal structures to the same degree as the surface of the body, so visceral sensations are often experienced as referred pain, such as feelings of pain in the left shoulder and arm in connection with a heart attack.

Review Questions

Q. Which of the following represents a sensory input that is *not* part of both the somatic and autonomic systems?

A. vision

B. taste

C. baroreception

D. proprioception

Answer

C

Q. What is the term for a reflex that does *not* include a CNS component?

A. long reflex

B. visceral reflex

C. somatic reflex

D. short reflex

Answer

D

Critical Thinking Questions

Q. A target effector, such as the heart, receives input from the sympathetic and parasympathetic systems. What is the actual difference between the sympathetic and parasympathetic divisions at the level of those connections (i.e., at the synapse)?

> A. The postganglionic sympathetic fiber releases norepinephrine, whereas the postganglionic parasympathetic fiber releases acetylcholine. Specific locations in the heart have adrenergic receptors and muscarinic receptors. Which receptors are bound is the signal that determines how the heart responds.

Q. Damage to internal organs will present as pain associated with a particular surface area of the body. Why would something like irritation to the diaphragm, which is between the thoracic and abdominal cavities, feel like pain in the shoulder or neck?

> A. The nerves that carry sensory information from the diaphragm enter the spinal cord in the cervical region where somatic sensory fibers from the shoulder and neck would enter. The brain superimposes this experience onto the sensory homunculus where the somatic nerves are connected.

Glossary

acetylcholine
: neurotransmitter that binds at a motor end-plate to trigger contraction

adrenergic
: cells that release norepinephrine or epinephrine, which bind to adrenergic receptors

adrenergic receptor
: receptors to which epinephrine and norepinephrine bind

afferent branch
: component of a reflex arc that represents the input from a sensory neuron, for either a special or general sense

autonomic reflex
: reflex involving an internal organ as the effector, under the control of the autonomic nervous system; also known as visceral reflex

autonomic tone
: tendency of an organ system to be governed by one division of the autonomic nervous system over the other, such as heart rate being lowered by parasympathetic input at rest

baroreceptor
: mechanoreceptor that senses the stretch of blood vessels to indicate changes in blood pressure

cholinergic
: cells that release acetylcholine, which binds to muscarinic or nicotinic receptors

dual innervation
: innervation of a target organ by both sympathetic and parasympathetic divisions

efferent branch
: component of a reflex arc that represents the output, with the target being an effector, such as muscle or glandular tissue

epinephrine
: signaling molecule released from the adrenal medulla into the bloodstream as part of the sympathetic response

long reflex
reflex arc that includes the central nervous system

muscarinic receptor
type of acetylcholine receptor protein that is characterized by also binding to muscarine

neurotransmitter
chemical signal that is released from the synaptic end bulb or varicosities of a neuron to cause a change in the target cell

neurotransmitter receptor
receptor specific for a neurotransmitter

nicotinic receptor
type of acetylcholine receptor protein that is characterized by also binding to nicotine

norepinephrine
signaling molecule released as a neurotransmitter by most postganglionic sympathetic fibers as part of the sympathetic response, or as a hormone into the bloodstream from the adrenal medulla

referred pain
the conscious perception of visceral sensation projected to a different region of the body, such as the left shoulder and arm pain as a sign for a heart attack

reflex arc
circuit of a reflex that involves a sensory input and motor output, or an afferent branch and an efferent branch, and an integrating center to connect the two branches

short reflex
reflex arc that does not include any components of the central nervous system

somatic reflex
reflex involving skeletal muscle as the effector, under the control of the somatic nervous system

varicosity
enlargement of neurons that release neurotransmitters into synaptic clefts

visceral reflex
reflex involving an internal organ as the effector, under the control of the autonomic nervous system; also known as autonomic reflex

Contributors and Attributions

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14.4: Central Control Autonomic Function

By the end of this section, you will be able to:

- Describe the role of higher centers of the brain in autonomic regulation
- Explain how the hypothalamus exercises autonomic control
- Explain how the amygdala influences the autonomic function
- Describe the function of the medulla and the pathways important to descending control of the autonomic system

Autonomic control is based on the visceral reflexes, composed of the afferent and efferent branches. These homeostatic mechanisms are based on the balance between the two divisions of the autonomic system, which results in tone for various organs that is based on the predominant input from the sympathetic or parasympathetic systems. Coordinating that balance requires integration that begins with forebrain structures like the hypothalamus and continues into the brainstem and spinal cord.

Central Control of Autonomic Reflexes

The autonomic nervous system is controlled and influenced by the cerebral cortex, hypothalamus, limbic system, medulla oblongata and spinal cord. In the next sections we will focus on the inputs from the hypothalamus, amygdala and medulla oblongata.

Hypothalamus

The **hypothalamus** is the control center for many homeostatic mechanisms. It regulates both autonomic function and endocrine function. The optic nerve projects primarily to the thalamus, which is the necessary relay to the occipital cortex for conscious visual perception. Another projection of the optic nerve, however, goes to the hypothalamus. The hypothalamus then uses this visual system input to drive the **pupillary reflexes**. If the retina is activated by high levels of light, the hypothalamus stimulates the parasympathetic response which stimulates the circular fibers of the iris to contract and constrict the pupil. If the optic nerve message shows that low levels of light are falling on the retina, the hypothalamus activates the sympathetic response which dilates the pupil. When light hits the retina in one eye, both pupils contract. When that light is removed, both pupils dilate again back to the resting position. When the stimulus is unilateral (presented to only one eye), the response is bilateral (both eyes). The same is not true for somatic reflexes. If you touch a hot radiator, you only pull that arm back, not both. Central control of autonomic reflexes is different than for somatic reflexes.

The hypothalamus also receives input from other areas of the forebrain through the **medial forebrain bundle** (Figure 14.4.1). The olfactory cortex, the basal nuclei, and the amygdala project into the hypothalamus through the medial forebrain bundle. These forebrain structures inform the hypothalamus about the state of the nervous system and can influence the regulatory processes of homeostasis. A good example of this is found in the amygdala, which is found beneath the cerebral cortex of the temporal lobe and plays a role in our ability to remember and feel emotions.

Output from the hypothalamus follows two main tracts, the **dorsal longitudinal fasciculus** and the medial forebrain bundle (Figure 14.4.1). Along these two tracts, the hypothalamus can influence major parasympathetic nuclei in the brainstem such as the **oculomotor complex**, the **dorsal motor nucleus** and the **nucleus ambiguus**, and preganglionic (central) neurons of the thoracolumbar spinal cord. Neurons in the dorsal nucleus of the vagus nerve and the nucleus ambiguus project through the vagus nerve (cranial nerve X) to the terminal ganglia of the thoracic and abdominal cavities.

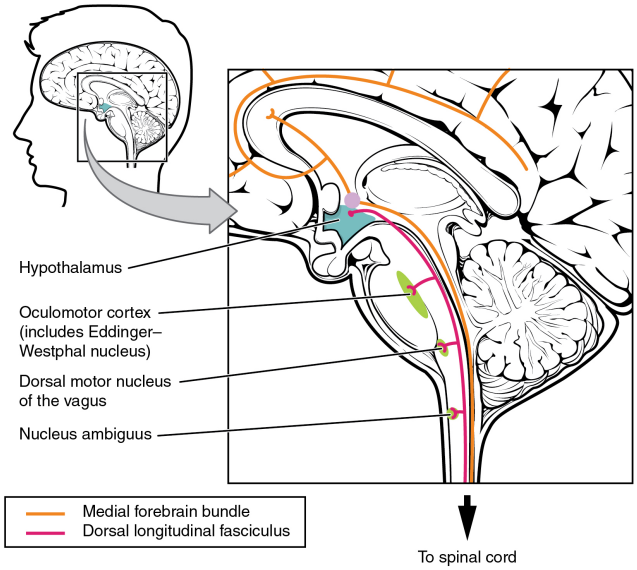

Figure 14.4.1: Fiber Tracts of the Central Autonomic System. The hypothalamus is the source of most of the central control of autonomic function. It receives input from cerebral structures through the medial forebrain bundle. The hypothalamus then projects to brainstem and spinal cord structures through the medial forebrain bundle and the dorsal longitudinal fasciculus. to regulate the balance of sympathetic and parasympathetic input to the organ systems of the body. (Image credit: "Fiber Tracts of the Central Autonomic System" by OpenStax is licensed under CC BY 3.0)

Amygdala

The **amygdala** is a group of nuclei in the medial region of the temporal lobe that is part of the **limbic lobe**, a C-shaped region of the cortex on the medial side of each cerebral hemisphere, consisting of portions of the temporal, parietal, and frontal lobes (Figure 14.4.2). The limbic lobe includes structures that are involved in emotional responses, as well as structures that contribute to memory function. The limbic lobe has strong connections with the hypothalamus and influences the state of its activity on the basis of emotional state. For example, when you are anxious or scared, the amygdala will send signals to the hypothalamus along the medial forebrain bundle that will stimulate the sympathetic fight-or-flight response. The hypothalamus will also stimulate the release of stress hormones through its control of the endocrine system in response to amygdala input.

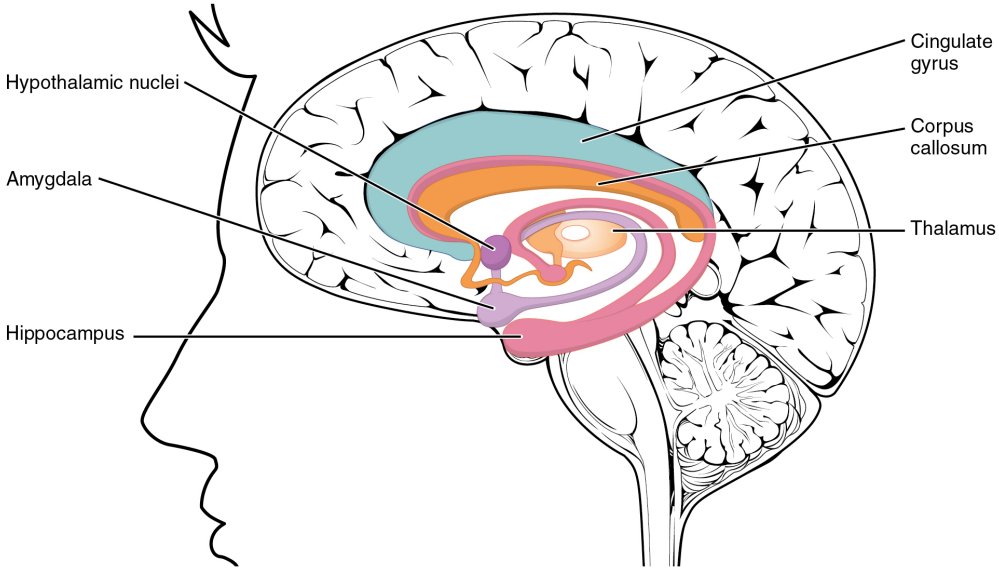

Figure 14.4.2: Limbic Lobe. Structures arranged around the edge of the cerebrum constitute the limbic lobe, which includes the amygdala, hippocampus, and cingulate gyrus, and connects to the hypothalamus, which sits inferior and anterior to the thalamus. (Image credit: "Limbic Lobe" by OpenStax is licensed under CC BY 3.0)

Medulla oblongata

The **medulla oblongata** contains nuclei referred to as the **cardiovascular center**, which controls the smooth and cardiac muscle of the cardiovascular system through autonomic connections. When the homeostasis of the cardiovascular system shifts, such as when blood pressure changes, the coordination of the autonomic system can be accomplished within this region. Furthermore, when descending inputs from the hypothalamus stimulate this area, the sympathetic system can increase activity in the cardiovascular system, such as in response to anxiety or stress. The preganglionic sympathetic fibers that are responsible for increasing heart rate are referred to as the **cardiac accelerator nerves**, whereas the preganglionic sympathetic fibers responsible for constricting blood vessels compose the **vasomotor nerves**.

Several brainstem nuclei are important for the visceral control of major organ systems. One brainstem nucleus involved in cardiovascular function is the **solitary nucleus**. It receives sensory input about blood pressure and cardiac function from the glossopharyngeal and vagus nerves, and its output will activate sympathetic stimulation of the heart or blood vessels through the upper thoracic lateral horn. Another brainstem nucleus important for visceral control is the **dorsal motor nucleus of the vagus nerve**, which is the motor nucleus for the parasympathetic functions ascribed to the vagus nerve, including decreasing the heart rate, relaxing bronchial tubes in the lungs, and activating digestive function through the enteric nervous system. The **nucleus ambiguus**, which is named for its ambiguous histology, also contributes to the parasympathetic output of the vagus nerve and targets muscles in the pharynx and larynx for swallowing and speech, as well as contributing to the parasympathetic tone of the heart along with the dorsal motor nucleus of the vagus.

EVERYDAY CONNECTIONS

Exercise and the Autonomic System

In addition to its association with the fight-or-flight response and rest-and-digest functions, the autonomic system is responsible for certain everyday functions. For example, it comes into play when homeostatic mechanisms dynamically change, such as the physiological changes that accompany exercise. Getting on the treadmill and putting in a good workout will cause the heart rate to increase, breathing to be stronger and deeper, sweat glands to activate, and the digestive system to suspend activity. These are the same physiological changes associated with the fight-or-flight response, but there is nothing chasing you on that treadmill.

This is not a simple homeostatic mechanism at work because “maintaining the internal environment” would mean getting all those changes back to their set points. Instead, the sympathetic system has become active during exercise so that your body can cope with what is happening. A homeostatic mechanism is dealing with the conscious decision to push the body away from a resting state. The heart, actually, is moving away from its homeostatic set point. Without any input from the autonomic system, the heart would beat at approximately 100 bpm, and the parasympathetic system slows that down to the resting rate of approximately 70 bpm. But in the middle of a good workout, you should see your heart rate at 120–140 bpm. You could say that the body is stressed because of what you are doing to it. Homeostatic mechanisms are trying to keep blood pH in the normal range, or to keep body temperature under control, but those are in response to the choice to exercise.

Concept Review

The autonomic system integrates sensory information and higher cognitive processes to generate output, which balances homeostatic mechanisms. The central autonomic structure is the hypothalamus, which coordinates sympathetic and parasympathetic efferent pathways to regulate activities of the organ systems of the body. The majority of hypothalamic output travels through the medial forebrain bundle and the dorsal longitudinal fasciculus to influence brainstem and spinal components of the autonomic nervous system. The medial forebrain bundle also connects the hypothalamus with higher centers of the limbic system where emotion can influence visceral responses. The amygdala is a structure within the limbic system that influences the hypothalamus in the regulation of the autonomic system, as well as the endocrine system.

These higher centers have descending control of the autonomic system through brainstem centers, primarily in the medulla, such as the cardiovascular center. This collection of medullary nuclei regulates cardiac function, as well as blood pressure. Sensory input from the heart, aorta, and carotid sinuses project to these regions of the medulla. The solitary nucleus increases sympathetic tone of the cardiovascular system through the cardiac accelerator and vasomotor nerves. The nucleus ambiguus and the dorsal motor nucleus both contribute fibers to the vagus nerve, which exerts parasympathetic control of the heart by decreasing heart rate.

Review Questions

Q. Which of these locations in the forebrain is the master control center for homeostasis through the autonomic and endocrine systems?

A. hypothalamus

B. thalamus

C. amygdala

D. cerebral cortex

Answer

A

Q. Which nerve projects to the hypothalamus to indicate the level of light stimuli in the retina?

A. glossopharyngeal

B. oculomotor

C. optic

D. vagus

Answer

C

Q. What region of the limbic lobe is responsible for generating stress responses via the hypothalamus?

A. hippocampus

B. amygdala

C. mammillary bodies

D. prefrontal cortex

Answer

B

Q. What is another name for the preganglionic sympathetic fibers that project to the heart?

A. solitary tract

B. vasomotor nerve

C. vagus nerve

D. cardiac accelerator nerve

Answer

D

Q. What central fiber tract connects forebrain and brainstem structures with the hypothalamus?

A. cardiac accelerator nerve

B. medial forebrain bundle

C. dorsal longitudinal fasciculus

D. corticospinal tract

Answer

B

Critical Thinking Questions

Q. Horner's syndrome is a condition that presents with changes in one eye, such as pupillary constriction and dropping of eyelids, as well as decreased sweating in the face. Why could a tumor in the thoracic cavity have an effect on these autonomic functions?

> A. Pupillary dilation and sweating, two functions lost in Horner's syndrome, are caused by the sympathetic system. A tumor in the thoracic cavity may interrupt the output of the thoracic ganglia that project to the head and face.

Q. The cardiovascular center is responsible for regulating the heart and blood vessels through homeostatic mechanisms. What tone does each component of the cardiovascular system have? What connections does the cardiovascular center invoke to keep these two systems in their resting tone?

> A. The heart—based on the resting heart rate—is under parasympathetic tone, and the blood vessels—based on the lack of parasympathetic input—are under sympathetic tone. The vagus nerve contributes to the lowered resting heart rate, whereas the vasomotor nerves maintain the slight constriction of systemic blood vessels.

Glossary

amygdala
: nucleus deep in the temporal lobe of the cerebrum that is related to memory and emotional behavior

cardiac accelerator nerves
: preganglionic sympathetic fibers that cause the heart rate to increase when the cardiovascular center in the medulla initiates a signal

cardiovascular center
: region in the medulla that controls the cardiovascular system through cardiac accelerator nerves and vasomotor nerves, which are components of the sympathetic division of the autonomic nervous system

dorsal longitudinal fasciculus
: major output pathway of the hypothalamus that descends through the gray matter of the brainstem and into the spinal cord

dorsal motor nucleus
: elongated nucleus within the medulla oblongata

hypothalamus
: major region of the diencephalon that is responsible for coordinating autonomic and endocrine control of homeostasis

limbic lobe
: structures arranged around the edges of the cerebrum that are involved in memory and emotion

medial forebrain bundle
: fiber pathway that extends anteriorly into the basal forebrain, passes through the hypothalamus, and extends into the brainstem and spinal cord

medulla oblongata
: the most inferior part of the brainstem

nucleus ambiguus
: brain-stem nucleus that contains neurons that project through the vagus nerve to terminal ganglia in the thoracic cavity; specifically associated with the heart

oculomotor complex
: A group of interrelated nuclei found near the midline in the rostral midbrain that innervate somatic and visceral muscles through the oculomotor nerve

pupillary reflex
: contraction of the pupil on exposure of the retina to light

solitary nucleus
: medullar nucleus that receives taste information from the facial and glossopharyngeal nerves

vasomotor nerves
: preganglionic sympathetic fibers that cause the constriction of blood vessels in response to signals from the cardiovascular center

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15: ENDOCRINE SYSTEM

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15.1: Introduction to the Endocrine System

15.2: An Overview of the Endocrine System

15.3: Pituitary Gland and Hypothalamus

15.4: Thyroid Gland

15.5: Parathyroid Glands

15.6: Adrenal Glands

15.7: Pineal Gland

15.8: Gonadal and Placental Hormones

15.9: Endocrine Pancreas

15.10: Organs with Secondary Endocrine Functions

15.11: Development and Aging of the Endocrine System

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15.1: Introduction to the Endocrine System

Chapter Learning Objectives:

After studying this chapter, you will be able to:

- Identify the contributions of the endocrine system to homeostasis
- Discuss the chemical composition of hormones and the mechanisms of hormone action
- Summarize the site of production, regulation, and effects of the hormones of the pituitary, thyroid, parathyroid, adrenal, and pineal glands
- Discuss the hormonal regulation of the reproductive system
- Explain the role of the pancreatic endocrine cells in the regulation of blood glucose
- Identify the hormones released by the heart, kidneys, and other organs with secondary endocrine functions
- Discuss several common diseases associated with endocrine system dysfunction
- Discuss the embryonic development of, and the effects of aging on, the endocrine system

You may never have thought of it this way, but when you send a text message to two friends to meet you at the dining hall at six, you're sending digital signals that (you hope) will affect their behavior—even though they are some distance away. Similarly, certain cells send chemical signals to other cells in the body that influence their behavior. This long-distance intercellular communication, coordination, and control is critical for homeostasis, and it is the fundamental function of the endocrine system.

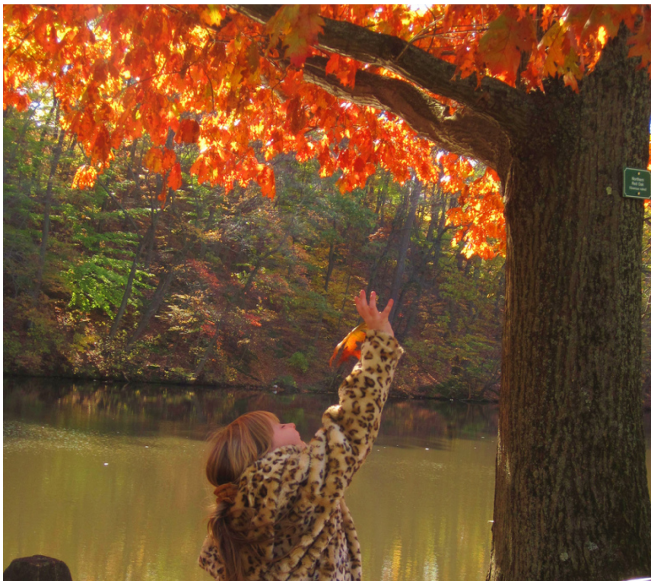

Figure 15.1.1: A Child Catches a Falling Leaf. Hormones of the endocrine system coordinate and control growth, metabolism, temperature regulation, the stress response, reproduction, and many other functions. Plants use similar mechanisms to control functions too, such as when a deciduous tree's leaves begin to change color and fall off in response to environmental signals. (Image credit: "Child Catching Leaf" by OpenStax is licensed under CC BY 4.0)

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15.2: An Overview of the Endocrine System

By the end of this section, you will be able to:

- Distinguish the types of intercellular communication and their importance
- Identify the major organs and tissues of the endocrine system and their location in the body
- Explain the role of hormones in controlling body functions via the bloodstream
- Discuss the role of feedback loops in hormone control

Communication is a process in which a sender transmits signals to one or more receivers to control and coordinate actions. In the human body, two major organ systems participate in relatively "long distance" communication: the nervous system and the endocrine system. Together, these two systems are primarily responsible for maintaining homeostasis in the body.

Neural and Endocrine Signaling

The nervous system uses two types of intercellular communication—electrical and chemical signaling—either by the direct action of an electrical potential, or in the latter case, through the action of chemical neurotransmitters such as serotonin or norepinephrine. In a synapse, neurotransmitters act locally and rapidly. When an electrical signal in the form of an action potential arrives at the synaptic terminal, neurotransmitters diffuse across the synaptic cleft (the gap between a sending neuron and a receiving cell). Once the neurotransmitters interact (bind) with receptors on the receiving (post-synaptic) cell, the receptor stimulation is transduced into a response such as continued electrical signaling or modification of cellular response. The target cell responds within milliseconds of receiving the chemical "message"; this response then ceases very quickly once the neural signaling ends. In this way, neural communication enables body functions that involve quick, brief actions, such as movement, sensation, and cognition.

In contrast, the **endocrine system** uses just one method of communication: chemical signaling. These signals are sent by the endocrine organs, which secrete chemicals—the **hormone**—into the extracellular fluid. Hormones are transported primarily via the bloodstream throughout the body, where they bind to receptors on target cells, inducing a characteristic response. As a result, endocrine signaling requires more time than neural signaling to prompt a response in target cells, though the precise amount of time varies with different hormones. For example, the hormones released when you are confronted with a dangerous or frightening situation, called the fight-or-flight response, occur by the release of adrenal hormones—epinephrine and norepinephrine—within seconds. In contrast, it may take up to 48 hours for target cells to respond to certain reproductive hormones.

In addition, endocrine signaling is typically less specific than neural signaling. The same hormone may play a role in a variety of different physiological processes depending on the target cells involved. For example, the hormone oxytocin promotes uterine contractions in women during labor. It is also important in breastfeeding, and may be involved in the sexual response and in feelings of emotional attachment in both males and females.

In general, the nervous system involves quick responses to rapid changes in the external environment, and the endocrine system is usually slower acting—taking care of the internal environment of the body, maintaining homeostasis, and controlling reproduction (Table 15.2.1). So how does the fight-or-flight response that was mentioned earlier happen so quickly if hormones are usually slower acting? It is because the two systems are connected. It is the fast action of the nervous system in response to the danger in the environment that stimulates the adrenal glands to secrete their hormones. As a result, the nervous system can cause rapid endocrine responses to keep up with sudden changes in both the external and internal environments when necessary.

Table 15.2.1: A Comparison of the Endocrine and Nervous Systems

	Endocrine system	Nervous system
Signaling mechanism(s)	Chemical	Chemical/electrical
Primary chemical signal	Hormones	Neurotransmitters
Distance traveled	Long or short	Always short
Response time	Fast or slow	Always fast

Structures of the Endocrine System

The endocrine system consists of cells, tissues, and organs that secrete hormones as a primary or secondary function. The **endocrine gland** is the major player in this system. The primary function of these ductless glands is to secrete their hormones directly into the surrounding fluid. The interstitial fluid and the blood vessels then transport the hormones throughout the body. The endocrine system includes the pituitary, thyroid, parathyroid, adrenal, and pineal glands (summarized in Figure 15.2.1 and covered in more detail in subsequent sections of this chapter). Some glands have both endocrine and non-endocrine functions. For example, the pancreas contains cells that function in digestion as well as cells that secrete the hormones insulin and glucagon, which regulate blood glucose levels. The hypothalamus, thymus, heart, kidneys, stomach, small intestine, liver, skin, female ovaries, and male testes are other organs that contain cells with endocrine function. Moreover, adipose tissue has long been known to produce hormones, and recent research has revealed that even bone tissue has endocrine functions.

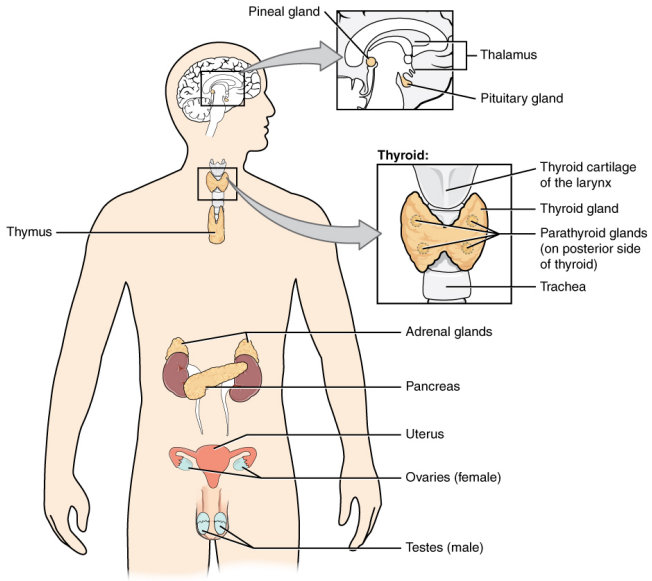

Figure 15.2.1: Endocrine System. Endocrine glands and cells are located throughout the body and play an important role in homeostasis. The pineal gland is posterior to the thalamus in the brain, while the pituitary gland is connected to the inferior hypothalamus by way of the infundibulum. The bilobed thyroid gland is between the thyroid cartilage of the larynx and the trachea, with two pairs of parathyroid glands bilateral on its posterior surface. The adrenal glands lie on the superior surface of the kidneys while the pancreas runs across the midline anterior to the kidneys, inferoposterior to the stomach. The gonads include the ovaries bilateral to the uterus in the female and the testes bilateral in the scrotum in the male. (Image credit: "The Endocrine System" by OpenStax is licensed under CC BY 3.0)

The ductless endocrine glands are not to be confused with the body's **exocrine system**, whose glands release their secretions through ducts. Examples of exocrine glands include the sebaceous and sweat glands of the skin. As just noted, the pancreas also has an exocrine function: most of its cells secrete pancreatic juice through the pancreatic and accessory ducts to the lumen (inside) of the small intestine.

Other Types of Chemical Signaling

In endocrine signaling, hormones secreted into the extracellular fluid diffuse into the blood or lymph (fluid of the lymphatic system), and can then travel great distances throughout the body. In contrast, autocrine signaling takes place within the same cell. An **autocrine** (auto- = "self") is a chemical that elicits a response in the same cell that secreted it. Interleukin-1, or IL-1, is a signaling molecule that plays an important role in the inflammatory response. The cells that secrete IL-1 have receptors on their cell surface that bind these molecules, resulting in autocrine signaling.

Local intercellular communication is carried out by a **paracrine**, also called a paracrine factor, which is a chemical that induces a response in neighboring cells within the same tissue. Although paracrine hormones may enter the bloodstream, their concentration is generally too low to elicit a response from distant tissues. Histamine, released by immune cells of the bronchial tree, is a familiar example of a paracrine that is harmful to people with asthma. Histamine causes the walls of the bronchi to become inflamed and causes the smooth muscle cells of the bronchi to constrict, narrowing the airways. Neurotransmitters of the nervous system, acting locally within the synaptic cleft, are another example of paracrine signaling.

Hormones

Although a given hormone may travel throughout the body in the bloodstream, it will affect the activity only of its target cells; that is, cells with receptors for that particular hormone. Once the hormone binds to the receptor, a chain of events is initiated that leads to the target cell's response. Hormones play a critical role in the regulation of physiological processes because of the target cell responses they regulate. These responses contribute to human reproduction, growth and development of body tissues, metabolism, fluid and electrolyte balance, sleep, and many other body functions. The major hormones of the human body and their effects are identified in Table 15.2.2.

Table 15.2.2: Endocrine Glands and Their Major Hormones

Endocrine gland	Associated hormones	Effect
Pituitary (anterior)	Growth hormone (GH)	Promotes growth of body tissues
Pituitary (anterior)	Prolactin (PRL)	Promotes milk production
Pituitary (anterior)	Thyroid-stimulating hormone (TSH)	Stimulates thyroid hormone release
Pituitary (anterior)	Adrenocorticotropic hormone (ACTH)	Stimulates glucocorticoid release by adrenal cortex
Pituitary (anterior)	Follicle-stimulating hormone (FSH)	Stimulates gamete (egg or sperm) production
Pituitary (anterior)	Luteinizing hormone (LH)	Stimulates androgen production by gonads
Pituitary (posterior)	Antidiuretic hormone (ADH; aka vasopressin)	Stimulates water reabsorption by kidneys
Pituitary (posterior)	Oxytocin	Stimulates uterine contractions during childbirth
Thyroid	Thyroxine (T_4), triiodothyronine (T_3)	Stimulate basal metabolic rate
Thyroid	Calcitonin	Reduces blood Ca^{2+} levels
Parathyroid	Parathyroid hormone (PTH)	Increases blood Ca^{2+} levels
Adrenal (cortex)	Aldosterone	Increases blood Na^{+} levels
Adrenal (cortex)	Cortisol, corticosterone, cortisone	Increase blood glucose levels, involved in stress response
Adrenal (medulla)	Epinephrine, norepinephrine	Stimulate fight-or-flight response
Pineal	Melatonin	Regulates sleep cycles
Pancreas	Insulin	Reduces blood glucose levels
Pancreas	Glucagon	Increases blood glucose levels
Testes	Testosterone	Stimulates development of male secondary sex characteristics and sperm production
Ovaries	Estrogens and progesterone	Stimulate development of female secondary sex characteristics and prepare the body for childbirth

Types of Hormones

The hormones of the human body can be divided into two major groups on the basis of their chemical properties: hormones that are soluble in water, most of which are derived from amino acids (the building blocks of proteins), and steroid hormones, which are not soluble in water as they are derived from the lipid cholesterol. The chemical properties of the hormones in each group affect much of how they work including how they are distributed to target cells, the type of receptors they bind to, and other aspects of function such as how long effects can last.

Pathways of Hormone Action

The message a hormone sends is received by a **hormone receptor**, a protein located either inside the cell or within the cell membrane. The receptor will process the message by initiating other signaling events or cellular mechanisms that result in the target cell's response. Hormone receptors recognize molecules with specific shapes and side groups, and respond only to those hormones that are recognized. The same type of receptor may be located on cells in different body tissues, and trigger somewhat different responses. Thus, the response triggered by a hormone depends not only on the hormone, but also on the target cell.

Once the target cell receives the hormone signal, it can respond in a variety of ways. The response may include the stimulation of protein synthesis, activation or deactivation of enzymes, alteration in the permeability of the cell membrane, altered rates of mitosis and cell growth, and stimulation of the secretion of products. Moreover, a single hormone may be capable of inducing different responses in a given cell.

Regulation of Hormone Secretion

To prevent abnormal hormone levels and a potential disease state, hormone levels must be tightly controlled. The body maintains this control by balancing hormone production and degradation. Feedback loops govern the initiation and maintenance of most hormone secretion in response to various stimuli.

Role of Feedback Loops

The contribution of feedback loops to homeostasis will only be briefly reviewed here. Positive feedback loops are characterized by the release of additional hormone in response to an original hormone release. The release of oxytocin during childbirth is a positive feedback loop. The initial release of oxytocin begins to signal the uterine muscles to contract, which pushes the fetus toward the cervix, causing it to stretch. This, in turn, signals the pituitary gland to release more oxytocin, causing labor contractions to intensify. The release of oxytocin decreases after the birth of the child.

The more common method of hormone regulation is the negative feedback loop. Negative feedback is characterized by the inhibition of further secretion of a hormone in response to adequate levels of that hormone. This allows blood levels of the hormone to be regulated within a narrow range. An example of a negative feedback loop is the release of glucocorticoid hormones from the adrenal glands, as directed by the hypothalamus and pituitary gland. Glucocorticoids such as cortisol help the body respond to stress. If glucocorticoid concentrations in the blood fall below optimal, as measured by sensors in the bloodstream, the hypothalamus releases corticotropin-releasing hormone (CRH). The release of CRH signals the pituitary gland to initiate a cascade of hormone releases that ultimately signal the adrenal gland (aka suprarenal gland) to release glucocorticoids into the bloodstream. As glucocorticoid concentrations in the blood rise, the hypothalamus and pituitary gland reduce their signaling to the adrenal glands to prevent additional glucocorticoid secretion (Figure 15.2.2).

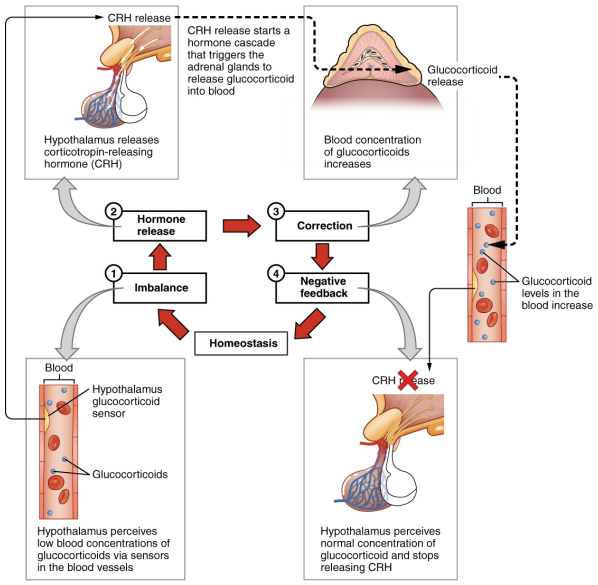

Figure 15.2.2: Negative Feedback Loop. The hypothalamus perceives low blood concentrations of glucocorticoids via sensors in the blood vessels. The imbalance triggers the hypothalamus to release corticotropin-releasing hormone (CRH) via the anterior pituitary. CRH releases starts a hormone cascade that triggers the adrenal glands to release glucocorticoids into the blood, increasing blood levels of glucocorticoids. Glucocorticoids such as cortisol regulate the body's stress responses. When the hypothalamus perceives normal blood concentrations of glucocorticoids, it stops releasing CRH, so this is an example of a negative-feedback loop. (Image credit: "Negative Feedback Loop" by OpenStax is licensed under CC BY 3.0)

Role of Endocrine Gland Stimuli

Reflexes triggered by both chemical and neural stimuli control endocrine activity. These reflexes may be simple, involving only one hormone response, or they may be more complex and involve many hormones, as is the case with the hypothalamic control of various anterior pituitary–controlled hormones.

Humoral stimuli are changes in blood levels of nutrients, ions, or other non-hormonal chemicals that cause the release or inhibition of a hormone to maintain homeostasis. For example, osmoreceptors in the hypothalamus detect changes in blood osmolarity (the concentration of solutes in the blood plasma). If blood osmolarity is too high, meaning that the blood is not dilute enough, osmoreceptors signal the hypothalamus to release ADH. The hormone causes the kidneys to reabsorb more water and reduce the volume of urine produced. This reabsorption causes a reduction of the osmolarity of the blood, diluting the blood to the appropriate level. The regulation of blood glucose is another example. High blood glucose levels cause the release of insulin from the pancreas, which increases glucose uptake by cells and liver storage of glucose as glycogen.

An endocrine gland may also secrete a hormone in response to the presence of another hormone produced by a different endocrine gland. Such **hormonal stimuli** often involve the hypothalamus, which produces releasing and inhibiting hormones that control the secretion of a variety of pituitary hormones.

In addition to these chemical signals, hormones can also be released in response to **neural stimuli**. A common example of neural stimuli is the activation of the fight-or-flight response by the sympathetic nervous system. When an individual perceives danger, sympathetic neurons signal the adrenal glands to secrete norepinephrine and epinephrine. The two hormones dilate blood vessels, increase the heart and respiratory rate, and suppress the digestive and immune systems. These responses boost the body's transport of oxygen to the brain and muscles, thereby improving the body's ability to fight or flee.

EVERYDAY CONNECTIONS

Bisphenol A and Endocrine Disruption

You may have heard news reports about the effects of a chemical called bisphenol A (BPA) in various types of food packaging. BPA is used in the manufacturing of hard plastics and epoxy resins. Common food-related items that may contain BPA include the lining of aluminum cans, plastic food-storage containers, drinking cups, as well as baby bottles and “sippy” cups. Other uses of BPA include medical equipment, dental fillings, and the lining of water pipes.

Research suggests that BPA is an endocrine disruptor, meaning that it negatively interferes with the endocrine system, particularly during the prenatal and postnatal development period. In particular, BPA mimics the hormonal effects of estrogens and has the opposite effect—that of androgens. The U.S. Food and Drug Administration (FDA) notes in their statement about BPA safety that although traditional toxicology studies have supported the safety of low levels of exposure to BPA, recent studies using novel approaches to test for subtle effects have led to some concern about the potential effects of BPA on the brain, behavior, and prostate gland in fetuses, infants, and young children. The FDA is currently facilitating decreased use of BPA in food-related materials. Many US companies have voluntarily removed BPA from baby bottles, “sippy” cups, and the linings of infant formula cans, and most plastic reusable water bottles sold today boast that they are “BPA free.” In contrast, both Canada and the European Union have completely banned the use of BPA in baby products.

The potential harmful effects of BPA have been studied in both animal models and humans and include a large variety of health effects, such as developmental delay and disease. For example, prenatal exposure to BPA during the first trimester of human pregnancy may be associated with wheezing and aggressive behavior during childhood. Adults exposed to high levels of BPA may experience altered thyroid signaling and male sexual dysfunction. BPA exposure during the prenatal or postnatal period of development in animal models has been observed to cause neurological delays, changes in brain structure and function, sexual dysfunction, asthma, and increased risk for multiple cancers. In vitro studies have also shown that BPA exposure causes molecular changes that initiate the development of cancers of the breast, prostate, and brain. Although these studies have implicated BPA in numerous ill health effects, some experts caution that some of these studies may be flawed and that more research needs to be done. In the meantime, the FDA recommends that consumers take precautions to limit their exposure to BPA. In addition to purchasing foods in packaging free of BPA, consumers should avoid carrying or storing foods or liquids in bottles with the recycling code 3 or 7. Foods and liquids should not be microwave-heated in any form of plastic: use paper, glass, or ceramics instead.

CAREER CONNECTIONS

Endocrinologist

Endocrinology is a specialty in the field of medicine that focuses on the treatment of endocrine system disorders. Endocrinologists—medical doctors who specialize in this field—are experts in treating diseases associated with hormonal systems, ranging from thyroid disease to diabetes mellitus. Endocrine surgeons treat endocrine disease through the removal, or resection, of the affected endocrine gland.

Patients who are referred to endocrinologists may have signs and symptoms or blood test results that suggest excessive or impaired functioning of an endocrine gland or endocrine cells. The endocrinologist may order additional blood tests to determine whether the patient’s hormonal levels are abnormal, or they may stimulate or suppress the function of the suspect endocrine gland and then have blood taken for analysis. Treatment varies according to the diagnosis. Some endocrine disorders, such as type 2 diabetes, may respond to lifestyle changes such as modest weight loss, adoption of a healthy diet, and regular physical activity. Other disorders may require medication, such as hormone replacement, and routine monitoring by the endocrinologist. These include disorders of the pituitary gland that can affect growth and disorders of the thyroid gland that can result in a variety of metabolic problems.

Some patients experience health problems as a result of the normal decline in hormones that can accompany aging. These patients can consult with an endocrinologist to weigh the risks and benefits of hormone replacement therapy intended to boost their natural levels of reproductive hormones.

In addition to treating patients, endocrinologists may be involved in research to improve the understanding of endocrine system disorders and develop new treatments for these diseases.

Concept Review

The endocrine system consists of cells, tissues, and organs that secrete hormones critical to homeostasis. The body coordinates

its functions through two major types of communication: neural and endocrine. Neural communication includes both electrical and chemical signaling between neurons and target cells. Endocrine communication involves chemical signaling via the release of hormones into the extracellular fluid. From there, hormones diffuse into the bloodstream and may travel to distant body regions, where they elicit a response in target cells. Endocrine glands are ductless glands that secrete hormones. Many organs of the body with other primary functions—such as the heart, stomach, and kidneys—also have hormone-secreting cells.

Hormones are released upon stimulation that is of either chemical or neural origin. Regulation of hormone release is primarily achieved through negative feedback. Various stimuli may cause the release of hormones, but there are three major types. Humoral stimuli are changes in ion or nutrient levels in the blood. Hormonal stimuli are changes in hormone levels that initiate or inhibit the secretion of another hormone. Finally, a neural stimulus occurs when a nerve impulse prompts the secretion or inhibition of a hormone.

Review Questions

Q. Endocrine glands _____.

A. secrete hormones that travel through a duct to the target organs

B. release neurotransmitters into the synaptic cleft

C. secrete chemical messengers that travel in the bloodstream

D. include sebaceous glands and sweat glands

Answer

Answer: C

Q. Chemical signaling that affects neighboring cells is called _____.

A. autocrine

B. paracrine

C. endocrine

D. neuron

Answer

Answer: B

Q. A student is in a car accident, and although not hurt, immediately experiences pupil dilation, increased heart rate, and rapid breathing. What type of endocrine system stimulus did the student receive?

A. humoral

B. hormonal

C. neural

D. positive feedback

Answer

Answer: C

Critical Thinking Questions

Q. Describe several main differences in the communication methods used by the endocrine system and the nervous system.

Answer

A. The endocrine system uses chemical signals called hormones to convey information from one part of the body to a distant part of the body. Hormones are released from the endocrine cell into the extracellular environment, but then travel in the bloodstream to target tissues. This communication and response can take seconds to days. In contrast, neurons transmit electrical signals along their axons. At the axon terminal, the electrical signal prompts the release of a chemical signal called a neurotransmitter that carries the message across the synaptic cleft to elicit a response in the neighboring cell. This method of communication is nearly instantaneous, of very brief duration, and is highly specific.

Q. Compare and contrast endocrine and exocrine glands.

Answer

A. Endocrine glands are ductless. They release their secretion into the surrounding fluid, from which it enters the bloodstream or lymph to travel to distant cells. Moreover, the secretions of endocrine glands are hormones. Exocrine glands release their secretions through a duct that delivers the secretion to the target location. Moreover, the secretions of exocrine glands are not hormones, but compounds that have an immediate physiologic function. For example, pancreatic juice contains enzymes that help digest food.

Q. True or false: Neurotransmitters are a special class of paracrines. Explain your answer.

Answer

A. True. Neurotransmitters can be classified as paracrines because, upon their release from a neuron's axon terminals, they travel across a microscopically small cleft to exert their effect on a nearby neuron or muscle cell.

Glossary

autocrine
chemical signal that elicits a response in the same cell that secreted it

endocrine gland
tissue or organ that secretes hormones into the blood and lymph without ducts such that they may be transported to organs distant from the site of secretion

endocrine system
cells, tissues, and organs that secrete hormones as a primary or secondary function and play an integral role in normal bodily processes

exocrine system
cells, tissues, and organs that secrete substances directly to target tissues via glandular ducts

hormonal stimuli
the presence of a hormone causes the release or inhibition of another hormone in an endocrine gland

hormone receptor
protein within a cell or on the cell membrane that binds a hormone, initiating the target cell response

hormone
secretion of an endocrine organ that travels via the bloodstream or lymphatics to induce a response in target cells or tissues in another part of the body

humoral stimuli
changes in blood levels of non-hormone chemicals such as ions or nutrients that cause release or inhibition of a

hormone to maintain homeostasis of the chemical

negative feedback loop
type of regulation in which increasing levels of a substance signal that the substance no longer needs to be released, resulting in lowered levels of the substance

neural stimuli
a nerve impulse causes the release or inhibition of a hormone in an endocrine gland

paracrine
chemical signal that elicits a response in neighboring cells; also called paracrine factor

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15.3: Pituitary Gland and Hypothalamus

By the end of this section, you will be able to:

- Explain the interrelationships of the anatomy and functions of the hypothalamus and the posterior and anterior lobes of the pituitary gland
- Identify the two hormones released from the posterior pituitary, their target cells, and their principal actions
- Identify the six hormones produced by the anterior lobe of the pituitary gland, their target cells, their principal actions, and their regulation by the hypothalamus

The hypothalamus–pituitary complex can be thought of as the “command center” of the endocrine system. This complex secretes several hormones that directly produce responses in target tissues, as well as hormones that regulate the synthesis and secretion of hormones of other glands. In addition, the hypothalamus–pituitary complex coordinates the messages of the endocrine and nervous systems. In many cases, a stimulus received by the nervous system must pass through the hypothalamus–pituitary complex to be translated into hormones that can initiate a response.

The **hypothalamus** is a structure of the diencephalon of the brain located anterior and inferior to the thalamus (Figure 15.3.1). It has both neural and endocrine functions, producing and secreting many hormones. In addition, the hypothalamus is anatomically and functionally related to the **pituitary gland** (or hypophysis), a bean-sized organ suspended from it by a stem called the **infundibulum** (or pituitary stalk). The pituitary gland is cradled within the sella turcica of the sphenoid bone of the skull. It consists of two lobes that arise from distinct parts of embryonic tissue: the posterior pituitary (neurohypophysis) is neural tissue, whereas the anterior pituitary (also known as the adenohypophysis) is glandular tissue that develops from the primitive digestive tract. The hormones secreted by the posterior and anterior pituitary, and the intermediate zone between the lobes are summarized in Table 15.3.1.

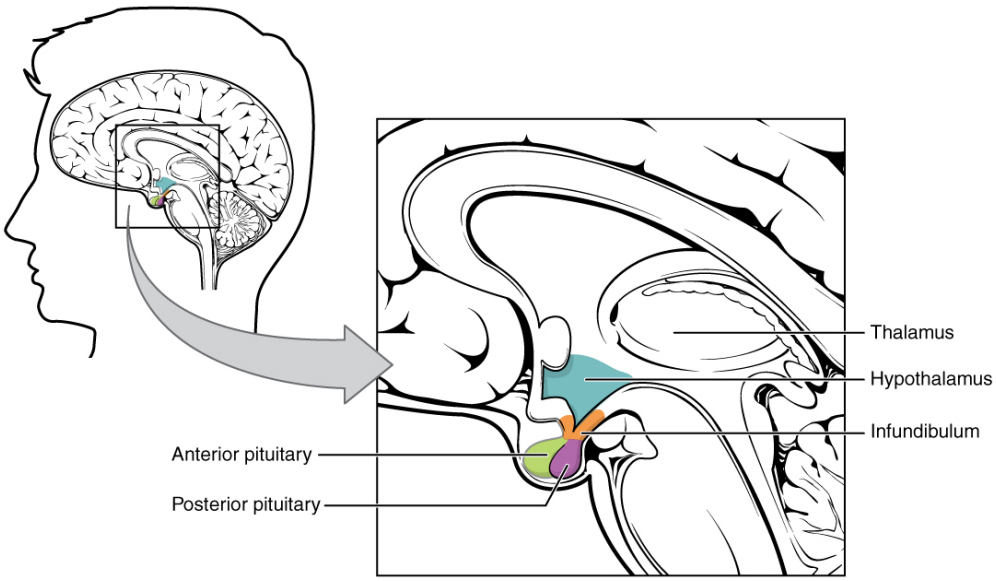

Figure 15.3.1: Hypothalamus–Pituitary Complex. The hypothalamus region of the brain lies inferior and anterior to the thalamus. It connects to the pituitary gland by way of the stalk-like infundibulum. The pituitary gland consists of an anterior and posterior lobe, with each lobe releasing different hormones in response to signals from the hypothalamus. (Image credit: "Hypothalamus-Pituitary Complex" by OpenStax is licensed under CC BY 3.0)

Table 15.3.1: Pituitary Hormones

Pituitary lobe	Associated hormones	Effect
Anterior	Growth hormone (GH)	Promotes growth of body tissues

Pituitary lobe	Associated hormones	Effect
Anterior	Prolactin (PRL)	Promotes milk production from mammary glands
Anterior	Thyroid-stimulating hormone (TSH)	Stimulates thyroid hormone release from thyroid
Anterior	Adrenocorticotropic hormone (ACTH)	Stimulates hormone release by adrenal cortex
Anterior	Follicle-stimulating hormone (FSH)	Stimulates gamete production in gonads
Anterior	Luteinizing hormone (LH)	Stimulates androgen production by gonads
Posterior	Antidiuretic hormone (ADH)	Stimulates water reabsorption by kidneys
Posterior	Oxytocin	Stimulates uterine contractions during childbirth
Intermediate zone	Melanocyte-stimulating hormone	Stimulates melanin formation in melanocytes

Posterior Pituitary

The posterior pituitary is actually an extension of the neurons of the paraventricular and supraoptic nuclei of the hypothalamus. The cell bodies of these regions rest in the hypothalamus, but their axons descend as the hypothalamic–hypophyseal tract within the infundibulum and end in axon terminals that comprise the posterior pituitary (Figure 15.3.2).

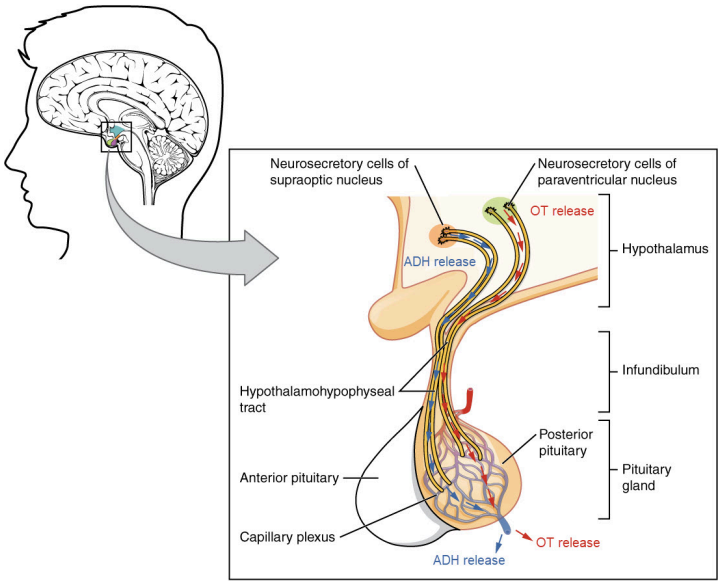

Figure 15.3.2: Posterior Pituitary. Neurosecretory cells in the supraoptic nucleus of the hypothalamus release antidiuretic hormone (ADH) and neurosecretory cells in the paraventricular nucleus of the hypothalamus release oxytocin (OT). The hormones move through axons of separate neurons in the hypothalamo-hypophyseal tract through the infundibulum to axon terminals located in the posterior lobe of the pituitary gland. These hormones are stored or released into the bloodstream via the capillary plexus in the posterior pituitary gland. (Image credit: "Posterior Pituitary Complex" by Julie Jenks is licensed under CC BY 4.0 / A derivative from the original work)

The posterior pituitary gland does not produce hormones, but rather stores and secretes hormones produced by the hypothalamus. The paraventricular nucleus produces the hormone oxytocin, whereas the supraoptic nucleus produces antidiuretic hormone (ADH). These hormones travel along the axons into storage sites in the axon terminals of the posterior pituitary. In response to signals from the same hypothalamic neurons, the hormones are released from the axon terminals into the bloodstream.

Oxytocin

When fetal development is complete, the peptide-derived hormone **oxytocin** (tocia- = “childbirth”) stimulates uterine contractions and dilation of the cervix. Throughout most of pregnancy, oxytocin hormone receptors are not expressed at high levels in the uterus. Toward the end of pregnancy, the synthesis of oxytocin receptors in the uterus increases, and the smooth muscle cells of the uterus become more sensitive to its effects. Oxytocin is continually released throughout childbirth through a

positive feedback mechanism. As noted earlier, oxytocin prompts uterine contractions that push the fetal head toward the cervix. In response, cervical stretching stimulates additional oxytocin to be synthesized by the hypothalamus and released from the pituitary. This increases the intensity and effectiveness of uterine contractions and prompts additional dilation of the cervix. The feedback loop continues until birth.

Although the mother's high blood levels of oxytocin begin to decrease immediately following birth, oxytocin continues to play a role in maternal and newborn health. First, oxytocin is necessary for the milk ejection reflex (commonly referred to as "let-down") in breastfeeding women. As the newborn begins suckling, sensory receptors in the nipples transmit signals to the hypothalamus. In response, oxytocin is secreted and released into the bloodstream. Within seconds, cells in the mother's milk ducts contract, ejecting milk into the infant's mouth. Secondly, in both males and females, oxytocin is thought to contribute to parent–newborn bonding, known as attachment. Oxytocin is also thought to be involved in feelings of love and closeness, as well as in the sexual response.

Antidiuretic Hormone (ADH)

The solute concentration of the blood, or blood osmolarity, may change in response to the consumption of certain foods and fluids, as well as in response to disease, injury, medications, or other factors. Blood osmolarity is constantly monitored by **osmoreceptors**—specialized cells within the hypothalamus that are particularly sensitive to the concentration of sodium ions and other solutes.

In response to high blood osmolarity, which can occur during dehydration or following a very salty meal, the osmoreceptors signal the posterior pituitary to release **antidiuretic hormone (ADH)**, also known as vasopressin. The target cells of ADH are located in the tubular cells of the kidneys, but it also targets sweat glands and smooth muscle of blood vessels. Its effect is to increase epithelial permeability to water, allowing increased water reabsorption. The more water reabsorbed from the filtrate, the greater the amount of water that is returned to the blood and the less that is excreted in the urine. A greater concentration of water results in a reduced concentration of solutes in the blood. ADH is also known as vasopressin because, in very high concentrations, it causes constriction of blood vessels, which increases blood pressure. The release of ADH is controlled by a negative feedback loop. As blood osmolarity decreases, the hypothalamic osmoreceptors sense the change and prompt a corresponding decrease in the secretion of ADH. As a result, less water is reabsorbed from the urine filtrate.

Interestingly, drugs can affect the secretion of ADH. For example, alcohol consumption inhibits the release of ADH, resulting in increased urine production that can eventually lead to dehydration and a hangover. A disease called diabetes insipidus is characterized by chronic underproduction of ADH that causes chronic dehydration. Because little ADH is produced and secreted, not enough water is reabsorbed by the kidneys. Although patients feel thirsty, and increase their fluid consumption, this doesn't effectively decrease the solute concentration in their blood because ADH levels are not high enough to trigger water reabsorption in the kidneys. Electrolyte imbalances can occur in severe cases of diabetes insipidus.

Anterior Pituitary

The anterior pituitary originates from the digestive tract in the embryo and migrates toward the brain during fetal development. There are three regions: the pars distalis is the most anterior, the pars intermedia is adjacent to the posterior pituitary, and the pars tuberalis is a slender "tube" that wraps the infundibulum.

Recall that the posterior pituitary does not synthesize hormones, but merely stores them. In contrast, the anterior pituitary does manufacture hormones. However, the secretion of hormones from the anterior pituitary is regulated by two classes of hormones. These hormones—secreted by the hypothalamus—are the releasing hormones that stimulate the secretion of hormones from the anterior pituitary and the inhibiting hormones that inhibit secretion.

Hypothalamic hormones are secreted by neurons, but enter the anterior pituitary through blood vessels (Figure 15.3.3). Within the infundibulum is a bridge of capillaries that connects the hypothalamus to the anterior pituitary. This network, called the **hypophyseal portal system**, allows hypothalamic hormones to be transported to the anterior pituitary without first entering the systemic circulation. The system originates from the superior hypophyseal artery, which branches off the carotid arteries and transports blood to the hypothalamus. The branches of the superior hypophyseal artery form the hypophyseal portal system (see Figure 15.3.3). Hypothalamic releasing and inhibiting hormones travel through a primary capillary plexus to the portal veins, which carry them into the anterior pituitary. Hormones produced by the anterior pituitary (in response to releasing hormones) enter a secondary capillary plexus, and from there drain into the circulation.

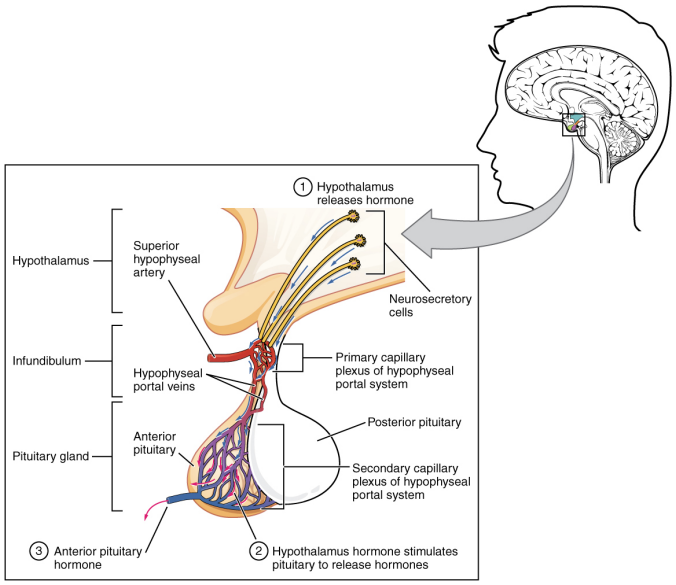

Figure 15.3.3: Anterior Pituitary. The anterior pituitary manufactures six hormones. Neurosecretory cells in the hypothalamus produces separate hormones that stimulate or inhibit hormone production in the anterior pituitary. Hormones from the hypothalamus travel by neuron axons to the primary capillary plexus of the hypophyseal portal system located in the infundibulum. The hormones move through hypophyseal portal veins in the infundibulum to the secondary capillary plexus in the anterior pituitary. Hormones produced in the anterior pituitary are released into the bloodstream via the secondary capillary plexus. (Image credit: "The Anterior Pituitary Complex" by OpenStax is licensed under CC BY 3.0)

Six hormones are synthesized in the anterior pituitary. These are the growth hormone (GH), thyroid-stimulating hormone (TSH), adrenocorticotropic hormone (ACTH), follicle-stimulating hormone (FSH), luteinizing hormone (LH), and prolactin. Of the hormones of the anterior pituitary, TSH, ACTH, FSH, and LH are collectively referred to as tropic hormones (trope- = “turning”) because they turn on or off the function of other endocrine glands.

Growth Hormone

The endocrine system regulates the growth of the human body, protein synthesis, and cellular replication. A major hormone involved in this process is **growth hormone (GH)**, also called somatotropin—a protein hormone produced and secreted by the anterior pituitary gland. Its primary function promotes protein synthesis and tissue building through direct and indirect mechanisms involving insulin-like growth factors (IGF) that also increase metabolic rate to support the growth.

Thyroid-Stimulating Hormone

The activity of the thyroid gland is regulated by **thyroid-stimulating hormone (TSH)**, also called thyrotropin. TSH is released from the anterior pituitary in response to thyrotropin-releasing hormone (TRH) from the hypothalamus. As discussed in the next section, it triggers the secretion of thyroid hormones by the thyroid gland. In a classic negative feedback loop, elevated levels of thyroid hormones in the bloodstream then trigger a drop in production of TRH and subsequently TSH.

Adrenocorticotropic Hormone

The **adrenocorticotropic hormone (ACTH)**, also called corticotropin, stimulates the adrenal cortex (the more superficial “bark” of the adrenal glands) to secrete corticosteroid hormones (also known as glucocorticoids) such as cortisol. ACTH come from a precursor molecule known as pro-opiomelanotropin (POMC) which produces several biologically active molecules when cleaved, including ACTH, melanocyte-stimulating hormone, and the brain opioid peptides known as endorphins.

The release of ACTH is regulated by the corticotropin-releasing hormone (CRH) from the hypothalamus in response to normal physiologic rhythms. CRH also stimulates the release of beta endorphins in response to stress or exercise. A variety of stressors can elicit a complex stress response, and the role of ACTH in the stress response is discussed later in this chapter.

Follicle-Stimulating Hormone and Luteinizing Hormone

The endocrine glands secrete a variety of hormones that control the development and regulation of the reproductive system (these glands include the anterior pituitary, the adrenal cortex, and the gonads—the testes and the ovaries). Much of the development of the reproductive system occurs during puberty and is marked by the development of sex-specific characteristics in adolescents. Puberty is initiated by gonadotropin-releasing hormone (GnRH), a hormone produced and secreted by the hypothalamus. GnRH stimulates the anterior pituitary to secrete **gonadotropins**—hormones that regulate the function of the gonads. The levels of GnRH are regulated through a negative feedback loop; high levels of reproductive hormones inhibit the release of GnRH. Throughout life, gonadotropins regulate reproductive function and, in the case of those with ovaries, the onset and cessation of reproductive capacity.

The gonadotropins include two glycoprotein hormones: **follicle-stimulating hormone (FSH)** stimulates the production and maturation of sex cells, or gametes, including ova in those with ovaries and sperm in those with testes. FSH also promotes follicular growth; these follicles then release estrogens in the ovaries. **Luteinizing hormone (LH)** triggers ovulation in those with ovaries, as well as the production of estrogens and progesterone by the ovaries. LH stimulates production of testosterone by the testes, and because testosterone is produced by interstitial cells within the testes, it is also known as interstitial cell stimulating hormone (ICSH) in those with testes.

Prolactin

As its name implies, **prolactin (PRL)** promotes lactation (milk production) in women. During pregnancy, it contributes to development of the mammary glands, and after birth, it stimulates the mammary glands to produce breast milk. However, the effects of prolactin depend heavily upon the permissive effects of estrogens, progesterone, and other hormones. And as noted earlier, the let-down of milk occurs in response to stimulation from oxytocin.

In a non-pregnant woman, prolactin secretion is inhibited by prolactin-inhibiting hormone (PIH), which is actually the neurotransmitter dopamine, and is released from neurons in the hypothalamus. Only during pregnancy do prolactin levels rise in response to prolactin-releasing hormone (PRH) from the hypothalamus.

Intermediate Pituitary: Melanocyte-Stimulating Hormone

The cells in the intermediate zone between the pituitary lobes secrete a hormone known as melanocyte-stimulating hormone (MSH) that is formed by cleavage of the pro-opiomelanocortin (POMC) precursor protein. Local production of MSH in the skin is responsible for melanin production in response to UV light exposure. The role of MSH made by the pituitary is more complicated. For instance, people with lighter skin generally have the same amount of MSH as people with darker skin. Nevertheless, this hormone is capable of darkening of the skin by inducing melanin production in the melanocytes of the epidermis. Women also show increased MSH production during pregnancy; in combination with estrogens, it can lead to darker skin pigmentation, especially the skin of the areolas and labia minora. Figure 15.3.4 is a summary of the pituitary hormones and their principal effects.

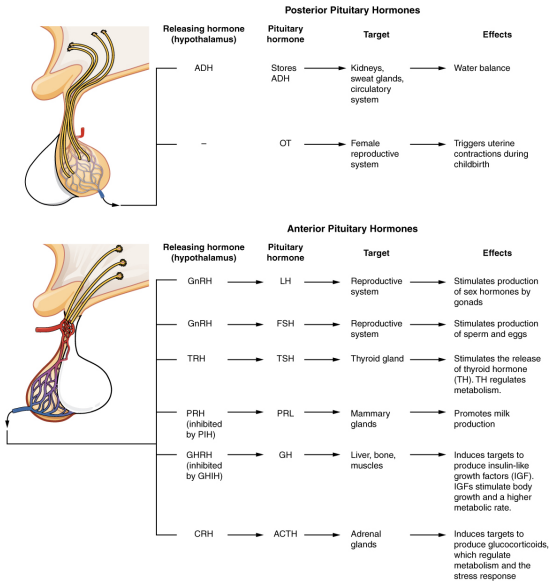

Figure 15.3.4: Major Pituitary Hormones. Major pituitary hormones and their target organs and effects. (Image credit: "Major Pituitary Hormones" by OpenStax is licensed under CC BY 3.0)

Concept Review

The hypothalamus–pituitary complex is located in the diencephalon of the brain. The hypothalamus and the pituitary gland are connected by a structure called the infundibulum, which contains vasculature and nerve axons. The pituitary gland is divided into two distinct structures with different embryonic origins. The posterior lobe houses the axon terminals of hypothalamic neurons. It stores and releases into the bloodstream two hypothalamic hormones: oxytocin (OT) and antidiuretic hormone (ADH). The anterior lobe is connected to the hypothalamus by the vasculature of the hypophyseal portal system in the infundibulum and produces and secretes six hormones. Their secretion is regulated, however, by releasing and inhibiting hormones from the hypothalamus. The six anterior pituitary hormones are: growth hormone (GH), thyroid-stimulating hormone (TSH), adrenocorticotropic hormone (ACTH), follicle-stimulating hormone (FSH), luteinizing hormone (LH), and prolactin (PRL).

Review Questions

Q. The hypothalamus is functionally and anatomically connected to the posterior pituitary lobe by a bridge of _____.

A. blood vessels

B. nerve axons

C. cartilage

D. bone

Answer

Answer: B

Q. Which of the following is an anterior pituitary hormone?

A. ADH

B. oxytocin

C. TSH

D. cortisol

Answer

Answer: C

Q. How many hormones are produced by the posterior pituitary?

A. 0

B. 1

C. 2

D. 6

Answer

Answer: A

Q. Which of the following hormones contributes to the regulation of the body's fluid and electrolyte balance?

A. oxytocin

B. antidiuretic hormone

C. luteinizing hormone

D. all of the above

Answer

Answer: B

Critical Thinking Questions

Q. Compare and contrast the anatomical relationship of the anterior and posterior lobes of the pituitary gland to the hypothalamus.

Answer

A. The anterior lobe of the pituitary gland is connected to the hypothalamus by vasculature, which allows regulating hormones from the hypothalamus to travel to the anterior pituitary. In contrast, the posterior lobe is connected to the hypothalamus by a bridge of nerve axons called the hypothalamic–hypophyseal tract, along which the hypothalamus sends hormones produced by hypothalamic nerve cell bodies to the posterior pituitary for storage and release into the circulation.

Glossary

adrenocorticotropic hormone (ACTH)
anterior pituitary hormone that stimulates the adrenal cortex to secrete corticosteroid hormones to regulate metabolism and the stress response (also called corticotropin)

antidiuretic hormone (ADH)
hypothalamic hormone that is stored by the posterior pituitary and that signals the kidneys to reabsorb water

follicle-stimulating hormone (FSH)
anterior pituitary hormone that stimulates the production and maturation of sex cells

gonadotropins
hormones that regulate the function of the gonads

growth hormone (GH)
anterior pituitary hormone that promotes tissue building and influences nutrient metabolism (also called somatotropin)

hypophyseal portal system
network of blood vessels that enables hypothalamic hormones to travel into the anterior lobe of the pituitary without entering the systemic circulation

hypothalamus
region of the diencephalon inferior to the thalamus that functions in neural and endocrine signaling

infundibulum
stalk containing vasculature and neural tissue that connects the pituitary gland to the hypothalamus (also called the pituitary stalk)

luteinizing hormone (LH)
anterior pituitary hormone that triggers ovulation and the production of ovarian hormones in those with ovaries, and the production of testosterone in those with testes

osmoreceptor
hypothalamic sensory receptor that is stimulated by changes in solute concentration (osmotic pressure) in the blood

oxytocin
hypothalamic hormone stored in the posterior pituitary gland and important in stimulating uterine contractions in labor, milk ejection during breastfeeding, and feelings of attachment (also produced in those with testes)

pituitary gland
bean-sized organ suspended from the hypothalamus that produces, stores, and secretes hormones in response to hypothalamic stimulation (also called hypophysis)

prolactin (PRL)
anterior pituitary hormone that promotes development of the mammary glands and the production of breast milk

thyroid-stimulating hormone (TSH)
anterior pituitary hormone that triggers secretion of thyroid hormones by the thyroid gland (also called thyrotropin)

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15.4: Thyroid Gland

By the end of this section, you will be able to:

- Describe the location and anatomy of the thyroid gland
- Explain the role of thyroid hormones in the regulation of basal metabolism
- Identify the hormone produced by the parafollicular cells of the thyroid

The **thyroid gland**, a butterfly-shaped organ, is located anterior to the trachea, just inferior to the larynx (Figure 15.4.1). The medial region, called the isthmus, is flanked by wing-shaped left and right lobes. Each of the thyroid lobes has a pair of parathyroid glands embedded on its posterior surface. The tissue of the thyroid gland is composed mostly of thyroid follicles lined with simple cuboidal epithelium. The follicles are made up of a central cavity filled with a sticky fluid called **colloid**. Surrounded by a wall of epithelial follicle cells, the colloid is the center of thyroid hormone production, and that production is dependent on the essential and unique component of thyroid hormones: iodine.

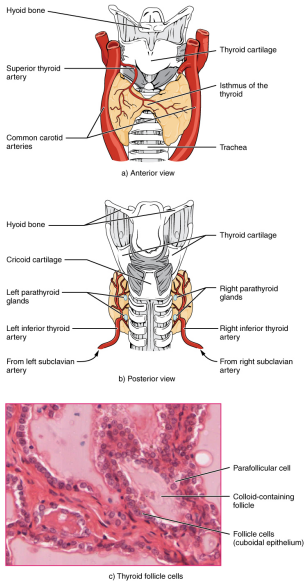

Figure 15.4.1: Thyroid Gland. The thyroid gland is located in the neck where it wraps around the anterior of the trachea. (a) Anterior view of the thyroid gland showing its location below the hyoid bone and thyroid cartilage of the larynx and between the common carotid arteries. The bilateral lobes are connected across the midline by the thinner isthmus of the thyroid, giving the gland a butterfly shape. The anterior of the thyroid gland is supplied blood by the superior thyroid artery. (b) Posterior view of the thyroid gland showing the bilateral pair of parathyroid glands on the thyroid gland's posterior surface just lateral to the trachea at its superior connection to the cricoid cartilage of the larynx. The posterior of the thyroid and the parathyroid glands are supplied blood by the right and left inferior thyroid arteries that branch from the right and left subclavian arteries, respectively. (c) A histological view show the glandular tissue is composed primarily of thyroid follicles lined with cuboidal follicle cells that surround a central cavity filled with colloid. The larger parafollicular cells often appear within the matrix of follicle cells. LM × 1332. (Image credit: "The Thyroid Gland" by OpenStax is licensed under CC BY 3.0 / Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Regulation of TH Synthesis

Thyroglobulin is the precursor to two thyroid hormones: **triiodothyronine** (T_3) with three iodines and **thyroxine** (T_4) with four iodines. Thyroglobulin is produced by the follicle cells and secreted into the colloid where the iodines are attached to form T_3 and T_4. Ninety-nine percent of circulating T_3 and T_4 is bound to specialized transport proteins called thyroxine-binding globulins (TBGs), to albumin, or to other plasma proteins. This “packaging” prevents their free diffusion into body cells. When blood levels of T_3 and T_4 begin to decline, bound T_3 and T_4 are released from these plasma proteins, now referred to as "unbound", and may readily cross the membrane of target cells. T_3 is more potent than T_4, and many cells convert T_4 to T_3 through the removal of an iodine atom.

The release of T_3 and T_4 from the thyroid gland is regulated by thyroid-stimulating hormone (TSH). As shown in Figure 15.4.2, low blood levels of T_3 and T_4 stimulate the release of thyrotropin-releasing hormone (TRH) from the hypothalamus, which triggers secretion of TSH from the anterior pituitary. In turn, TSH stimulates the thyroid gland to secrete T_3 and T_4. The levels of TRH, TSH, T_3, and T_4 are regulated by a negative feedback system in which increasing levels of T_3 and T_4 decrease the production and secretion of TSH.

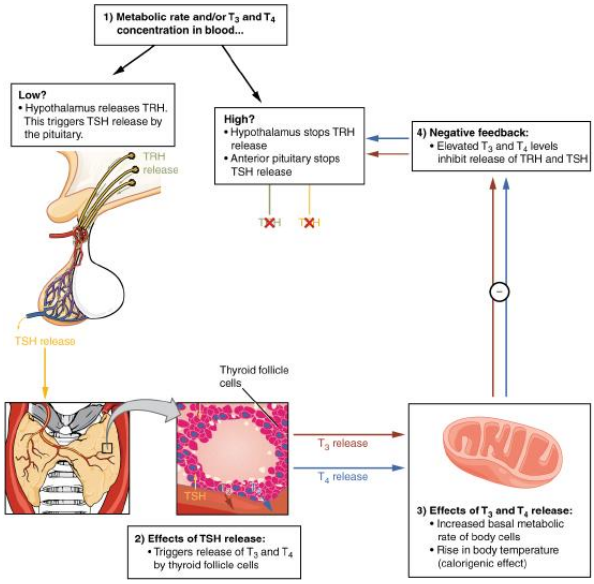

Figure 15.4.2: Regulation of Thyroid Hormone Release. A classic negative feedback loop controls the regulation of thyroid hormone levels. If metabolic rate and/or T_3 and T_4 levels are low, the hypothalamus releases TRH, which triggers TSH release by the anterior pituitary gland. TSH release triggers the thryoid gland to release T_3 and T_4 from thyroid follicles. T_3 and T_4 release cause an increased balal metabolic rate of body cells and rise in body temperature (the calorigenic effect). If metabolic rate and/or T_3 and T_4 levels are high, the hypothalamus stops TRH release, which stops the release of TSH from the anterior pituitary. This inhibition is referred to as negative feedback. (Image credit: "A Classic Negative Feedback Loop" by OpenStax is licensed under CC BY 3.0)

Functions of Thyroid Hormones

The thyroid hormones, T_3 and T_4, are often referred to as metabolic hormones because their levels influence the body's basal metabolic rate, the amount of energy used by the body at rest. When T_3 and T_4 bind to intracellular receptors located on the mitochondria, they cause an increase in nutrient breakdown and the use of oxygen to produce ATP. In addition, T_3 and T_4 initiate the transcription of genes involved in glucose oxidation. Although these mechanisms prompt cells to produce more ATP, the process is inefficient, and an abnormally increased level of heat is released as a byproduct of these reactions. This so-called calorigenic effect (calor- = "heat") raises body temperature.

Adequate levels of thyroid hormones are also required for protein synthesis and for fetal and childhood tissue development and growth. They are especially critical for normal development of the nervous system both in utero and in early childhood, and they continue to support neurological function in adults. As noted earlier, these thyroid hormones have a complex interrelationship with reproductive hormones, and deficiencies can influence libido, fertility, and other aspects of reproductive function. Finally, thyroid hormones increase the body's sensitivity to catecholamines (epinephrine and norepinephrine) from the adrenal medulla by upregulation of receptors in the blood vessels. When levels of T_3 and T_4 hormones are excessive, this effect accelerates the heart rate, strengthens the heartbeat, and increases blood pressure. Because thyroid hormones regulate metabolism, heat production, protein synthesis, and many other body functions, thyroid disorders can have severe and widespread consequences.

DISORDERS OF THE...

Endocrine System: Iodine Deficiency, Hypothyroidism, and Hyperthyroidism

As discussed above, dietary iodine is required for the synthesis of T_3 and T_4. But for much of the world's population, foods do not provide adequate levels of this mineral, because the amount varies according to the level in the soil in which the food was grown, as well as the irrigation and fertilizers used. Marine fish and shrimp tend to have high levels because they concentrate iodine from seawater, but many people in landlocked regions lack access to seafood. Thus, the primary source of dietary iodine in many countries is iodized salt. Fortification of salt with iodine began in the United States in 1924, and international efforts to iodize salt in the world's poorest nations continue today.

Dietary iodine deficiency can result in the impaired ability to synthesize T_3 and T_4, leading to a variety of severe disorders. When T_3 and T_4 cannot be produced, TSH is secreted in increasing amounts. As a result of this hyperstimulation, thyroglobulin accumulates in the thyroid gland follicles, increasing their deposits of colloid. The accumulation of colloid increases the overall size of the thyroid gland, a condition called a goiter (Figure 15.4.3). A goiter is only a visible indication of the deficiency. Other iodine deficiency disorders include impaired growth and development, decreased fertility, and prenatal and infant death. Moreover, iodine deficiency is the primary cause of preventable intellectual disability worldwide. Neonatal hypothyroidism (cretinism) is characterized by cognitive deficits, short stature, and sometimes deafness and muteness in children and adults born to mothers who were iodine-deficient during pregnancy.

Figure 15.4.3: Goiter. A goiter is the abnormal enlargement of the thyroid gland. (Image credit: "Goiter" by Almazi is licensed under CC BY 4.0)

In the absence of iodine deficiency, inflammation of the thyroid gland is the more common cause of low blood levels of thyroid hormones. Called hypothyroidism, the condition is characterized by a low metabolic rate, weight gain, cold extremities, constipation, reduced libido, menstrual irregularities, and intellectual disability.

In contrast, hyperthyroidism—an abnormally elevated blood level of thyroid hormones—is often caused by a pituitary or thyroid tumor. In Graves' disease, the hyperthyroid state results from an autoimmune reaction in which antibodies overstimulate the follicle cells of the thyroid gland. Hyperthyroidism can lead to an increased metabolic rate, excessive body heat and sweating, diarrhea, weight loss, tremors, and increased heart rate. The person's eyes may bulge (called exophthalmos) as antibodies produce inflammation in the soft tissues of the orbits.

Calcitonin

The thyroid gland also secretes a hormone called **calcitonin** that is produced by the parafollicular cells (also called clear cells or C thyrocytes) that stud the tissue between distinct follicles. Calcitonin is released in response to a rise in blood calcium levels. It appears to have a function in decreasing blood calcium concentrations by:

- Inhibiting the activity of osteoclasts, bone cells that release calcium into the circulation by degrading bone matrix
- Increasing osteoblastic activity
- Decreasing calcium absorption in the intestines

- Decreasing calcium reabsorption in the kidneys, which increases calcium loss in the urine

However, these functions are usually not significant in maintaining calcium homeostasis, so the importance of calcitonin is not entirely understood. Pharmaceutical preparations of calcitonin are sometimes prescribed to reduce osteoclast activity in people with osteoporosis and to reduce the degradation of cartilage in people with osteoarthritis. The hormones secreted by thyroid are summarized in Table 15.4.1.

Table 15.4.1: Thyroid Hormones

Associated hormones	Effect
Thyroxine (T_4), triiodothyronine (T_3)	Stimulate basal metabolic rate
Calcitonin	Reduces blood Ca^{2+} levels

Of course, calcium is critical for many other biological processes. It is a second messenger in many signaling pathways, and is essential for muscle contraction, nerve impulse transmission, and blood clotting. Given these roles, it is not surprising that blood calcium levels are tightly regulated by the endocrine system. The parathyroid glands, which will be discussed in more detail in the next section, are also involved in the regulation of calcium.

Concept Review

The thyroid gland is a butterfly-shaped organ located in the neck anterior to the trachea. Its hormones regulate basal metabolism, oxygen use, nutrient metabolism, the production of ATP, and calcium homeostasis. They also contribute to protein synthesis and the normal growth and development of body tissues, including maturation of the nervous system, and they increase the body's sensitivity to catecholamines. The thyroid hormones triiodothyronine (T_3) and thyroxine (T_4) are produced and secreted by the thyroid gland in response to thyroid-stimulating hormone (TSH) from the anterior pituitary. Synthesis of the amino acid–derived T_3 and T_4 hormones requires iodine. Insufficient amounts of iodine in the diet can lead to goiter and many other disorders.

Review Questions

Q. Which of the following statements about the thyroid gland is true?

A. It is located anterior to the trachea and inferior to the larynx.

B. The parathyroid glands are embedded within it.

C. It manufactures three hormones.

D. all of the above

Answer

Answer: D

Q. The secretion of thyroid hormones is controlled by _____.

A. TSH from the hypothalamus

B. TSH from the anterior pituitary

C. thyroxine from the anterior pituitary

D. thyroglobulin from the thyroid's parafollicular cells

Answer

Answer: B

Q. The development of a goiter indicates that _____.

A. the anterior pituitary is abnormally enlarged

B. there is hypertrophy of the thyroid's follicle cells

C. there is an excessive accumulation of colloid in the thyroid follicles

D. the anterior pituitary is secreting excessive growth hormone

Answer

Answer: C

Critical Thinking Questions

Q. Explain why maternal iodine deficiency might lead to neurological impairment in the fetus.

Answer

A. Iodine deficiency in a pregnant woman would also deprive the fetus. Iodine is required for the synthesis of thyroid hormones, which contribute to fetal growth and development, including maturation of the nervous system. Insufficient amounts would impair these functions.

Q. Define hyperthyroidism and explain why one of its symptoms is weight loss.

Answer

A. Hyperthyroidism is an abnormally elevated blood level of thyroid hormones due to an overproduction of T_3 and T_4. An individual with hyperthyroidism is likely to lose weight because one of the primary roles of thyroid hormones is to increase the body's basal metabolic rate, increasing the breakdown of nutrients and the production of ATP.

Glossary

calcitonin
peptide hormone produced and secreted by the parafollicular cells (C cells) of the thyroid gland that functions to decrease blood calcium levels

colloid
viscous fluid in the central cavity of thyroid follicles, containing the glycoprotein thyroglobulin

goiter
enlargement of the thyroid gland either as a result of iodine deficiency or hyperthyroidism

hyperthyroidism
clinically abnormal, elevated level of thyroid hormone in the blood; characterized by an increased metabolic rate, excess body heat, sweating, diarrhea, weight loss, and increased heart rate

hypothyroidism
clinically abnormal, low level of thyroid hormone in the blood; characterized by low metabolic rate, weight gain, cold extremities, constipation, and reduced mental activity

neonatal hypothyroidism
condition characterized by cognitive deficits, short stature, and other signs and symptoms in people born to women who were iodine-deficient during pregnancy

thyroid gland
large endocrine gland responsible for the synthesis of thyroid hormones

thyroxine
: (also, tetraiodothyronine, T_4) amino acid–derived thyroid hormone that is more abundant but less potent than T_3 and often converted to T_3 by target cells

triiodothyronine
: (also, T_3) amino acid–derived thyroid hormone that is less abundant but more potent than T_4

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15.5: Parathyroid Glands

By the end of this section, you will be able to:

- Describe the location and structure of the parathyroid glands
- Describe the hormonal control of blood calcium levels

The **parathyroid glands** are tiny, round structures usually found embedded in the posterior surface of the thyroid gland (Figure 15.5.1). A thick connective tissue capsule separates the glands from the thyroid tissue. Most people have four parathyroid glands, but occasionally there are more in tissues of the neck or chest.

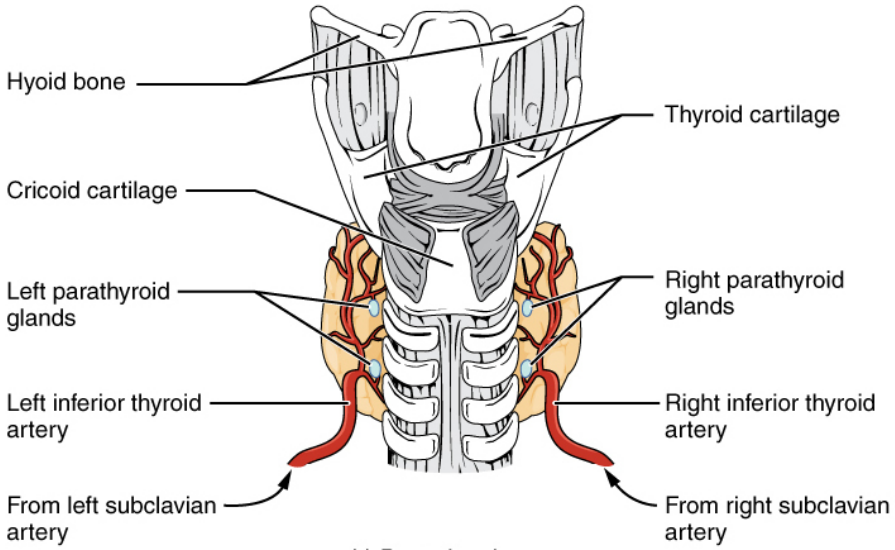

Figure 15.5.1: The Parathyroid Glands. Typically four parathyroid glands are embedded in the posterior surface of the thyroid gland alongside the superior portion of the trachea, two on the left and two on the right, with the superior set just inferior to the cricoid cartilage of the larynx. Also labeled in the image are the hyoid bone and the thyroid cartilage of the larynx for orientation, as well as the left and right inferior thyroid arteries that branch from the left and right subclavian arteries, respectively, and supply the posterior thyroid and parathyroid glands with blood. (Image credit: "Posterior Thyroid" by OpenStax is licensed under CC BY-SA 3.0)

The primary functional cells of the parathyroid glands are the chief cells. These epithelial cells produce and secrete **parathyroid hormone (PTH)**, the major hormone involved in the regulation of blood calcium levels (Figure 15.5.2). When blood calcium levels drop too low, PTH is released from the parathyroid glands into the bloodstream. Parathyroid hormone targets the bones and kidneys. In bones, PTH inhibits osteoblast activity while stimulating osteoclast activity, resulting in stored calcium being released from bone matrix into the bloodstream. In the kidneys, PTH stimulates an increase in calcium reabsorption into the bloodstream and also stimulates the release of **calcitriol**. Calcitriol targets the intestines to stimulate increased absorption of calcium from food.

When blood calcium levels are high, calcitonin is produced and secreted by the parafollicular cells of the thyroid gland. As discussed in the previous section, calcitonin inhibits the activity of osteoclasts, reduces the absorption of dietary calcium in the intestine, and signals the kidneys to reabsorb less calcium, resulting in larger amounts of calcium excreted in the urine.

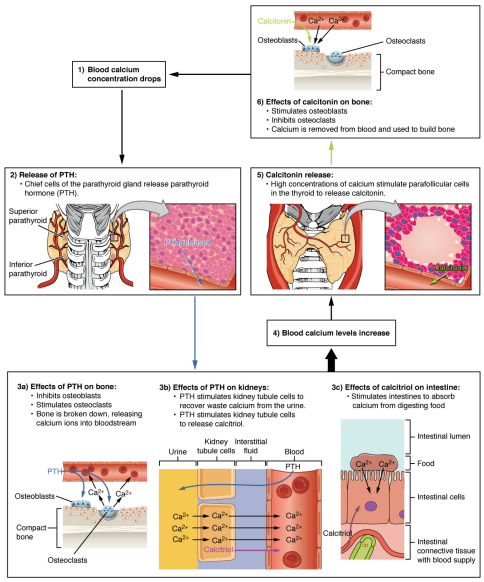

Figure 15.5.2: Hormonal Control of Blood Calcium Homeostasis. When the blood calcium concentration drops too low, chief cells within the superior and inferior pairs of parathyroid glands release parathyroid hormone (PTH) into the bloodstream. PTH effects on bone include inhibition of osteoblasts and stimulation of osteoclasts to break down bone, releasing calcium ions into the bloodstream. PTH effects on the kidneys include stimulating kidney tubule cells to recover waste calcium from the urine, reabsorbing it back into the bloodstream, and stimulating kidney tubule cells to release calcitriol into the bloodstream. The effect of calcitriol on the intestine is to stimulate the absorption of calcium ions from digested food. All of these mechanisms increase blood calcium levels. High concentrations of calcium in the blood stimulate parafollicular cells in the thyroid gland to release calcitonin. Calcitonin targets bone, stimulating osteoblasts and inhibiting osteoclasts so calcium is removed from the bloodstream and used to build bone. These two mechanisms constantly maintain homeostasis of blood calcium levels. (Image credit: "The Role of Parathyroid Hormone in Maintaining Blood Calcium Homeostasis" by OpenStax is licensed under CC BY 3.0)

DISORDERS OF THE...

Endocrine System: Hyperparathyroidism and Hypoparathyroidism

Abnormally high activity of the parathyroid gland can cause **hyperparathyroidism**, a disorder caused by an overproduction of PTH that results in excessive calcium reabsorption from bone. Hyperparathyroidism can significantly decrease bone density, leading to spontaneous fractures or deformities. As blood calcium levels rise, cell membrane permeability to sodium is decreased, and the responsiveness of the nervous system is reduced. At the same time, calcium deposits may collect in the body's tissues and organs, impairing their functioning.

In contrast, abnormally low blood calcium levels may be caused by parathyroid hormone deficiency, called **hypoparathyroidism**, which may develop following injury or surgery involving the thyroid gland. Low blood calcium increases membrane permeability to sodium, resulting in muscle twitching, cramping, spasms, or convulsions. Severe deficits can paralyze muscles, including those involved in breathing, and can be fatal.

Concept Review

Calcium is required for a variety of important physiologic processes, including neuromuscular functioning; thus, blood calcium levels are closely regulated. The parathyroid glands are small structures located on the posterior of the thyroid gland that produce parathyroid hormone (PTH), which regulates blood calcium levels. Low blood calcium levels cause the production and secretion of PTH. In contrast, elevated blood calcium levels inhibit secretion of PTH and trigger secretion of the thyroid hormone calcitonin. Underproduction of PTH can result in hypoparathyroidism. In contrast, overproduction of PTH can result in hyperparathyroidism.

Review Questions

Q. When blood calcium levels are low, PTH stimulates _____.

A. urinary excretion of calcium by the kidneys

B. a reduction in calcium absorption from the intestines

C. the activity of osteoblasts

D. the activity of osteoclasts

Answer

Answer: D

Q. Which of the following can result from hyperparathyroidism?

A. increased bone deposition

B. fractures

C. convulsions

D. all of the above

Answer

Answer: B

Critical Thinking Questions

Q. Describe the role of negative feedback in the function of the parathyroid gland.

Answer

A. The production and secretion of PTH is regulated by a negative feedback loop. Low blood calcium levels initiate the production and secretion of PTH. PTH increases bone resorption, calcium absorption from the intestines, and calcium reabsorption by the kidneys. As a result, blood calcium levels begin to rise. This, in turn, inhibits the further production and secretion of PTH.

Q. Explain why someone with a parathyroid gland tumor might develop kidney stones.

Answer

A. A parathyroid gland tumor can prompt hypersecretion of PTH. This can raise blood calcium levels so excessively that calcium deposits begin to accumulate throughout the body, including in the kidney tubules, where they are referred to as kidney stones.

Glossary

calcitriol
hormone released by kidney tubule cells in response to parathyroid hormone that stimulates increased absorption of calcium from digested food in the intestines

hyperparathyroidism
disorder caused by overproduction of PTH that results in abnormally elevated blood calcium

hypoparathyroidism
disorder caused by underproduction of PTH that results in abnormally low blood calcium

parathyroid glands
small, round glands embedded in the posterior thyroid gland that produce parathyroid hormone (PTH)

parathyroid hormone (PTH)
: peptide hormone produced and secreted by the parathyroid glands that targets bone and the kidneys to raise blood calcium levels and targets the kidneys to release calcitriol

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15.6: Adrenal Glands

By the end of this section, you will be able to:

- Describe the location and structure of the adrenal glands
- Identify the hormones produced by the adrenal cortex and adrenal medulla, and summarize their target cells and effects

The **adrenal glands**, also known as the suprarenal glands, are wedges of glandular and neuroendocrine tissue adhering to the top of the kidneys by a fibrous capsule of dense connective tissue (Figure 15.6.1). The adrenal glands have a rich blood supply and experience one of the highest rates of blood flow in the body. They are served by several arteries branching off the aorta, including the suprarenal and renal arteries. Blood flows to each adrenal gland at the adrenal cortex and then drains into the adrenal medulla. Adrenal hormones are released into the circulation via the left and right suprarenal veins.

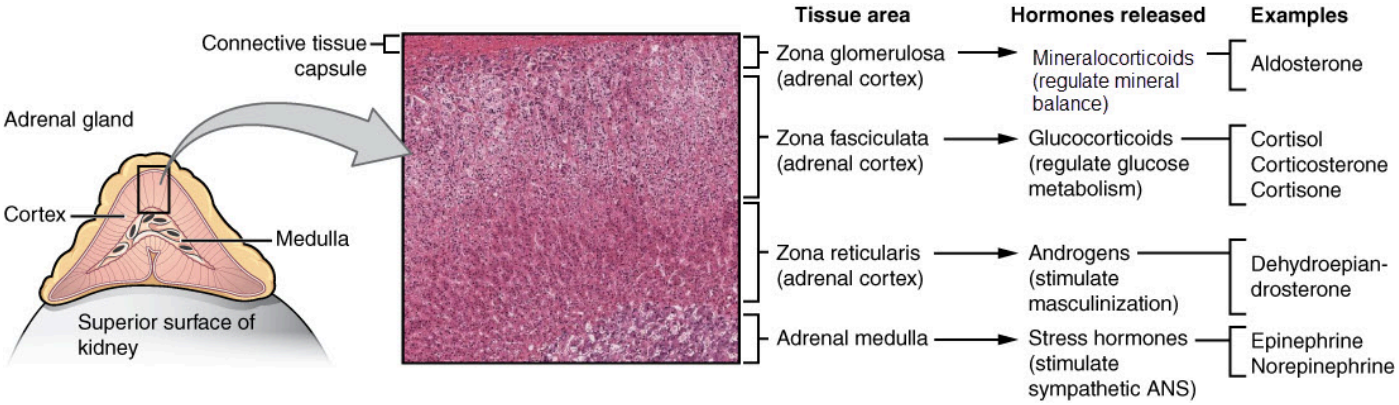

Figure 15.6.1: The Adrenal Glands. Both adrenal glands sit atop the kidneys and are composed of an outer cortex and an inner medulla, all surrounded by a connective tissue capsule. The cortex can be subdivided into additional zones listed from superficial to deep: the zona glomerulosa that releases mineralocorticoids such as aldosterone to regulate mineral balance, the zona fasciculata that releases glucocorticoids such as cortisol, corticosterone, and cortisone to regulate glucose metabolism, and the zona reticularis that releases androgens such as dehydroepiandrosterone that stimulate masculinization. The adrenal medulla releases stress hormones such as epinephrine and norepinephrine that stimulate the sympathetic autonomic nervous system (ANS). LM × 204. (Image credit: "The Adrenal Glands" by Julie Jenks is licensed under CC BY 4.0 / A derivative from the original work / Micrograph provided by the Regents of University of Michigan Medical School © 2012)

The adrenal gland consists of an outer cortex of glandular tissue and an inner medulla of nervous tissue.

The **adrenal cortex**, as a component of the hypothalamic-pituitary-adrenal (HPA) axis, secretes steroid hormones important for the regulation of the long-term stress response, blood pressure and blood volume, nutrient uptake and storage, fluid and electrolyte balance, and inflammation. The HPA axis involves the stimulation of hormone release of adrenocorticotropic hormone (ACTH) from the pituitary by the hypothalamus. ACTH then stimulates the adrenal cortex to produce the hormone cortisol.

The **adrenal medulla** is neuroendocrine tissue composed of postganglionic sympathetic nervous system (SNS) neurons. It is really an extension of the autonomic nervous system, which regulates homeostasis in the body. The sympathomedullary (or SAM: Sympathetic-Adrenal-Medulla) pathway involves the stimulation of the medulla by impulses from the hypothalamus via neurons from the thoracic spinal cord. The medulla is stimulated to secrete the amine hormones epinephrine and norepinephrine.

One of the major functions of the adrenal gland is to respond to stress. Stress can be either physical or psychological or both. Physical stresses include exposing the body to injury, walking outside in cold and wet conditions without a coat on, or malnutrition. Psychological stresses include the perception of a physical threat, a fight with a loved one, or just a bad day at school.

The body responds in different ways to short-term stress and long-term stress following a pattern known as the **general adaptation syndrome (GAS)**. Stage one of GAS is called the **alarm reaction**. This is short-term stress, the fight-or-flight response, mediated by the hormones epinephrine and norepinephrine from the adrenal medulla via the SAM pathway. Their function is to prepare the body for extreme physical exertion. Once this stress is relieved, the body quickly returns to normal. The

section on the adrenal medulla covers this response in more detail.

If the stress is not relieved quickly, the body adapts to the stress in the second stage called the **stage of resistance**. If a person is starving for example, the body may send signals to the gastrointestinal tract to maximize the absorption of nutrients from food.

If the stress continues for a longer term however, the body responds with symptoms quite different than the fight-or-flight response. During the **stage of exhaustion**, individuals may begin to suffer depression, the suppression of their immune response, severe fatigue, or even a fatal heart attack. These symptoms are mediated by the hormones of the adrenal cortex, especially cortisol, released as a result of signals from the HPA axis.

Adrenal hormones also have several non–stress-related functions, including the increase of blood sodium and glucose levels, which will be described in detail below.

Adrenal Cortex

The adrenal cortex consists of multiple layers of lipid-storing cells that occur in three structurally distinct regions: the **zona glomerulosa**, the **zona fasciculata**, and the **zona reticularis**. Each region secretes its own set of hormones.

Hormones of the Zona Glomerulosa

The most superficial region of the adrenal cortex is the zona glomerulosa, which produces a group of hormones collectively referred to as **mineralocorticoids** because of their effect on body minerals, especially sodium and potassium. These hormones are essential for fluid and electrolyte balance.

Aldosterone is the major mineralocorticoid. It is important in the regulation of the concentration of sodium (Na^+) and potassium (K^+) ions in urine, sweat, and saliva. For example, it is released in response to elevated blood K^+, low blood Na^+, low blood pressure, or low blood volume. In response, aldosterone increases the excretion of K^+ and the retention of Na^+, which in turn increases blood volume and blood pressure. Its secretion is prompted when CRH from the hypothalamus triggers ACTH release from the anterior pituitary.

Aldosterone is also a key component of the renin-angiotensin-aldosterone system (RAAS) in which specialized cells of the kidneys secrete the enzyme renin in response to low blood volume or low blood pressure. Renin then catalyzes the conversion of the blood protein angiotensinogen, produced by the liver, to the hormone angiotensin I. Angiotensin I is converted in the lungs to angiotensin II by **angiotensin-converting enzyme (ACE)**. Angiotensin II has three major functions:

1. Initiating vasoconstriction of the arterioles, decreasing blood flow
2. Stimulating kidney tubules to reabsorb NaCl and water, increasing blood volume
3. Signaling the adrenal cortex to secrete aldosterone, the effects of which further contribute to fluid retention, restoring blood pressure and blood volume

For individuals with hypertension, or high blood pressure, drugs are available that block the production of angiotensin II. These drugs, known as ACE inhibitors, block the ACE enzyme from converting angiotensin I to angiotensin II, thus mitigating the latter's ability to increase blood pressure.

Hormones of the Zona Fasciculata

The intermediate region of the adrenal cortex is the zona fasciculata, named as such because the cells form small fascicles (bundles) separated by tiny blood vessels. The cells of the zona fasciculata produce hormones called **glucocorticoids** because of their role in glucose metabolism. The most important of these is **cortisol**, some of which the liver converts to cortisone. A glucocorticoid produced in much smaller amounts is corticosterone. In response to long-term stressors, the hypothalamus secretes CRH, which in turn triggers the release of ACTH by the anterior pituitary. ACTH triggers the release of the glucocorticoids. Their overall effect is to inhibit tissue building while stimulating the breakdown of stored nutrients to maintain adequate fuel supplies. In conditions of long-term stress, for example, cortisol promotes the catabolism of glycogen to glucose, the catabolism of stored triglycerides into fatty acids and glycerol, and the catabolism of muscle proteins into amino acids. These raw materials can then be used to synthesize additional glucose and ketones for use as body fuels. The hippocampus, which is part of the temporal lobe of the cerebral cortices and important in memory formation, is highly sensitive to stress levels because of its many

glucocorticoid receptors.

You are probably familiar with prescription and over-the-counter medications containing glucocorticoids, such as cortisone injections into inflamed joints, prednisone tablets and steroid-based inhalers used to manage severe asthma, and hydrocortisone creams applied to relieve itchy skin rashes. These drugs reflect another role of cortisol—the downregulation of the immune system, which inhibits the inflammatory response.

Hormones of the Zona Reticularis

The deepest region of the adrenal cortex is the zona reticularis, which produces small amounts of a class of steroid sex hormones called androgens. During puberty and most of adulthood, androgens are produced in the gonads. The androgens produced in the zona reticularis supplement the gonadal androgens. They are produced in response to ACTH from the anterior pituitary and are converted in the tissues to testosterone or estrogens. After menopause in those with ovaries, as the functions of the ovaries decline, the main source of estrogens becomes the androgens produced by the zona reticularis.

Adrenal Medulla

As noted earlier, the adrenal cortex releases glucocorticoids in response to long-term stress such as severe illness. In contrast, the adrenal medulla releases its hormones in response to acute, short-term stress mediated by the sympathetic nervous system (SNS).

The medullary tissue is composed of unique postganglionic SNS neurons called **chromaffin** cells, which are large and irregularly shaped, and produce the neurotransmitters **epinephrine** (also called adrenaline) and **norepinephrine** (or noradrenaline). Epinephrine is produced in greater quantities—approximately a 4 to 1 ratio with norepinephrine—and is the more powerful hormone. Because the chromaffin cells release epinephrine and norepinephrine into the systemic circulation, where they travel widely and exert effects on distant cells, they are considered hormones.

The secretion of medullary epinephrine and norepinephrine is controlled by a neural pathway that originates from the hypothalamus in response to danger or stress (the SAM pathway). Both epinephrine and norepinephrine signal the liver and skeletal muscle cells to convert glycogen into glucose, resulting in increased blood glucose levels. These hormones increase the heart rate, pulse, and blood pressure to prepare the body to fight the perceived threat or flee from it. In addition, the pathway dilates the airways, raising blood oxygen levels. It also prompts vasodilation, further increasing the oxygenation of important organs such as the lungs, brain, heart, and skeletal muscle. At the same time, it triggers vasoconstriction to blood vessels serving less essential organs such as the gastrointestinal tract, kidneys, and skin, and downregulates some components of the immune system. Other effects include a dry mouth, loss of appetite, pupil dilation, and a loss of peripheral vision. The major hormones of the adrenal glands are summarized in Table 15.6.1.

Table 15.6.1: Hormones of the Adrenal Glands

Adrenal gland	Associated hormones	Effect
Adrenal cortex	Aldosterone	Increases blood Na^+ levels
Adrenal cortex	Cortisol, corticosterone, cortisone	Increase blood glucose levels
Adrenal medulla	Epinephrine, norepinephrine	Stimulate fight-or-flight response

DISORDERS OF THE...

Endocrine System: Disorders Involving the Adrenal Glands

Several disorders are caused by the dysregulation of the hormones produced by the adrenal glands. For example, Cushing's disease is a disorder characterized by high blood glucose levels and the accumulation of lipid deposits on the face and neck. It is caused by hypersecretion of cortisol. The most common source of Cushing's disease is a pituitary tumor that secretes cortisol or ACTH in abnormally high amounts. Other common signs of Cushing's disease include the development of a moon-

shaped face, a buffalo hump on the back of the neck, rapid weight gain, and hair loss. Chronically elevated glucose levels are also associated with an elevated risk of developing type 2 diabetes. In addition to hyperglycemia, chronically elevated glucocorticoids compromise immunity, resistance to infection, and memory, and can result in rapid weight gain and hair loss.

In contrast, the hyposecretion of corticosteroids can result in Addison's disease, a rare disorder that causes low blood glucose levels and low blood sodium levels. The signs and symptoms of Addison's disease are vague and are typical of other disorders as well, making diagnosis difficult. They may include general weakness, abdominal pain, weight loss, nausea, vomiting, sweating, and cravings for salty food.

Concept Review

The adrenal glands, located superior to each kidney, consist of two regions: the adrenal cortex and adrenal medulla. The adrenal cortex—the outer layer of the gland—produces mineralocorticoids, glucocorticoids, and androgens. The adrenal medulla, at the core of the gland, produces epinephrine and norepinephrine.

The adrenal glands mediate a short-term stress response and a long-term stress response. A perceived threat results in the secretion of epinephrine and norepinephrine from the adrenal medulla, which mediate the fight-or-flight response. The long-term stress response is mediated by the secretion of CRH from the hypothalamus, which triggers ACTH, which in turn stimulates the secretion of corticosteroids from the adrenal cortex. The mineralocorticoids, chiefly aldosterone, cause sodium and fluid retention, which increases blood volume and blood pressure.

Review Questions

Q. The adrenal glands are attached superiorly to which organ?

A. thyroid

B. liver

C. kidneys

D. hypothalamus

Answer

C

Q. What secretory cell type is found in the adrenal medulla?

A. chromaffin cells

B. neuroglial cells

C. follicle cells

D. oxyphil cells

Answer

A

Q. Cushing's disease is a disorder caused by _____.

A. abnormally low levels of cortisol

B. abnormally high levels of cortisol

C. abnormally low levels of aldosterone

D. abnormally high levels of aldosterone

Answer

B

Q. Which of the following responses is not part of the fight-or-flight response?

A. pupil dilation

B. increased oxygen supply to the lungs

C. suppressed digestion

D. reduced heart rate

Answer

D

Critical Thinking Questions

Q. What are the three regions of the adrenal cortex and what hormones do they produce?

Answer

A. The outer region is the zona glomerulosa, which produces mineralocorticoids such as aldosterone; the next region is the zona fasciculata, which produces glucocorticoids such as cortisol; the inner region is the zona reticularis, which produces androgens.

Q. Compare and contrast the short-term and long-term stress response.

Answer

A. The short-term stress response involves the hormones epinephrine and norepinephrine, which work to increase the oxygen supply to organs important for extreme muscular action such as the brain, lungs, and muscles. In the long-term stress response, the hormone cortisol is involved in catabolism of glycogen stores, proteins, and triglycerides, glucose and ketone synthesis, and downregulation of the immune system.

Glossary

adrenal cortex
outer region of the adrenal glands consisting of multiple layers of epithelial cells and capillary networks that produces mineralocorticoids and glucocorticoids

adrenal glands
endocrine glands located at the top of each kidney that are important for the regulation of the stress response, blood pressure and blood volume, water homeostasis, and electrolyte levels; also known as suprarenal glands

adrenal medulla
inner layer of the adrenal glands that plays an important role in the stress response by producing epinephrine and norepinephrine

angiotensin-converting enzyme
the enzyme that converts angiotensin I to angiotensin II

alarm reaction
the short-term stress, or the fight-or-flight response, of stage one of the general adaptation syndrome mediated by

the hormones epinephrine and norepinephrine

aldosterone
hormone produced and secreted by the adrenal cortex that stimulates sodium and fluid retention and increases blood volume and blood pressure

chromaffin
neuroendocrine cells of the adrenal medulla

cortisol
glucocorticoid important in gluconeogenesis, the catabolism of glycogen, and downregulation of the immune system

epinephrine
primary and most potent catecholamine hormone secreted by the adrenal medulla in response to short-term stress; also called adrenaline

general adaptation syndrome (GAS)
the human body's three-stage response pattern to short- and long-term stress

glucocorticoids
hormones produced by the zona fasciculata of the adrenal cortex that influence glucose metabolism

mineralocorticoids
hormones produced by the zona glomerulosa cells of the adrenal cortex that influence fluid and electrolyte balance

norepinephrine
secondary catecholamine hormone secreted by the adrenal medulla in response to short-term stress; also called noradrenaline

stage of exhaustion
stage three of the general adaptation syndrome; the body's long-term response to stress mediated by the hormones of the adrenal cortex

stage of resistance
stage two of the general adaptation syndrome; the body's continued response to stress after stage one diminishes

zona fasciculata
intermediate region of the adrenal cortex that produce hormones called glucocorticoids

zona glomerulosa
most superficial region of the adrenal cortex, which produces the hormones collectively referred to as mineralocorticoids

zona reticularis
deepest region of the adrenal cortex, which produces the steroid sex hormones called androgens

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15.7: Pineal Gland

By the end of this section, you will be able to:

- Describe the location and structure of the pineal gland
- Discuss the function of melatonin

Recall that the hypothalamus, part of the diencephalon of the brain, sits inferior and somewhat anterior to the thalamus. Inferior but somewhat posterior to the thalamus is the **pineal gland**, a tiny endocrine gland whose functions are not entirely clear. The **pinealocyte** cells that make up the pineal gland are known to produce and secrete the hormone **melatonin**, which is derived from serotonin.

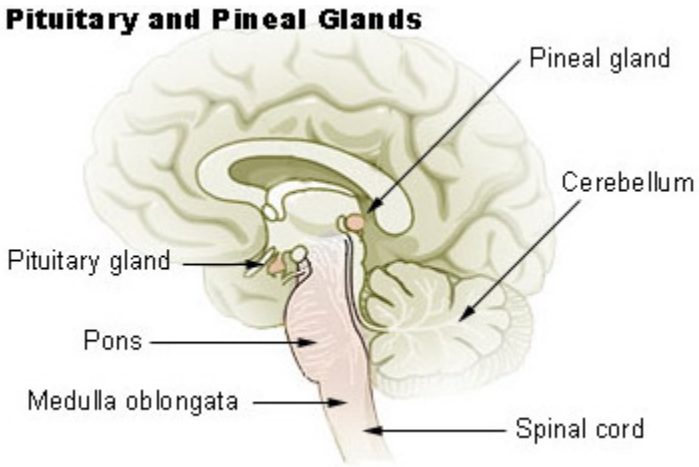

Figure 15.7.1: The Pineal Gland. The pineal gland is situated inferoposterior and medial to the left and right thalami. Also labeled in this image for orientation are several landmark structures that are all inferior to the pineal gland. The pituitary gland is inferior to the hypothalamus. The cerebellum is located posterior to the pons and inferior to the occipital lobe of the cerebrum. The pons is superior to the medulla oblongata which is the most inferior structure of the brainstem that is continuous with the spinal cord. (Image credit: "Pituitary Pineal Glands" by unknown author is in the Public Domain)

The secretion of melatonin varies according to the level of light received from the environment. When photons of light stimulate the retinas of the eyes, a nerve impulse is sent to a region of the hypothalamus called the suprachiasmatic nucleus (SCN), which is important in regulating biological rhythms. From the SCN, the nerve signal is carried to the spinal cord and eventually to the pineal gland, where the production of melatonin is inhibited. As a result, blood levels of melatonin fall, promoting wakefulness. In contrast, as light levels decline—such as during the evening—melatonin production increases, boosting blood levels and causing drowsiness.

The secretion of melatonin may influence the body's circadian rhythms, the dark-light fluctuations that affect not only sleepiness and wakefulness, but also appetite and body temperature. Interestingly, children have higher melatonin levels than adults, which may prevent the release of gonadotropins from the anterior pituitary, thereby inhibiting the onset of puberty. Finally, an antioxidant role of melatonin is the subject of current research.

Jet lag occurs when a person travels across several time zones and feels sleepy during the day or wakeful at night. Traveling across multiple time zones significantly disturbs the light-dark cycle regulated by melatonin. It can take up to several days for melatonin synthesis to adjust to the light-dark patterns in the new environment, resulting in jet lag. Some air travelers take melatonin supplements to induce sleep.

Concept Review

The pineal gland is an endocrine structure of the diencephalon of the brain, and is located inferior and posterior to the thalamus.

It is made up of pinealocytes. These cells produce and secrete the hormone melatonin in response to low light levels. High blood levels of melatonin induce drowsiness. Jet lag, caused by traveling across several time zones, occurs because melatonin synthesis takes several days to readjust to the light-dark patterns in the new environment.

Review Questions

Q. What cells secrete melatonin?

A. melanocytes

B. pinealocytes

C. suprachiasmatic nucleus cells

D. retinal cells

Answer

B

Q. The production of melatonin is inhibited by _____.

A. declining levels of light

B. exposure to bright light

C. the secretion of serotonin

D. the activity of pinealocytes

Answer

B

Critical Thinking Questions

Q. Seasonal affective disorder (SAD) is a mood disorder characterized by, among other symptoms, increased appetite, sluggishness, and increased sleepiness. It occurs most commonly during the winter months, especially in regions with long winter nights. Propose a role for melatonin in SAD and a possible non-drug therapy.

Answer

A. SAD is thought to occur in part because low levels and duration of sunlight allow excessive and prolonged secretion of melatonin. Light therapy—daytime exposure to very bright lighting—is one common therapy.

Q. Retinitis pigmentosa (RP) is a disease that causes deterioration of the retinas of the eyes. Describe the impact RP would have on melatonin levels.

Answer

A. The retina is important for melatonin production because it senses light. Bright light inhibits the production of melatonin, whereas low light levels promote the production of melatonin. Therefore, deterioration of the retinas would most likely disturb the sleep-wake pattern because melatonin production would be elevated.

Glossary

melatonin
amino acid–derived hormone that is secreted in response to low light and causes drowsiness

pineal gland
: endocrine gland that secretes melatonin, which is important in regulating the sleep-wake cycle

pinealocyte
: cell of the pineal gland that produces and secretes the hormone melatonin

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15.8: Gonadal and Placental Hormones

By the end of this section, you will be able to:

- Identify the primary hormones produced by the testes and ovaries
- Name the hormones produced by the placenta and state their functions

This section briefly discusses the hormonal role of the gonads—the testes and ovaries—which produce the sex cells (sperm and ova, respectively) and secrete the gonadal hormones. The roles of the gonadotropins released from the anterior pituitary (FSH and LH/ICSH) were discussed earlier. The anatomy of these organs is covered in more detail in the Reproductive System chapter.

The primary hormone produced by the testes is **testosterone**, a steroid hormone important in the development of the male reproductive system, the maturation of sperm cells, and the development of male secondary sex characteristics such as a deepened voice, body hair, and increased muscle mass. Interestingly, testosterone is also produced in the ovaries, but at a much reduced level. In addition, the testes produce the peptide hormone **inhibin**, which inhibits the secretion of FSH from the anterior pituitary gland. FSH stimulates spermatogenesis, or sperm cell production.

The primary hormones produced by the ovaries are **estrogens**, which include estradiol, estriol, and estrone. Estrogens play an important role in a larger number of physiological processes, including the development of the female reproductive system, regulation of the menstrual cycle, the development of female secondary sex characteristics such as increased adipose tissue and the development of breast tissue, and the maintenance of pregnancy. Another significant ovarian hormone is **progesterone**, which contributes to regulation of the menstrual cycle and is important in preparing the body for pregnancy as well as maintaining pregnancy. In addition, the granulosa cells of the ovarian follicles produce inhibin, which—as in those with testes—inhibits the secretion of FSH. During the initial stages of pregnancy, an organ called the placenta develops within the uterus. The placenta supplies oxygen and nutrients to the fetus, excretes waste products, and produces and secretes estrogens and progesterone. The placenta produces human chorionic gonadotropin (hCG) as well. The hCG hormone promotes progesterone synthesis and reduces the mother's immune function to protect the fetus from immune rejection. The hormones controlling reproduction are summarized in Table 15.8.1.

Table 15.8.1: Reproductive Hormones

Gonad	Associated hormones	Effect
Testes	Testosterone	Stimulates development of male secondary sex characteristics and sperm production
Testes	Inhibin	Inhibits FSH release from pituitary
Ovaries	Estrogens and progesterone	Stimulate development of female secondary sex characteristics and prepare the body for childbirth
Placenta	Human chorionic gonadotropin	Promotes progesterone synthesis during pregnancy and inhibits immune response against fetus

EVERYDAY CONNECTIONS

Anabolic Steroids

The endocrine system can be exploited for illegal or unethical purposes. A prominent example of this is the use of steroid drugs by professional athletes.

Commonly used for performance enhancement, anabolic steroids are synthetic versions of the sex hormone testosterone. By boosting natural levels of this hormone, athletes experience increased muscle mass. Synthetic versions of human growth hormone are also used to build muscle mass.

The use of performance-enhancing drugs is banned by all major collegiate and professional sports organizations in the United States because they impart an unfair advantage to athletes who take them. In addition, the drugs can cause significant and dangerous side effects. For example, anabolic steroid use can increase cholesterol levels, raise blood pressure, and damage the liver. Altered testosterone levels (both too low or too high) have been implicated in causing structural damage to the heart, and increasing the risk for cardiac arrhythmias, heart attacks, congestive heart failure, and sudden death. Paradoxically, steroids can cause shriveled testes and enlarged breast tissue in men. In females, their use can cause analogous effects such as an enlarged clitoris and growth of facial hair. In both sexes, their use can promote increased aggression (commonly known as “roid-rage”), depression, sleep disturbances, severe acne, and infertility.

Concept Review

The reproductive system in both males and females is regulated by follicle-stimulating hormone (FSH) and luteinizing hormone (LH, also called interstitial cell stimulating hormone or ICSH in males) produced by the anterior lobe of the pituitary gland in response to gonadotropin-releasing hormone (GnRH) from the hypothalamus. In males, FSH stimulates sperm maturation, which is inhibited by the hormone inhibin. The steroid hormone testosterone, a type of androgen, is released in response to ICSH and is responsible for the maturation and maintenance of the reproductive system, as well as the development of male secondary sex characteristics. In females, FSH promotes egg maturation and LH signals the secretion of sex hormones: estrogens and progesterone. Both of these hormones are important in the development and maintenance of the female reproductive system, as well as maintaining pregnancy. The placenta develops during early pregnancy, and secretes several hormones important for maintaining the pregnancy.

Review Questions

Q. The gonads primarily produce what class of hormones?

A. amine hormones

B. peptide hormones

C. steroid hormones

D. catecholamines

Answer

Answer: C

Q. The production of FSH by the anterior pituitary is reduced by which hormone?

A. estrogens

B. progesterone

C. testosterone

D. inhibin

Answer

Answer: D

Critical Thinking Questions

Q. Compare and contrast the role of estrogens and progesterone.

Answer

A. Both estrogens and progesterone are steroid hormones produced by the ovaries that help regulate the menstrual cycle. Estrogens play an important role in the development of the reproductive tract and secondary sex characteristics in females. They also help maintain pregnancy. Progesterone prepares the body for pregnancy and helps maintain pregnancy.

Glossary

estrogens
class of sex hormones important for the development and growth of the reproductive tract, secondary sex characteristics, and the reproductive cycle in females, and the maintenance of pregnancy

inhibin
hormone secreted by the gonads that inhibits FSH production by the anterior pituitary

progesterone
sex hormone important in regulating the reproductive cycle in those with ovaries and the maintenance of pregnancy

testosterone
steroid hormone secreted by the testes and important in the maturation of sperm cells, growth and development of the reproductive system, and the development of secondary sex characteristics in males

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15.9: Endocrine Pancreas

By the end of this section, you will be able to:

- Describe the location and structure of the pancreas, and the morphology and function of the pancreatic islets
- Compare and contrast the functions of insulin and glucagon

The **pancreas** is a long, slender retroperitoneal organ, most of which is located posterior to the bottom half of the stomach (Figure 15.9.1). It is bordered on its right by the retroperitoneal section of the duodenum and on its left by the spleen. The acinar cells of the pancreas line many short cul-de-sac-shaped areas connected directly to the pancreatic duct that drains transversely through the core of the pancreas to the duodenum nestled against its right side. Although it is primarily an exocrine gland, with its acinar cells secreting a variety of digestive enzymes that comprise pancreatic juice that will function outside the epithelial lining of the small intestine, the pancreas also has an endocrine function. Scattered around the cul-de-sacs of acinar cells throughout the pancreas are about a million **pancreatic islets**—clusters of cells formerly known as the islets of Langerhans— that secrete the hormones glucagon, insulin, somatostatin, and pancreatic polypeptide (PP).

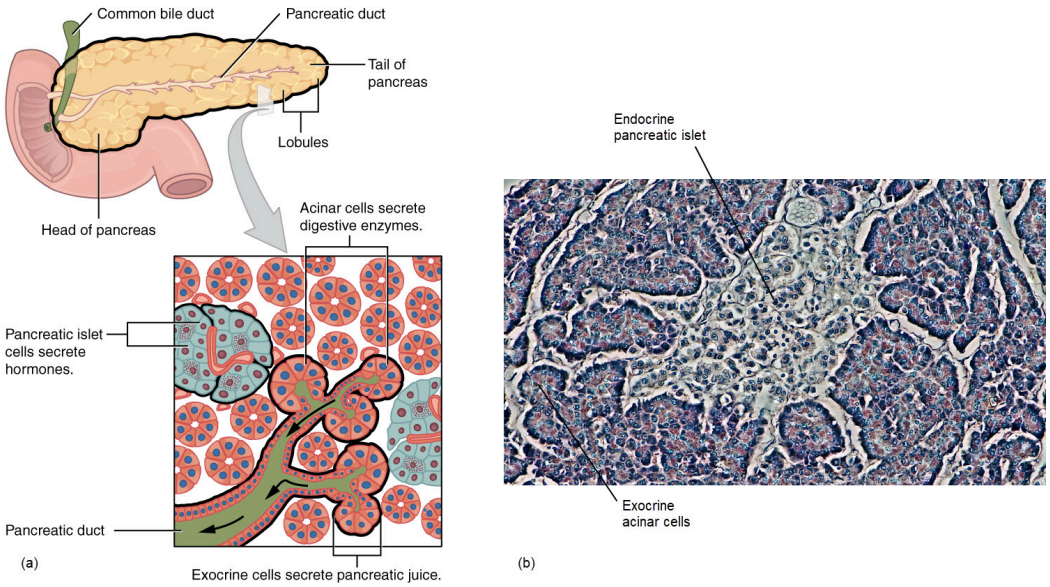

Figure 15.9.1: The Pancreas. (a) The taller head of the pancreas is attached to the left surface of the duodenum of the small intestine, just inferior to the stomach. The thinner tail of the pancreas extends across the midline toward the spleen. The pancreas consists of many functional lobules. Within a pancreatic lobule are two functional areas: Acinar cells have an exocrine function to secrete digestive enzymes into the pancreatic duct at the center of the organ in which pancreatic juice travels to the duodenum just after the duct merges with the common bile duct. Pancreatic islets are not connected to the pancreatic duct and have an endocrine function; alpha and beta cells of the islets secrete pancreatic hormones into the bloodstream. (b) A lighter-staining pancreatic islet is shown at the center of this micrograph surrounded by darker-staining acinar cells. LM X 200. (Image credit: "Exocrine and Endocrine Pancreas" by Julie Jenks is licensed under CC BY 4.0 / A derivative from the original work in (a) and the original work in (b))

Cells and Secretions of the Pancreatic Islets

Each pancreatic islet contains four types of cells whose secretions move into the bloodstream to travel to their target cells:

- The **alpha cell** produces the hormone glucagon and makes up approximately 20 percent of each islet. Glucagon plays an important role in blood glucose regulation; low blood glucose levels stimulate its release.
- The **beta cell** produces the hormone insulin and makes up approximately 75 percent of each islet. Elevated blood glucose levels stimulate the release of insulin.
- The **delta cell** accounts for four percent of the islet cells and secretes the peptide hormone somatostatin. Recall that somatostatin is also released by the hypothalamus (as GHIH), and the stomach and intestines also secrete it. An inhibiting

hormone, pancreatic somatostatin inhibits the release of both glucagon and insulin.
- The **PP cell** accounts for about one percent of islet cells and secretes the pancreatic polypeptide hormone. It is thought to play a role in appetite, as well as in the regulation of pancreatic exocrine and endocrine secretions. Pancreatic polypeptide released following a meal may reduce further food consumption; however, it is also released in response to fasting.

Regulation of Blood Glucose Levels by Insulin and Glucagon

Glucose is required for cellular respiration and is the preferred fuel for all body cells. The body derives glucose from the breakdown of the carbohydrate-containing foods and drinks we consume. Glucose not immediately taken up by cells for fuel can be stored by the liver and muscles as glycogen, or converted to triglycerides and stored in the adipose tissue. Hormones regulate both the storage and the utilization of glucose as required. Receptors located in the pancreas sense blood glucose levels, and subsequently the pancreatic cells secrete glucagon or insulin to maintain normal levels.

Glucagon

Receptors in the pancreas can sense the decline in blood glucose levels, such as during periods of fasting or during prolonged labor or exercise (Figure 15.9.2). In response, the alpha cells of the pancreas secrete the hormone **glucagon**, which has several effects:

- It stimulates the liver to convert its stores of glycogen back into glucose. This response is known as glycogenolysis. The glucose is then released into the circulation for use by body cells.
- It stimulates the liver to take up amino acids from the blood and convert them into glucose. This response is known as gluconeogenesis.
- It stimulates lipolysis, the breakdown of stored triglycerides into free fatty acids and glycerol. Some of the free glycerol released into the bloodstream travels to the liver, which converts it into glucose. This is also a form of gluconeogenesis.

Taken together, these actions increase blood glucose levels. The activity of glucagon is regulated through a negative feedback mechanism; rising blood glucose levels inhibit further glucagon production and secretion.

Insulin

The primary function of **insulin** is to facilitate the uptake of glucose into body cells. Red blood cells, as well as cells of the brain, liver, kidneys, and the lining of the small intestine, do not have insulin receptors on their cell membranes and do not require insulin for glucose uptake. Although all other body cells do require insulin if they are to take glucose from the bloodstream, skeletal muscle cells and adipose cells are the primary targets of insulin.

The presence of food in the intestine leads to insulin production and secretion by the beta cells of the pancreas. Once nutrient absorption occurs, the resulting surge in blood glucose levels further stimulates insulin secretion.

INTERACTIVE LINK

Pancreas Location and Endocrine Function

QR Code representing a URL

Watch this video describing the location and endocrine function of the pancreas. What goes wrong in the function of insulin in type 2 diabetes?

Answer available at the end of this section.

Insulin also reduces blood glucose levels by stimulating glycolysis, the metabolism of glucose for generation of ATP. Moreover, it stimulates the liver to convert excess glucose into glycogen for storage, and it inhibits enzymes involved in glycogenolysis and gluconeogenesis because the body doesn't need to free more glucose. Finally, insulin promotes triglyceride and protein synthesis. The secretion of insulin is regulated through a negative feedback mechanism. As blood glucose levels decrease, further insulin release is inhibited. The pancreatic hormones are summarized in Table 15.9.1.

Table 15.9.1: Hormones of the Pancreas

Associated hormone (and the cells that secretes it)	Effect
Insulin (beta cells)	Reduces blood glucose levels
Glucagon (alpha cells)	Increases blood glucose levels
Somatostatin (delta cells)	Inhibits insulin and glucagon release

DISORDERS OF THE...

Endocrine System: Diabetes Mellitus

Dysfunction of insulin production and secretion, as well as the target cells' responsiveness to insulin, can lead to a condition called diabetes mellitus. An increasingly common disease, diabetes mellitus has been diagnosed in more than 18 million adults in the United States, and more than 200,000 children. It is estimated that up to 7 million more adults have the condition but have not been diagnosed. In addition, approximately 79 million people in the US are estimated to have pre-diabetes, a condition in which blood glucose levels are abnormally high, but not yet high enough to be classified as diabetes.

There are two main forms of diabetes mellitus. Type 1 diabetes is an autoimmune disease affecting the beta cells of the pancreas. Certain genes are recognized to increase susceptibility. The beta cells of people with type 1 diabetes do not produce insulin; thus, synthetic insulin must be administered by injection or infusion. This form of diabetes accounts for less than five percent of all diabetes cases.

Type 2 diabetes accounts for approximately 95 percent of all cases. It is acquired, and lifestyle factors such as poor diet, inactivity, and the presence of pre-diabetes greatly increase a person's risk. About 80 to 90 percent of people with type 2 diabetes are overweight or obese. In type 2 diabetes, cells become resistant to the effects of insulin. In response, the pancreas increases its insulin secretion, but over time, the beta cells become exhausted. In many cases, type 2 diabetes can be reversed by moderate weight loss, regular physical activity, and consumption of a healthy diet; however, if blood glucose levels cannot be controlled, the diabetic will eventually require insulin.

Two of the early manifestations of diabetes are excessive urination and excessive thirst. They demonstrate how the out-of-control levels of glucose in the blood affect kidney function. The kidneys are responsible for filtering glucose from the blood. Excessive blood glucose draws water into the urine, and as a result the person eliminates an abnormally large quantity of sweet urine. The use of body water to dilute the urine leaves the body dehydrated, and so the person is unusually and continually thirsty. The person may also experience persistent hunger because the body cells are unable to access the glucose in the bloodstream.

Over time, persistently high levels of glucose in the blood injure tissues throughout the body, especially those of the blood vessels and nerves. Inflammation and injury of the lining of arteries lead to atherosclerosis and an increased risk of heart attack and stroke. Damage to the microscopic blood vessels of the kidney impairs kidney function and can lead to kidney failure. Damage to blood vessels that serve the eyes can lead to blindness. Blood vessel damage also reduces circulation to the limbs, whereas nerve damage leads to a loss of sensation, called neuropathy, particularly in the hands and feet. Together, these changes increase the risk of injury, infection, and tissue death (necrosis), contributing to a high rate of toe, foot, and lower leg amputations in people with diabetes. Uncontrolled diabetes can also lead to a dangerous form of metabolic acidosis called ketoacidosis. Deprived of glucose, cells increasingly rely on fat stores for fuel. However, in a glucose-deficient state, the liver is forced to use an alternative lipid metabolism pathway that results in the increased production of ketone bodies (or ketones), which are acidic. The build-up of ketones in the blood causes ketoacidosis, which—if left untreated—may lead to a life-threatening "diabetic coma." Together, these complications make diabetes the seventh leading cause of death in the United States.

Diabetes is diagnosed when lab tests reveal that blood glucose levels are higher than normal, a condition called hyperglycemia. The treatment of diabetes depends on the type, the severity of the condition, and the ability of the patient to make lifestyle changes. As noted earlier, moderate weight loss, regular physical activity, and consumption of a healthful diet can reduce blood glucose levels. Some patients with type 2 diabetes may be unable to control their disease with these lifestyle changes, and will require medication. Historically, the first-line treatment of type 2 diabetes was insulin. Research advances have resulted in alternative options, including medications that enhance pancreatic function.

Concept Review

The pancreas has both exocrine and endocrine functions. The pancreatic islet cell types include alpha cells, which produce glucagon; beta cells, which produce insulin; delta cells, which produce somatostatin; and PP cells, which produce pancreatic polypeptide. Insulin and glucagon are involved in the regulation of glucose metabolism. Insulin is produced by the beta cells in response to high blood glucose levels. It enhances glucose uptake and utilization by target cells, as well as the storage of excess glucose for later use. Dysfunction of the production of insulin or target cell resistance to the effects of insulin causes diabetes mellitus, a disorder characterized by high blood glucose levels. The hormone glucagon is produced and secreted by the alpha cells of the pancreas in response to low blood glucose levels. Glucagon stimulates mechanisms that increase blood glucose levels, such as the catabolism of glycogen into glucose.

Review Questions

Q. If an autoimmune disorder targets the alpha cells, production of which hormone would be directly affected?

A. somatostatin

B. pancreatic polypeptide

C. insulin

D. glucagon

Answer

Answer: D

Q. Which of the following statements about insulin is true?

A. Insulin acts as a transport protein, carrying glucose across the cell membrane.

B. Insulin facilitates the movement of intracellular glucose transporters to the cell membrane.

C. Insulin stimulates the breakdown of stored glycogen into glucose.

D. Insulin stimulates the kidneys to reabsorb glucose into the bloodstream.

Answer

Answer: B

Critical Thinking Questions

Q. Compare and contrast the anatomy related to the exocrine and endocrine functions of the pancreas.

Answer

A. The pancreas produces a variety of secretions that leave the pancreas to function in other organs of the body. The destination of the secretion defines whether it is part of the exocrine or endocrine function of the pancreas. The acinar cells of the pancreas produce and secrete digestive enzymes. The acinar cells are arranged in cul-de-sacs connected to the pancreatic duct, through which the digestive enzymes are delivered to the duodenum of the small intestine. They are considered exocrine in nature because they will pass through the epithelial lining of the small intestine in the opposite direction of nutrient absorption to mix with and chemically digest intestinal contents. Pancreatic islets are scattered throughout the remainder of the pancreas and contain four types of endocrine cells whose secretions enter the bloodstream to travel to their target organs. Alpha cells secrete glucagon which causes an increase in blood sugar by stimulating the liver to release glucose into the bloodstream. Beta cells secrete insulin which signals cells to take in glucose, thereby reducing blood sugar levels. Delta cells

secrete somatostatin, which inhibits the release of both glucagon and insulin. PP cells secrete the pancreatic polypeptide hormone that regulates appetite as well as both exocrine and endocrine functions of the pancreas.

Glossary

alpha cell
pancreatic islet cell type that produces the hormone glucagon

beta cell
pancreatic islet cell type that produces the hormone insulin

delta cell
minor cell type in the pancreas that secretes the hormone somatostatin

diabetes mellitus
condition caused by destruction or dysfunction of the beta cells of the pancreas or cellular resistance to insulin that results in abnormally high blood glucose levels

glucagon
pancreatic hormone that stimulates the catabolism of glycogen to glucose, thereby increasing blood glucose levels

hyperglycemia
abnormally high blood glucose levels

insulin
pancreatic hormone that enhances the cellular uptake and utilization of glucose, thereby decreasing blood glucose levels

pancreas
organ with both exocrine and endocrine functions located posterior to the stomach that is important for digestion and the regulation of blood glucose

pancreatic islets
specialized clusters of pancreatic cells that have endocrine functions; also called islets of Langerhans

PP cell
minor cell type in the pancreas that secretes the hormone pancreatic polypeptide

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Answers

INTERACTIVE LINK

Answer: Insulin is overproduced after cells become resistant to insulin's effect.

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15.10: Organs with Secondary Endocrine Functions

By the end of this section, you will be able to:

- Identify the organs with a secondary endocrine function, the hormone(s) they produce, and the effects of the hormone(s)

In your study of anatomy and physiology, you have already encountered a few of the many organs of the body that have secondary endocrine functions. Here, you will learn about the hormone-producing activities of the heart, gastrointestinal tract, kidneys, skeleton, adipose tissue, skin, and thymus.

Heart

When the body experiences an increase in blood volume or pressure, the cells of the heart's atrial wall stretch. In response, specialized cells in the wall of the atria produce and secrete the hormone **atrial natriuretic peptide (ANP)**. ANP signals the kidneys to reduce sodium reabsorption, thereby decreasing the amount of water reabsorbed from the urine filtrate and reducing blood volume. Other actions of ANP include the inhibition of renin secretion, thus inhibition of the renin-angiotensin-aldosterone system (RAAS) and vasodilation. Therefore, ANP aids in decreasing blood pressure, blood volume, and blood sodium levels.

Gastrointestinal Tract

The endocrine cells of the GI tract are located in the mucosa of the stomach and small intestine. Some of these hormones are secreted in response to eating a meal and aid in digestion. An example of a hormone secreted by the stomach cells is gastrin, a peptide hormone secreted in response to stomach distention that stimulates the release of hydrochloric acid. Secretin is a peptide hormone secreted by the small intestine as acidic chyme (partially digested food and fluid) moves from the stomach. It stimulates the release of bicarbonate from the pancreas, which buffers the acidic chyme, and inhibits the further secretion of hydrochloric acid by the stomach. Cholecystokinin (CCK) is another peptide hormone released from the small intestine. It promotes the secretion of pancreatic enzymes and the release of bile from the gallbladder, both of which facilitate digestion. Other hormones produced by the intestinal cells aid in glucose metabolism, such as by stimulating the pancreatic beta cells to secrete insulin, reducing glucagon secretion from the alpha cells, or enhancing cellular sensitivity to insulin.

Kidneys

The kidneys participate in several complex endocrine pathways and produce certain hormones. A decline in blood flow to the kidneys stimulates them to release the enzyme renin, triggering the renin-angiotensin-aldosterone (RAAS) system, and stimulating the reabsorption of sodium and water. The reabsorption increases blood flow and blood pressure. The kidneys also play a role in regulating blood calcium levels through the production of calcitriol from vitamin D_3, which is released in response to the secretion of parathyroid hormone (PTH). In addition, the kidneys produce the hormone **erythropoietin (EPO)** in response to low oxygen levels. EPO stimulates the production of red blood cells (erythrocytes) in the bone marrow, thereby increasing oxygen delivery to tissues. You may have heard of EPO as a performance-enhancing drug (in a synthetic form).

Skeleton

Although bone has long been recognized as a target for hormones, only recently have researchers recognized that the skeleton itself produces at least two hormones. Fibroblast growth factor 23 (FGF23) is produced by bone cells in response to increased blood levels of vitamin D_3 or phosphate. It triggers the kidneys to inhibit the formation of calcitriol from vitamin D_3 and to increase phosphorus excretion. Osteocalcin, produced by osteoblasts, stimulates the pancreatic beta cells to increase insulin production. It also acts on peripheral tissues to increase their sensitivity to insulin and their utilization of glucose.

Adipose Tissue

Adipose tissue produces and secretes several hormones involved in lipid metabolism and storage. One important example is

leptin, a protein manufactured by adipocytes that circulates in amounts directly proportional to levels of body fat. Leptin is released in response to food consumption and acts by binding to brain neurons involved in energy intake and expenditure. Binding of leptin produces a feeling of satiety after a meal, thereby reducing appetite. It also appears that the binding of leptin to brain receptors triggers the sympathetic nervous system to regulate bone metabolism, increasing deposition of cortical bone. Adiponectin—another hormone synthesized by adipocytes—appears to reduce cellular insulin resistance and to protect blood vessels from inflammation and atherosclerosis. Its levels are lower in people who are obese, and rise following weight loss.

Skin

The skin functions as an endocrine organ in the production of the inactive form of vitamin D_3, cholecalciferol. When cholesterol present in the epidermis is exposed to ultraviolet radiation, it is converted to cholecalciferol, which then enters the blood. In the liver, cholecalciferol is converted to an intermediate that travels to the kidneys and is further converted to calcitriol, the active form of vitamin D_3. Vitamin D is important in a variety of physiological processes, including intestinal calcium absorption and immune system function. In some studies, low levels of vitamin D have been associated with increased risks of cancer, severe asthma, and multiple sclerosis. Vitamin D deficiency in children causes rickets, and in adults, osteomalacia—both of which are characterized by bone deterioration.

Thymus

The thymus is an organ of the immune system that is larger and more active during infancy and early childhood, and begins to atrophy as we age. Its endocrine function is the production of a group of hormones called thymosins that contribute to the development and differentiation of T lymphocytes, which are immune cells. Although the role of thymosins is not yet well understood, it is clear that they contribute to the immune response. Thymosins have been found in tissues other than the thymus and have a wide variety of functions, so the thymosins cannot be strictly categorized as thymic hormones.

Liver

The liver is responsible for secreting at least four important hormones or hormone precursors: insulin-like growth factor (somatomedin), angiotensinogen, thrombopoetin, and hepcidin. Insulin-like growth factor-1 is the immediate stimulus for growth in the body, especially of the bones. Angiotensinogen is the precursor to angiotensin, mentioned earlier, which increases blood pressure. Thrombopoetin stimulates the production of the blood's platelets. Hepcidins block the release of iron from cells in the body, helping to regulate iron homeostasis in our body fluids.

The major hormones of these organs with secondary endocrine functions are summarized in Table 15.10.1.

Table 15.10.1: Organs with Secondary Endocrine Functions and Their Major Hormones

Organ	Major hormones	Effects
Heart	Atrial natriuretic peptide (ANP)	Reduces blood volume, blood pressure, and Na^+ concentration
Gastrointestinal tract	Gastrin, secretin, and cholecystokinin	Aid digestion of food and buffering of stomach acids
Gastrointestinal tract	Glucose-dependent insulinotropic peptide (GIP) and glucagon-like peptide 1 (GLP-1)	Stimulate beta cells of the pancreas to release insulin
Kidneys	Renin	Stimulates release of aldosterone
Kidneys	Calcitriol	Aids in the absorption of Ca^{2+}
Kidneys	Erythropoietin	Triggers the formation of red blood cells in the bone marrow
Skeleton	FGF23	Inhibits production of calcitriol and increases phosphate excretion
Skeleton	Osteocalcin	Increases insulin production
Adipose tissue	Leptin	Promotes satiety signals in the brain

Organ	Major hormones	Effects
Adipose tissue	Adiponectin	Reduces insulin resistance
Skin	Cholecalciferol	Modified to form vitamin D
Thymus (and other organs)	Thymosins	Among other things, aids in the development of T lymphocytes of the immune system
Liver	Insulin-like growth factor-1	Stimulates bodily growth
Liver	Angiotensinogen	Raises blood pressure
Liver	Thrombopoetin	Causes increase in platelets
Liver	Hepcidin	Blocks release of iron into body fluids

Concept Review

Some organs have a secondary endocrine function. For example, the walls of the atria of the heart produce the hormone atrial natriuretic peptide (ANP), the gastrointestinal tract produces the hormones gastrin, secretin, and cholecystokinin, which aid in digestion, and the kidneys produce erythropoietin (EPO), which stimulates the formation of red blood cells. Even bone, adipose tissue, and the skin have secondary endocrine functions.

Review Questions

Q. The walls of the atria produce which hormone?

A. cholecystokinin
B. atrial natriuretic peptide
C. renin
D. calcitriol

Answer

Answer: B

Q. The end result of the RAAS is to _____.

A. reduce blood volume
B. increase blood glucose
C. reduce blood pressure
D. increase blood pressure

Answer

Answer: D

Q. Athletes may take synthetic EPO to boost their _____.

A. blood calcium levels
B. secretion of growth hormone
C. blood oxygen levels
D. muscle mass

Answer

Answer: C

Q. Hormones produced by the thymus play a role in the _____.

A. development of T cells
B. preparation of the body for childbirth
C. regulation of appetite
D. release of hydrochloric acid in the stomach

Answer

Answer: A

Critical Thinking Questions

Q. Summarize the role of GI tract hormones following a meal.

Answer

Answer: The presence of food in the GI tract stimulates the release of hormones that aid in digestion. For example, gastrin is secreted in response to stomach distention and causes the release of hydrochloric acid in the stomach. Secretin is secreted when acidic chyme enters the small intestine, and stimulates the release of pancreatic bicarbonate. In the presence of fat and protein in the duodenum, cholecystokinin (CCK) stimulates the release of pancreatic digestive enzymes and bile from the gallbladder. Other GI tract hormones aid in glucose metabolism and other functions.

Glossary

atrial natriuretic peptide (ANP)
hormone secreted by the atria of the heart to signal for a reduction in blood volume, blood pressure, and blood sodium levels

erythropoietin (EPO)
hormone secreted by the kidney to stimulate production of red blood cells in order to increase blood oxygen levels

leptin
protein hormone secreted by adipose tissues in response to food consumption that promotes satiety

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15.11: Development and Aging of the Endocrine System

By the end of this section, you will be able to:

- Describe the embryonic origins of the endocrine system
- Discuss the effects of aging on the endocrine system

The endocrine system arises from all three embryonic germ layers. The endocrine glands that produce the steroid hormones, such as the gonads and adrenal cortex, arise from the mesoderm. In contrast, endocrine glands that arise from the endoderm and ectoderm produce the amino acid-based hormones. The pituitary gland arises from two distinct areas of the ectoderm: the anterior pituitary gland arises from the oral ectoderm, whereas the posterior pituitary gland arises from the neural ectoderm at the base of the hypothalamus. The pineal gland also arises from the ectoderm. The two structures of the adrenal glands arise from two different germ layers: the adrenal cortex from the mesoderm and the adrenal medulla from ectoderm neural cells. The endoderm gives rise to the thyroid and parathyroid glands, as well as the pancreas and the thymus.

As the body ages, changes occur that affect the endocrine system, sometimes altering the production, secretion, and catabolism of hormones. For example, the structure of the anterior pituitary gland changes as vascularization decreases and the connective tissue content increases with increasing age. This restructuring affects the gland's hormone production. For example, the amount of human growth hormone that is produced declines with age, resulting in the reduced muscle mass commonly observed in the elderly.

The adrenal glands also undergo changes as the body ages; as fibrous tissue increases, the production of cortisol and aldosterone decreases. Interestingly, the production and secretion of epinephrine and norepinephrine remain normal throughout the aging process.

A well-known example of the aging process affecting an endocrine gland is menopause and the decline of ovarian function. With increasing age, the ovaries decrease in both size and weight and become progressively less sensitive to gonadotropins. This gradually causes a decrease in estrogen and progesterone levels, leading to menopause and the inability to reproduce. Low levels of estrogens and progesterone are also associated with some disease states, such as osteoporosis, atherosclerosis, and hyperlipidemia, or abnormal blood lipid levels.

Testosterone levels also decline with age, a condition called andropause (or viropause); however, this decline is much less dramatic than the decline of estrogens in women, and much more gradual, rarely affecting sperm production until very old age. Although this means that males maintain their ability to father children for decades longer than females, the quantity, quality, and motility of their sperm is often reduced.

As the body ages, the thyroid gland produces less of the thyroid hormones, causing a gradual decrease in the basal metabolic rate. The lower metabolic rate reduces the production of body heat and increases levels of body fat. Parathyroid hormones, on the other hand, increase with age. This may be because of reduced dietary calcium levels, causing a compensatory increase in parathyroid hormone. However, increased parathyroid hormone levels combined with decreased levels of calcitonin (and estrogens in women) can lead to osteoporosis as PTH stimulates demineralization of bones to increase blood calcium levels. Notice that osteoporosis is common in both elderly males and females.

Increasing age also affects glucose metabolism, as blood glucose levels spike more rapidly and take longer to return to normal in the elderly. In addition, increasing glucose intolerance may occur because of a gradual decline in cellular insulin sensitivity. Almost 27 percent of Americans aged 65 and older have diabetes.

Concept Review

The endocrine system originates from all three germ layers of the embryo, including the endoderm, ectoderm, and mesoderm. In general, different hormone classes arise from distinct germ layers. Aging affects the endocrine glands, potentially affecting hormone production and secretion, and can cause disease. The production of hormones, such as human growth hormone, cortisol, aldosterone, sex hormones, and the thyroid hormones, decreases with age.

Review Questions

Q. The anterior pituitary gland develops from which embryonic germ layer?

A. oral ectoderm
B. neural ectoderm
C. mesoderm
D. endoderm

Answer

Answer: A

Q. In the elderly, decreased thyroid function causes _____.

A. increased tolerance for cold
B. decreased basal metabolic rate
C. decreased body fat
D. osteoporosis

Answer

Answer: B

Critical Thinking Questions

Q. Compare and contrast the thymus gland in infancy and adulthood.

Answer

Answer: The thymus gland is important for the development and maturation of T cells. During infancy and early childhood, the thymus gland is large and very active, as the immune system is still developing. During adulthood, the thymus gland atrophies because the immune system is already developed.

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16: CARDIOVASCULAR SYSTEM - BLOOD

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16.1: Introduction to Blood

16.2: An Overview of Blood

16.3: Erythrocytes

16.4: Leukocytes and Platelets

16.5: Production of the Formed Elements

16.6: Blood Typing

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16.1: Introduction to Blood

Chapter Learning Objectives:

After studying this chapter, you will be able to:

- Identify the primary functions of blood, its fluid and cellular components, and its physical characteristics
- Identify the most important proteins and other solutes present in blood plasma
- Describe the formation of the formed element components of blood
- Discuss the structure and function of red blood cells and hemoglobin
- Classify and characterize white blood cells
- Describe the structure and function of platelets
- Explain the significance of ABO and Rh blood groups in blood transfusions
- Discuss a variety of blood disorders

Single-celled organisms do not need blood. They obtain nutrients directly from and excrete wastes directly into their environment. The human organism cannot do that. Our large, complex bodies need blood to deliver nutrients to and remove wastes from our trillions of cells. The heart pumps blood throughout the body in a network of blood vessels. Together, these three components—blood, heart, and vessels—make up the cardiovascular system. This chapter focuses on the fluid connective tissue that serves as a medium of transport: blood.

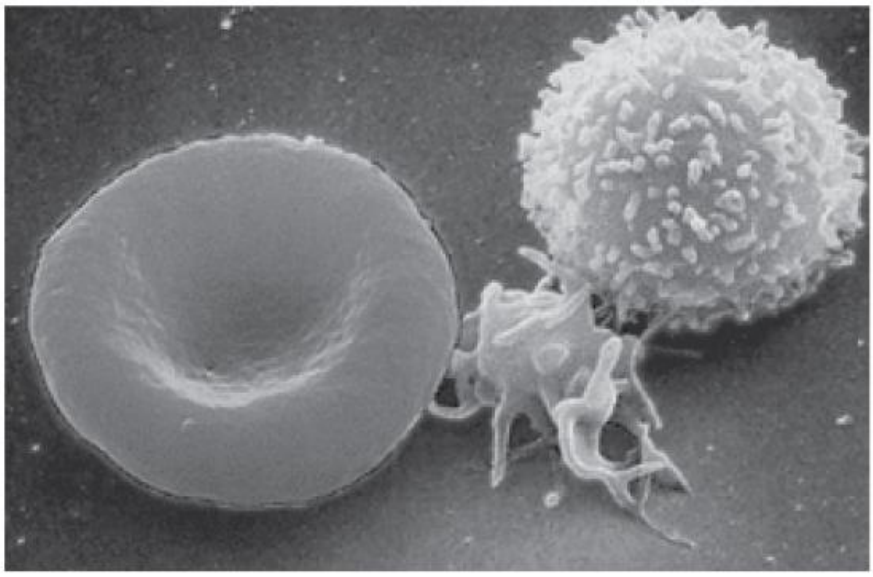

Figure 16.1.1: Red Blood Cell, Platelet, and White Blood Cell. A single drop of blood contains millions of red blood cells, white blood cells, and platelets. A red blood cell (left), platelet (middle), and a white blood cell (right) are shown here, isolated from a scanning electron micrograph. (Image credit: "Blood Cells" by OpenStax is licensed under CC BY 3.0)

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16.2: An Overview of Blood

By the end of this section, you will be able to:

- Identify the primary functions of blood in transportation, defense, and maintenance of homeostasis
- Name the fluid component of blood and the three major types of formed elements, and identify their relative proportions in a blood sample
- Discuss the unique physical characteristics of blood
- Identify the composition of blood plasma, including its most important solutes and plasma proteins

Recall that **blood** is a connective tissue. Like all connective tissues, it is made up of cellular elements and an extracellular matrix. The cellular elements—referred to as the **formed elements**—include **erythrocytes** (aka red blood cells or RBCs), **leukocytes** (aka white blood cells or WBCs), and cell fragments called **platelets** (aka thrombocytes). The extracellular matrix, called **plasma**, makes blood unique among connective tissues because it is fluid. This fluid, which is mostly water, perpetually suspends the formed elements and enables them to circulate throughout the body within the cardiovascular system.

Functions of Blood

The primary function of blood is to deliver oxygen and nutrients to and remove wastes from body cells, but that is only the beginning of the story. The specific functions of blood also include defense, distribution of heat, and maintenance of homeostasis.

Transportation

Nutrients from the foods you eat are absorbed in the digestive tract. Most of these travel in the bloodstream directly to the liver, where they are processed and released back into the bloodstream for delivery to body cells. Oxygen from the air you breathe diffuses into the blood, moving it from the lungs to the heart, which in turn pumps it out to the rest of the body. Moreover, endocrine glands scattered throughout the body release their products, called hormones, into the bloodstream so they may be delivered to distant target cells to regulate body processes like growth, repair, and the reproductive cycles. Blood also picks up cellular wastes and byproducts and transports them to various organs for removal. For instance, blood moves carbon dioxide to the lungs for exhalation from the body, and various waste products are transported to the kidneys and liver for excretion from the body in the form of urine or bile.

Defense

Many types of leukocytes traveling in blood protect the body from external threats, such as disease-causing bacteria that have entered the bloodstream in a wound. Other leukocytes seek out and destroy internal threats, such as cells with mutated DNA that could multiply to become cancerous or body cells infected with viruses.

When damage to the vessels results in bleeding, blood platelets and certain proteins dissolved in blood interact to clot blood in the area and block the ruptured areas of the blood vessels. This protects the body from further blood loss.

Maintenance of Homeostasis

Body temperature is regulated via a classic negative-feedback loop. If you were exercising on a warm day, your rising core body temperature would trigger several homeostatic mechanisms to cool it back down, including increased transport of blood from your core to your body periphery, which is typically cooler. As blood passes through the vessels of the skin, heat would be dissipated to the environment, and the blood returning to your body core would be cooler. In contrast, on a cold day, blood is diverted away from the skin to maintain a warmer body core. In extreme cases, this may result in frostbite.

Blood also helps to maintain the chemical balance of the body. Proteins and other compounds in blood act as buffers, which thereby help to regulate the pH of body tissues. Blood also helps to regulate the water content of body cells.

Composition of Blood

You have probably had blood drawn from a superficial vein in your arm, which was then sent to a lab for analysis. Some of the most common blood tests—for instance, those measuring lipid or glucose levels in plasma—determine which substances are present within blood and in what quantities. Other blood tests check for the composition of the blood itself, including the quantities and types of formed elements.

One such test, called a **hematocrit**, measures the percentage of erythrocytes in a blood sample. Erythrocytes are the specific cells that carry oxygen in the blood. The hematocrit test is performed by spinning the blood sample in a specialized centrifuge, a process that causes the heavier elements suspended within the blood sample to separate from the lightweight, liquid plasma (Figure 16.2.1). Because the heaviest elements in blood are the iron-containing erythrocytes, these settle at the very bottom of the hematocrit tube. Located above the erythrocytes is a pale, thin layer composed of the remaining formed elements of blood: leukocytes and platelets. The layer containing the leukocytes and platelets is referred to as the **buffy coat** because of its color; it normally constitutes less than 1 percent of a blood sample. Above the buffy coat is the blood plasma, normally a pale, straw-colored fluid matrix, that constitutes the remainder of the sample.

The hematocrit test allows one to measure the volume of erythrocytes after centrifugation and the result is also commonly referred to as **packed cell volume (PCV)**. In normal blood, about 45 percent of a sample is erythrocytes. The hematocrit of any one sample can vary significantly, ranging from 37–52 percent based on sex and other factors. Normal hematocrit values for females range from 37 to 47 percent, with a mean value of 41 percent; for males, hematocrit values range from 42 to 52 percent, with a mean of 47 percent. The percentage of other formed elements, the leukocytes and platelets, is extremely small so it is not normally considered with the hematocrit. Thus the mean plasma percentage is the percent of blood that is not erythrocytes: for females, it is approximately 59 percent (or 100 minus 41 percent), and for males, it is approximately 53 percent (or 100 minus 47 percent).

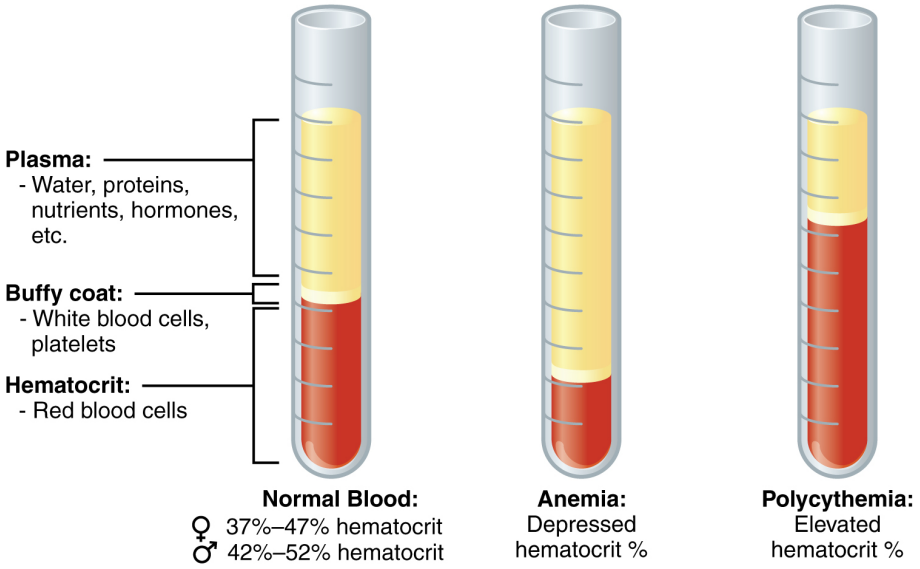

Figure 16.2.1: Composition of Blood. The cellular elements of blood include a vast number of erythrocytes and comparatively fewer leukocytes and platelets. Plasma is the fluid in which the formed elements are suspended. A sample of blood spun in a centrifuge reveals a straw-colored plasma as the lightest component. It floats at the top of the tube separated from the heaviest elements, the erythrocytes, by a buffy coat of leukocytes and platelets. Hematocrit is the percentage of the total sample that is comprised of erythrocytes. A normal hematocit (shown just above 40 percent) is compared with a depressed hematocrit (shown just above 20 percent), which indicates anemia, and an elevated hematocrit (shown above 60 percent), which indicates polycythemia. (Image credit: "Composition of Blood" by OpenStax is licensed under CC BY 3.0)

Characteristics of Blood

When you think about blood, the first characteristic that probably comes to mind is its color. Blood that has just taken up oxygen in the lungs is bright red, and blood that has released oxygen in the tissues is a more dusky red. This is because hemoglobin is a pigment that changes color depending upon the degree of oxygen saturation.

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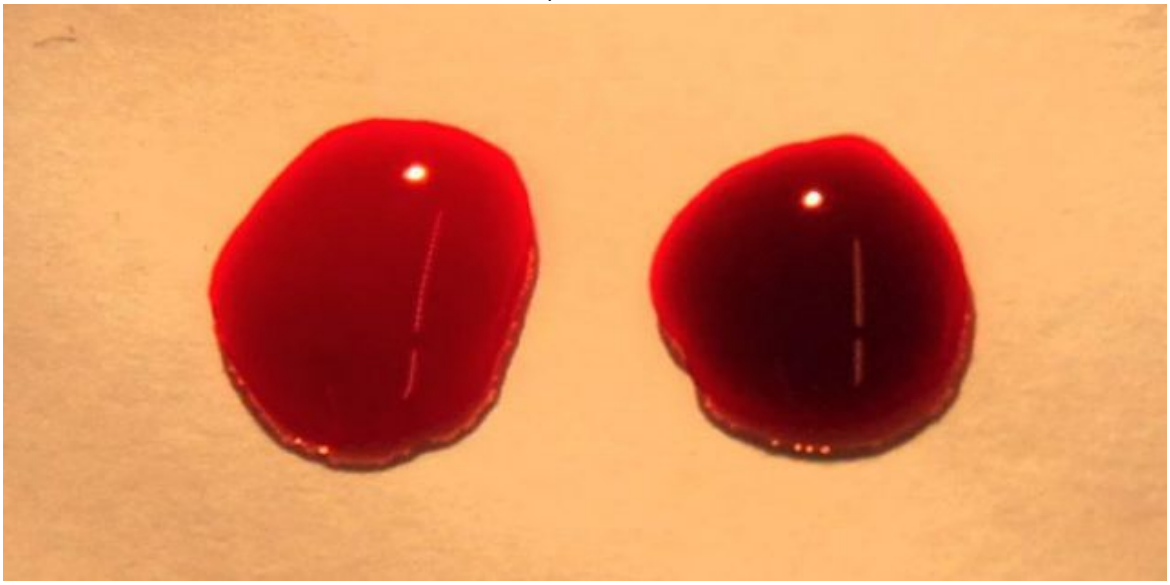

Figure 16.2.2: Shades of Red Blood. The bright red hue of oxygenated blood is shown on the left while the deeper red hue of deoxygenated blood is shown on the right. ("Drops of Blood Medium" by unknown author is licensed under CC BY 3.0)

Blood is viscous and somewhat sticky to the touch. It has a viscosity approximately five times greater than water. Viscosity is a measure of a fluid's thickness or resistance to flow, and is influenced by the presence of the plasma proteins and formed elements within the blood. The viscosity of blood has a dramatic impact on blood pressure and flow. Consider the difference in flow between water and honey. The more viscous honey would demonstrate a greater resistance to flow than the less viscous water. The same principle applies to blood.

The normal temperature of blood is slightly higher than normal body temperature—about 38 °C (or 100.4 °F), compared to 37 °C (or 98.6 °F) for an internal body temperature reading, although daily variations of 0.5 °C are normal. Although the surface of blood vessels is relatively smooth, as blood flows through them, it experiences some friction and resistance, especially as vessels age and lose their elasticity, thereby producing heat. This accounts for its slightly higher temperature.

The pH of blood averages about 7.4; it is maintained within an extremely tight range from 7.35 to 7.45 in a healthy person. At an average pH of 7.4, blood is somewhat more basic (alkaline) on a chemical scale than pure water, which has a pH of 7.0. Blood contains numerous buffers that contribute to the regulation of pH.

Blood constitutes approximately 8 percent of adult body weight. Adult males typically average about 5 to 6 liters of blood. Females average 4 to 5 liters.

Blood Plasma

Like other fluids in the body, plasma is composed primarily of water; in fact, it is about 92 percent water. Dissolved or suspended within this water is a mixture of substances, most of which are proteins. There are literally hundreds of substances dissolved or suspended in the plasma, although many of them are found only in very small quantities.

Plasma Proteins

About 7 percent of the volume of plasma—nearly all that is not water—is made of proteins. These include several plasma proteins (proteins that are unique to the plasma), plus a much smaller number of regulatory proteins, including enzymes and some hormones. The major components of plasma are summarized in Table 16.2.1.

The three major groups of plasma proteins are as follows:

- **Albumin** is the most abundant of the plasma proteins. Manufactured by the liver, albumin molecules serve as binding proteins—transport vehicles for lipids such as fatty acids and steroid hormones like testosterone. Recall that lipids are hydrophobic; however, their binding to albumin enables them to be transported in the watery plasma. Albumin is also the

most significant contributor to the osmotic pressure of blood; that is, its presence holds water inside the blood vessels and draws water from the tissues, across blood vessel walls, and into the bloodstream. This in turn helps to maintain both blood volume and blood pressure. Albumin normally accounts for approximately 54 percent of the total plasma protein content; clinically, this measures as 3.5–5.0 g/dL blood.

- The second most common plasma proteins are the **globulins**. A heterogeneous group, there are three main subgroups known as alpha, beta, and gamma globulins. The alpha and beta globulins transport iron, lipids, and the fat-soluble vitamins A, D, E, and K to the cells; like albumin, they also contribute to osmotic pressure. The gamma globulins are proteins involved in immunity and are better known as an **antibodies** or **immunoglobulins**. Although other plasma proteins are produced by the liver, immunoglobulins are produced by specialized leukocytes known as plasma cells. Globulins make up approximately 38 percent of the total plasma protein volume; clinically, this measures as 1.0–1.5 g/dL blood.
- The least abundant plasma protein is **fibrinogen**. Like albumin and the alpha and beta globulins, fibrinogen is produced by the liver. It is essential for blood clotting, a process described later in this chapter. Fibrinogen accounts for about 7 percent of the total plasma protein volume; clinically, this measures as 0.2–0.45 g/dL blood.

Other Plasma Solutes

In addition to proteins, plasma contains a wide variety of other substances. These include various electrolytes, such as sodium, potassium, and calcium ions; dissolved gases, such as oxygen, carbon dioxide, and nitrogen; various organic nutrients, such as vitamins, lipids, glucose, and amino acids; and metabolic wastes. All of these non-protein solutes combined contribute approximately 1 percent to the total volume of plasma.

Table 16.2.1*: Summary of Major Blood Components*

Component and % of blood	Subcomponent and % of component	Type and % (where appropriate)	Site of production	Major function(s)
Plasma 46-63 percent	Water 92 percent	Fluid	Absorbed by intestinal tract or produced by metabolism	Transport medium
	Plasma proteins 7 percent	Albumin 54-60 percent	Liver	Maintain osmotic concentration, transport lipid molecules
		Globulins 35-38 percent	Alpha globulins Liver	Transport, maintain osmotic concentration
			Beta globulins Liver	Transport, maintain osmotic concentration
			Gamma globulins (immunoglobulins) Plasma Cells	Antibody immune responses
		Fibrinogen 4-7 percent	Liver	Blood clotting in hemostasis
	Regulatory proteins <1 percent	Hormones and enzymes	Various sources	Regulate various body functions
	Other solutes 1 percent	Nutrients, gases, and wastes	Absorbed by intestinal tract, exchanged in respiratory system, or produced by cells	Numerous and varied
Formed Elements 37-54 percent	Erythrocytes 99 percent	Erythrocytes	Red bone marrow	Transports gases, primarily oxygen and some carbon dioxide
	Leukocytes <1 percent	Granular leukocytes: neutrophils, eosinophils, basophils	Red bone marrow	Nonspecific immune responses

Component and % of blood	Subcomponent and % of component	Type and % (where appropriate)	Site of production	Major function(s)
		Agranular leukocytes: lymphocytes, monocytes	Lymphocytes: red bone marrow and lymphatic tissues	Specific immune responses
			Monocytes: red bone marrow	Nonspecific immune responses
	Platelets <1 percent	Platelets	Megakaryocytes: red bone marrow	Hemostasis

CAREER CONNECTIONS

Phlebotomy and Medical Lab Technology

Phlebotomists are professionals trained to draw blood (phleb- = “a blood vessel”; -tomy = “to cut”). When more than a few drops of blood are required, phlebotomists perform a venipuncture, typically of a surface vein in the arm. They perform a capillary stick on a finger, an earlobe, or the heel of an infant when only a small quantity of blood is required. An arterial stick is collected from an artery and used to analyze blood gases. After collection, the blood may be analyzed by medical laboratories or perhaps used for transfusions, donations, or research. While many allied health professionals practice phlebotomy, the American Society of Phlebotomy Technicians issues certificates to individuals passing a national examination, and some large labs and hospitals hire individuals expressly for their skill in phlebotomy.

Medical or clinical laboratories employ a variety of individuals in technical positions:

Medical technologists (MT), also known as clinical laboratory technologists (CLT), typically hold a bachelor’s degree and certification from an accredited training program. They perform a wide variety of tests on various body fluids, including blood. The information they provide is essential to the primary care providers in determining a diagnosis and in monitoring the course of a disease and response to treatment.
Medical laboratory technicians (MLT) typically have an associate’s degree but may perform duties similar to those of an MT.
Medical laboratory assistants (MLA) spend the majority of their time processing samples and carrying out routine assignments within the lab. Clinical training is required, but a degree may not be essential to obtaining a position.

Formed Elements

The formed elements include erythrocytes (RBCs), leukocytes (WBCs), and platelets (thrombocytes). They are formed mostly in the red bone marrow (not within the blood itself) and one of them, platelets, are circulating fragments of a much larger cell so referring to them as cells (even thrombocytes) is a misnomer. It is for this reason that this group is not labeled as cellular components of blood.

Erythrocytes function to carry oxygen through the bloodstream so it may be delivered throughout the body. There are several different types of leukocytes that have unique functions contributing to the body's housekeeping and sickness fighting efforts. Platelets function in helping to maintain blood volume (a process called hemostasis) by forming blood clots to prevent blood loss.

The formed elements are summarized in Table 16.2.2. Each category of formed element is covered in more detail in a dedicated section of this chapter.

Table 16.2.2 Summary of Formed Elements in Blood

Formed Element	Major subtypes	Numbers present per microliter (µL); mean (range)	Appearance in a standard blood smear	Summary of functions	Comments
Erythrocytes (red blood cells)		5.2 million (4.4-6.0 million)	Flattened biconcave disc; no nucleus; pale red color	Transport oxygen and some carbon dioxide between tissues and lungs	Lifespan of approximately 120 days
Leukocytes (white blood cells)	Granulocytes (neutrophils, eosinophils, and basophils)	7000 (5000-10,000)	Obvious dark-staining nucleus	All function in body defenses	Exit capillaries and move into tissues; lifespan of usually a few hours or days
	Neutrophils	4150 (1800-7300)	Nuclear lobes increase with age; pale lilac granules	Phagocytic; particularly effective against bacteria; Release cytotoxic chemicals from granules	Most common leukocyte; lifespan of minutes to days
	Eosinophils	165 (0-700)	Nucleus generally two-lobed; bright red-orange granules	Phagocytic cells; effective with antigen-antibody complexes; release antihistamines; increase in allergies and parasitic infections.	Lifespan of minutes to days.
	Basophils	44 (0-150)	Nucleus generally two-lobed but difficult to see due to presence of heavy, dense, dark purple granules	Promotes inflammation	Least common leukocyte; lifespan unknown
	Agranulocytes (lymphocytes and monocytes)	2640 (1700-4950)	Lack abundant granules in cytoplasm; have a simple-shaped nucleus that may be indented	Body defenses	Group consists of two major cell types from different lineages

Formed Element	Major subtypes	Numbers present per microliter (µL); mean (range)	Appearance in a standard blood smear	Summary of functions	Comments
	Lymphocytes	2185 (1500-4000)	Spherical cells with a single often large nucleus occupying much of the cell's volume; stains purple; seen in large (natural killer cells) and small (B and T cells) variants	Primarily specific (adaptive) immunity: T cells directly attack other cells; B cells release antibodies; natural killer cells are like T cells but nonspecific	Initial cells originate in bone marrow, but secondary production occurs in lymphatic tissue; several distinct subtypes; memory cells form after exposure to a pathogen and rapidly increase responses to subsequent exposure; lifespan of many years
	Monocytes	455 (200-950)	Largest leukocyte with an indented or horseshoe-shaped nucleus	Very effective phagocytic cells engulfing pathogens or worn-out cells; also serve as antigen-presenting cells (APCs) for other components of the immune system	Produced in red bone marrow; referred to as macrophages after leaving circulation
Platelets		350,000 (150,000-500,000)	Cellular fragments surrounded by a plasma membrane and containing granules; purple stain	Hemostasis plus release growth factors for repair and healing of tissue	Formed from megakaryocytes that remain in the red bone marrow and shed platelets into circulation

In addition to measuring the hematocrit, a very common blood test is a **complete blood count (or CBC) with differential**. A small amount of blood is taken and smeared onto a gridded microscope slide and then stained to allow for proper examination under a microscope. A trained technician will then view the blood under the microscope and count the numbers of each different type of formed element visible. The report includes numbers for each specific type of leukocyte for the differential portion, along with some other information about the sizes, shapes, and characteristics of each element. The grid on the slide allows counts to be converted into concentrations of each formed element in the blood that can be compared with expected values such as those listed in Table 16.2.2. Elevated or low levels of each type of formed element can indicate specific health concerns.

Concept Review

Blood is a fluid connective tissue critical to the transportation of nutrients, gases, and wastes throughout the body; to defend the body against infection and other threats; and to the homeostatic regulation of pH, temperature, and other internal conditions. Blood is composed of formed elements—erythrocytes, leukocytes, and cell fragments called platelets—and a fluid extracellular matrix called plasma. More than 90 percent of plasma is water. The remainder is mostly plasma proteins—mainly albumin, globulins, and fibrinogen—and other dissolved solutes such as glucose, lipids, electrolytes, and dissolved gases. Because of the formed elements, the plasma proteins, and other solutes, blood is sticky and more viscous than water. It is also slightly alkaline, and its temperature is slightly higher than normal body temperature.

Review Questions

Q. Which of the following statements about blood is true?

A. Blood is about 92 percent water.

B. Blood is slightly more acidic than water.

C. Blood is slightly more viscous than water.

D. Blood is slightly more salty than seawater.

Answer

Answer: C

Q. Which of the following statements about albumin is true?

A. It draws water out of the blood vessels and into the body's tissues.

B. It is the most abundant plasma protein.

C. It is produced by specialized leukocytes called plasma cells.

D. All of the above are true.

Answer

Answer: B

Q. Which of the following plasma proteins is *not* produced by the liver?

A. fibrinogen

B. alpha globulin

C. beta globulin

D. immunoglobulin

Answer

Answer: D

Critical Thinking Questions

Q. A patient's hematocrit is 42 percent. Approximately what percentage of the patient's blood is plasma?

Answer

A. The patient's blood is approximately 58 percent plasma (since the buffy coat is less than 1 percent).

Q. Why would it be incorrect to refer to all formed elements as cells?

Answer

A. The formed elements include erythrocytes and leukocytes, which are cells (although mature erythrocytes do not have a nucleus); however, the formed elements also include platelets, which are not true cells but cell fragments.

Q. True or false: The buffy coat is the portion of a blood sample that is made up of its proteins.

Answer

A. False. The buffy coat is the portion of blood that is made up of its leukocytes and platelets.

Glossary

albumin
most abundant plasma protein, accounting for most of the osmotic pressure of plasma

antibodies
(also, immunoglobulins or gamma globulins) antigen-specific proteins produced by specialized B lymphocytes that protect the body by binding to foreign objects such as bacteria and viruses

blood
liquid connective tissue composed of formed elements—erythrocytes, leukocytes, and platelets—and a fluid extracellular matrix called plasma; component of the cardiovascular system

buffy coat
thin, pale layer of leukocytes and platelets that separates the erythrocytes from the plasma in a sample of centrifuged blood

complete blood count (CBC) with differential
a test in which a prepared microscope slide of a patient's blood is used to count the numbers of each type of formed element visible in a given volume of blood; observations about the size, shape, and characteristics of each type of formed element are also made

erythrocytes
one of the formed elements of blood that transports oxygen (also, red blood cells or RBCs)

fibrinogen
plasma protein produced in the liver and involved in blood clotting

formed elements
cell-derived components of blood; that is, erythrocytes, leukocytes, and platelets

globulins
heterogeneous group of plasma proteins that includes transport proteins, clotting factors, immune proteins, and others

hematocrit
(also, packed cell volume) volume percentage of erythrocytes in a sample of centrifuged blood

immunoglobulins
(also, antibodies or gamma globulins) antigen-specific proteins produced by specialized B lymphocytes that protect the body by binding to foreign objects such as bacteria and viruses

leukocytes
one of the formed elements of blood that provides defense against disease agents and foreign materials (also, white blood cells or WBCs)

packed cell volume (PCV)
(also, hematocrit) volume percentage of erythrocytes present in a sample of centrifuged blood

plasma
in blood, the liquid extracellular matrix composed mostly of water that circulates the formed elements and dissolved materials throughout the cardiovascular system

platelets
one of the formed elements of blood that consists of cell fragments broken off from megakaryocytes (also,

thrombocytes)

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16.3: Erythrocytes

By the end of this section, you will be able to:

- Describe the structure and function of erythrocytes
- Discuss the various steps in the lifecycle of an erythrocyte

The **erythrocyte**, commonly known as a red blood cell (or RBC), is by far the most common formed element. A single drop of blood contains millions of erythrocytes and just thousands of leukocytes. Specifically, males have about 5.4 million erythrocytes per microliter (μL) of blood, and females have approximately 4.8 million per μL. In fact, erythrocytes are estimated to make up about 25 percent of the total cells in the body. Erythrocytes are also smaller than leukocytes and most other body cells, with a mean diameter of only about 7–8 micrometers (μm) (Figure 16.3.1, see Table 16.2.2 Summary of Formed Elements in Blood).

Due to their chemical properties, oxygen and carbon dioxide molecules largely cannot be transported dissolved in plasma. Thus, the primary functions of erythrocytes are to pick up inhaled oxygen from the lungs and transport it to the body's tissues, and to pick up some (about 24 percent) carbon dioxide waste at the tissues and transport it to the lungs for exhalation. Although leukocytes typically leave the blood vessels to perform their defensive functions, erythrocytes remain in the blood vessels and movement of erythrocytes from the blood vessels is abnormal.

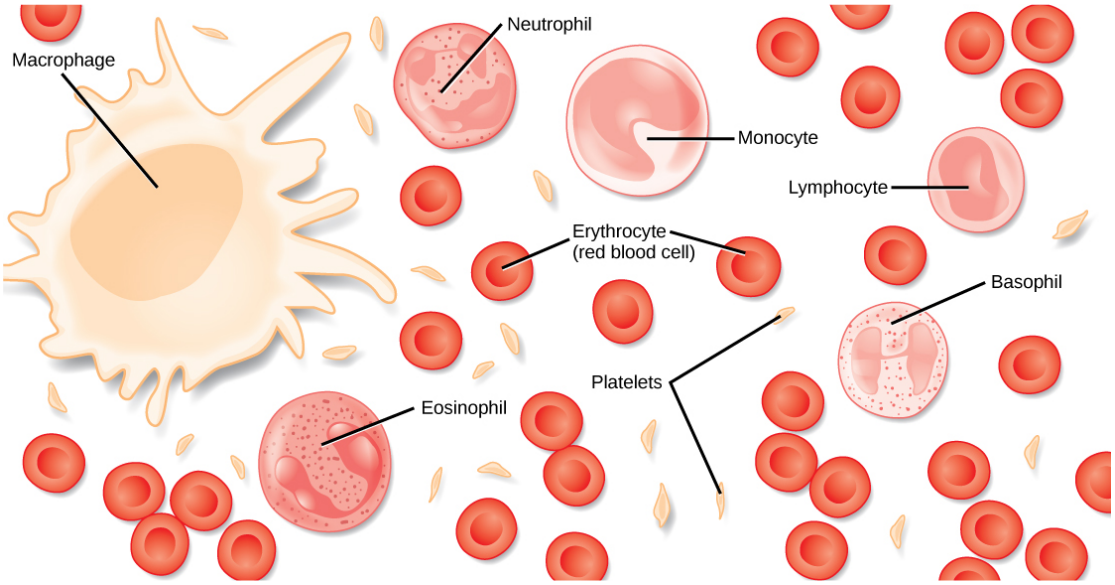

Figure 16.3.1: Formed Elements Visible in a Sample of Blood. Erythrocytes are most numerous, significantly smaller than leukocytes, red in color, and biconcave in shape. Leukocytes are the largest and the only formed elements with a discernable nucleus in circulating blood; the shape and position of the nucleus along with the visibility and color of any granules and overall size of the cell distinguish specific leukocytes. Platelets, fragments of a larger cell, are also numerous, but are also the smallest and appear like grains of rice among the other formed elements. (Image credit: "Figure_40_02_01" by OpenStax is licensed under CC BY 4.0)

Shape and Structure of Erythrocytes

As an erythrocyte matures in the red bone marrow, it extrudes (pushes out) its nucleus and most of its other organelles. During the first day or two that it is in the circulation, an immature erythrocyte, known as a **reticulocyte**, will still typically contain remnants of organelles focused on making functional hemoglobin protein complexes. After the first day or two in circulation however, the erythrocyte matures and finishes the differentiation process by shedding its remaining membrane-bound organelles, meaning it will no longer make any new proteins, essentially leaving it as a sac of roughly 300 million hemoglobin molecules. Being absent of organelles also means erythrocytes lack mitochondria, causing them to rely on anaerobic respiration. This means that they do not utilize any of the oxygen they are transporting, maximizing its delivery to the tissues. Reticulocytes do retain some structural proteins, such as the cytoskeletal element spectrin, that help them maintain their unique shape and also enable them to change

their shape to squeeze through capillaries. Reticulocytes should comprise approximately 1–2 percent of the erythrocyte count and provide a rough estimate of the rate of erythrocyte production, with abnormally low or high rates indicating problems with underproduction or overproduction of erythrocytes, respectively.

Erythrocytes are uniquely shaped as biconcave discs; that is, they are plump at their periphery and very thin in the center (Figure 16.3.2). Since they lack most organelles, there is more interior space for the presence of the hemoglobin molecules that transport gases. The biconcave shape also provides a greater surface area across which gas exchange can occur, relative to its volume; a sphere of a similar diameter would have a lower surface area-to-volume ratio. In the capillaries, the oxygen carried by the erythrocytes can diffuse into the plasma and then through the capillary walls to reach the cells, whereas some of the carbon dioxide produced by the cells as a waste product diffuses into the capillaries to be picked up by the erythrocytes. Capillary beds are extremely narrow, slowing the passage of the erythrocytes and providing an extended opportunity for gas exchange to occur. However, the space within capillaries can be so minute that, despite their own small size, erythrocytes may have to fold in on themselves if they are to make their way through. Fortunately, their structural proteins like spectrin are flexible, allowing them to bend over themselves to a surprising degree, then spring back again when they enter a wider vessel. In wider vessels, erythrocytes may stack up much like a roll of coins, forming a rouleaux, from the French word for “roll.”

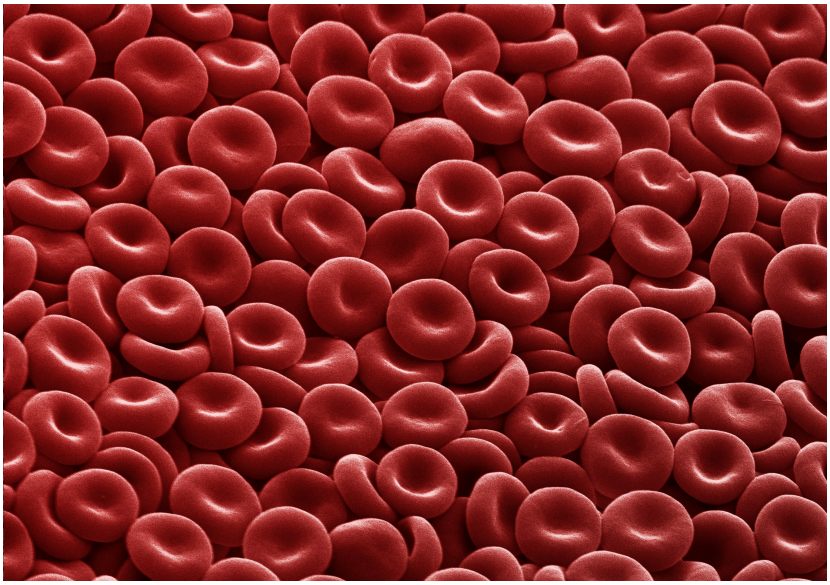

Figure 16.3.2: Shape of Erythrocytes. Erythrocytes are biconcave discs with very shallow centers. This shape optimizes the ratio of surface area to volume, facilitating gas exchange. It also enables them to fold up as they move through narrow blood vessels. (Image credit: "Jn7ws94a-2" by Annie Cavanagh is licensed under CC BY-SA 4.0)

Hemoglobin

Hemoglobin is a large molecule made up of proteins and iron. It consists of four folded chains of a protein called **globin**, designated alpha chain 1 and 2, and beta chain 1 and 2. Each of these globin molecules is bound to a red pigment molecule called **heme**, which contains an ion of iron (Fe^{2+}) (Figure 16.3.3). Each iron ion in the heme can bind to one oxygen molecule; therefore, each hemoglobin molecule can transport four oxygen molecules. An individual erythrocyte may contain about 300 million hemoglobin molecules, and therefore can bind to and transport up to 1.2 billion oxygen molecules.

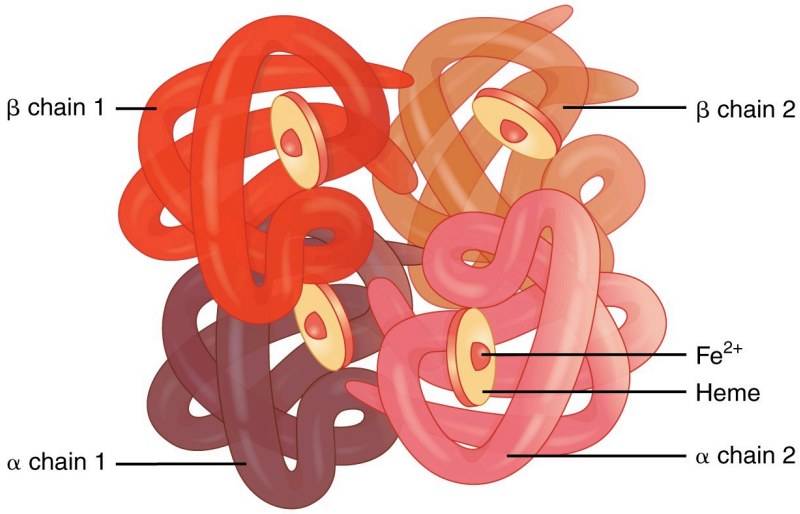

Figure 16.3.3: Hemoglobin. A molecule of hemoglobin contains four globin protein subunits, each of which is bound to one molecule of the iron-containing red pigmented heme. A single erythrocyte can contain 300 million hemoglobin molecules, and thus more than 1 billion oxygen molecules. (Image credit: "Hemoglobin" by OpenStax is licensed under CC BY 3.0)

In the lungs, hemoglobin picks up oxygen, which binds to the iron ions, forming **oxyhemoglobin**. The bright red, oxygenated hemoglobin travels to the body tissues, where it releases some of the oxygen molecules, becoming darker red **deoxyhemoglobin**, sometimes referred to as reduced hemoglobin. Oxygen release depends on the need for oxygen in the surrounding tissues, so hemoglobin rarely if ever leaves all of its oxygen behind. In the capillaries, carbon dioxide enters the bloodstream. About 76 percent dissolves in the plasma, some of it remaining as dissolved CO_2, and the remainder forming bicarbonate ions. About 23–24 percent of it binds to the amino acids in hemoglobin, forming a molecule known as **carbaminohemoglobin**. From the capillaries, the hemoglobin carries carbon dioxide back to the lungs, where it releases it for exchange of oxygen.

In determining oxygenation of tissues, the value of greatest interest in healthcare is the percent saturation; that is, the percentage of hemoglobin sites occupied by oxygen in a patient's blood. Percent saturation is normally monitored using a device known as a pulse oximeter, which is applied to a thin part of the body, typically the tip of the patient's finger. The device works by sending two different wavelengths of light (one red, the other infrared) through the finger and measuring the light with a photodetector as it exits. Hemoglobin absorbs light differentially depending upon its saturation with oxygen. The machine calibrates the amount of light received by the photodetector against the amount absorbed by the partially oxygenated hemoglobin and presents the data as percent saturation. Normal pulse oximeter readings range from 95–100 percent. Lower percentages reflect **hypoxemia**, or low blood oxygen. The term hypoxia is more generic and simply refers to low oxygen levels. Oxygen levels are also directly monitored from free oxygen in the plasma typically following an arterial stick. When this method is applied, the amount of oxygen present is expressed in terms of partial pressure of oxygen or simply pO_2 and is typically recorded in units of millimeters of mercury, mm Hg.

The kidneys filter about 180 liters (~380 pints) of blood in an average adult each day, or about 20 percent of the total resting blood volume, and thus serve as ideal sites for receptors that monitor oxygen saturation for the body. In response to hypoxemia, less oxygen will exit the vessels supplying the kidney, resulting in hypoxia (low oxygen concentration) in the tissue fluid of the kidney where oxygen concentration is actually monitored. Interstitial fibroblasts in the connective tissue within the kidney secrete a hormone called erythropoietin (EPO) to stimulate erythrocyte production and restore oxygen levels. In a classic negative-feedback loop, as oxygen saturation rises, EPO secretion falls, and vice versa, thereby maintaining homeostasis. Populations dwelling at high elevations, with inherently lower levels of oxygen in the atmosphere, naturally maintain a hematocrit higher than people living at sea level. Consequently, people traveling to high elevations may experience symptoms of hypoxemia, such as fatigue, headache, and shortness of breath, for a few days after their arrival. In response to the hypoxemia, the kidneys secrete EPO to step up the production of erythrocytes until homeostasis is achieved once again. To avoid the symptoms of hypoxemia, or altitude sickness, mountain climbers typically rest for several days to a week or more at a series of camps situated at increasing elevations to allow EPO levels and, consequently, erythrocyte counts to rise. When climbing the tallest peaks, such as Mt. Everest and K2 in the Himalayas, many mountain climbers rely upon bottled oxygen as they near the summit.

Lifecycle of Erythrocytes

Production of erythrocytes in red bone marrow occurs at the staggering rate of more than 2 million cells per second. For this production to occur, a number of raw materials must be present in adequate amounts. These include the same nutrients that are essential to the production and maintenance of any cell, such as glucose, lipids, and amino acids. However, erythrocyte production also requires several trace elements including not only iron, but copper, zinc, and the B vitamins folic acid (folate) and vitamin B_{12}.

Erythrocytes live up to 120 days in circulation, after which the worn-out cells are removed by a type of myeloid phagocytic cell called a **macrophage**, located primarily within the red bone marrow, liver, and spleen. Organelles within the macrophages break down the hemoglobin and plasma membrane components of the erythrocytes. The amino acid, heme, and iron components of the degraded erythrocytes' hemoglobin are recycled when possible. Iron is transported in the blood plasma bound to transferrin and may be transferred to the protein ferritin for storage in the liver. The non-iron portion of heme is degraded into the waste products **biliverdin**, a green pigment, and then **bilirubin**, a yellow pigment. Bilirubin binds to albumin and travels in the blood to the liver, which uses it in the synthesis of bile, a compound released into the intestines to help emulsify dietary fats. In the large intestine, bacteria breaks the bilirubin apart from the bile and converts it to urobilinogen and then into stercobilin. It is then eliminated from the body in the feces. Broad-spectrum antibiotics typically eliminate these bacteria, which may alter the color of feces. The kidneys also remove any circulating bilirubin and other related metabolic byproducts such as urobilins and secrete them into the urine.

The breakdown pigments formed from the destruction of hemoglobin can be seen in a variety of situations. At the site of an injury, biliverdin from damaged erythrocytes produces some of the dramatic colors associated with bruising. With a failing liver (or an underdeveloped one soon after birth), bilirubin cannot be removed effectively from circulation and causes the body to assume a yellowish tinge associated with jaundice. Stercobilins within the feces produce the typical brown color associated with this waste while the yellow of urine is associated with the urobilins.

The erythrocyte lifecycle is summarized in Figure 16.3.4.

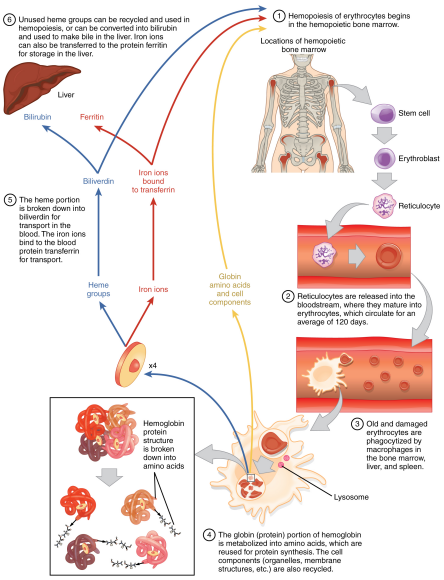

Figure 16.3.4: Erythrocyte Lifecycle. Hemopoiesis of erythrocytes begins in the hemopoietic bone marrow, where erythroblasts are derived from stem cells and then differentiate into reticulocytes. Reticulocytes are released into the bloodstream, where they mature into erythrocytes, which circulate for an average of 120 days. Old and damaged erythrocytes are phagocytized by macrophages in the bone marrow, liver, and spleen. The globin (protein) portion of hemoglobin is metabolized into amino acids, which are reused for protein synthesis. Lysosomes in the macrophage recycle the other cell components (organelles, membrane structures, etc). The heme portion is broken down into biliverdin for transport in the blood. The iron ions bind to the protein transferrin for transport. Unused heme groups can be recycled and used in hemopoiesis, or can be converted into bilirubin and used to make bile in the liver. Iron ions can also be transferred to the protein ferritin for storage in the liver. (Image credit: "Erythrocyte Life Cycle" by OpenStax is licensed under CC BY 3.0)

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Erythrocytes

Changes in the levels of erythrocytes can have significant effects on the body's ability to effectively deliver oxygen to the tissues. Ineffective hematopoiesis results in insufficient numbers of erythrocytes and results in one of several forms of anemia. An overproduction of erythrocytes produces a condition called polycythemia. The primary drawback with polycythemia is not a failure to directly deliver enough oxygen to the tissues, but rather the increased viscosity of the blood, which makes it more difficult for the heart to circulate the blood.

The size, shape, and number of erythrocytes, and the number of hemoglobin molecules can have a major impact on a person's health. When the blood is not carrying sufficient oxygen to the tissues, the general condition is called **anemia**. There are more than 400 types of anemia and more than 3.5 million Americans suffer from this condition related typically to an insufficient number of erythrocytes or a deficiency of hemoglobin. Anemia can be broken down into three major groups: those caused by blood loss, those caused by faulty or decreased erythrocyte production, and those caused by excessive destruction of erythrocytes. Clinicians often use two groupings in diagnosis: The kinetic approach focuses on evaluating the production, destruction, and removal of erythrocytes, whereas the morphological approach examines the erythrocytes themselves, paying particular emphasis to their size and shape. A common test is the mean corpuscle volume (MCV), which measures size. Normal-sized cells are referred to as normocytic, smaller-than-normal cells are referred to as microcytic, and larger-than-normal cells are referred to as macrocytic. Reticulocyte counts are also important and may reveal inadequate production of erythrocytes. The effects of the various anemias are widespread, because reduced numbers of erythrocytes or hemoglobin will result in lower levels of oxygen being delivered to body tissues. Since oxygen is required for tissue functioning, anemia produces fatigue, lethargy, and an increased risk for infection. An oxygen deficit in the brain impairs the ability to think clearly, and may prompt headaches and irritability. Lack of oxygen leaves the patient short of breath, even as the heart and lungs work harder in response to the deficit.

Blood loss anemias are fairly straightforward. In addition to bleeding from wounds or other lesions, these forms of anemia may be due to ulcers, hemorrhoids, inflammation of the stomach (gastritis), and some cancers of the gastrointestinal tract. The excessive use of aspirin or other non-steroidal anti-inflammatory drugs (NSAIDs) such as ibuprofen can trigger ulceration and gastritis. Excessive menstruation and loss of blood during childbirth are also potential causes.

Anemias caused by faulty or decreased erythrocyte production include sickle cell anemia, iron deficiency anemia, vitamin deficiency anemia, and diseases of the red bone marrow and stem cells.

- A characteristic change in the shape of erythrocytes is seen in **sickle cell disease** (also referred to as sickle cell anemia). A genetic disorder, it is caused by production of an abnormal type of hemoglobin, called hemoglobin S, which delivers less oxygen to tissues and causes erythrocytes to assume a sickle (or crescent) shape, especially at low oxygen concentrations (Figure 16.3.5). These abnormally shaped cells can then become lodged in narrow capillaries because they are unable to fold in on themselves to squeeze through, blocking blood flow to tissues and causing a variety of serious problems from painful joints to delayed growth and even blindness and cerebrovascular accidents (strokes). Sickle cell anemia is a genetic condition particularly found in individuals of African descent.

Figure 16.3.5: Sickle Cells. Sickle cell anemia is caused by a mutation in one of the hemoglobin genes. Erythrocytes produce an abnormal type of hemoglobin, which causes the cell to take on a sickle or crescent shape. (Image credit: "Sickle Cells" by OpenStax is licensed under CC BY 3.0)

- Iron deficiency anemia is the most common type and results when the amount of available iron is insufficient to allow production of sufficient heme. This condition can occur in individuals with a deficiency of iron in the diet and is especially common in teens and children as well as in vegans and vegetarians. Additionally, iron deficiency anemia may be caused by either an inability to absorb and transport iron or slow, chronic bleeding.
- Vitamin-deficient anemias generally involve insufficient vitamin B_{12} and folate.
  - Megaloblastic anemia involves a deficiency of vitamin B_{12} and/or folate, and often involves diets deficient in these essential nutrients. Lack of meat or a viable alternate source, and overcooking or eating insufficient amounts of vegetables may lead to a lack of folate.
  - Pernicious anemia is caused by poor absorption of vitamin B_{12} and is often seen in patients with Crohn's disease (a severe intestinal disorder often treated by surgery), surgical removal of the intestines or stomach (common in some weight loss surgeries), intestinal parasites, and AIDS.
  - Pregnancies, some medications, excessive alcohol consumption, and some diseases such as celiac disease are also associated with vitamin deficiencies. It is essential to provide sufficient folic acid during the early stages of pregnancy to reduce the risk of neurological defects, including spina bifida, a failure of the neural tube to close.
- Assorted disease processes can also interfere with the production and formation of erythrocytes and hemoglobin. If myeloid stem cells are defective or replaced by cancer cells, there will be insufficient quantities of erythrocytes produced.
  - Aplastic anemia is the condition in which there are deficient numbers of the stem cells used to produce erythrocytes. Aplastic anemia is often inherited, or it may be triggered by radiation, medication, chemotherapy, or infection.
  - **Thalassemia** is an inherited condition typically occurring in individuals from the Middle East, the Mediterranean, African, and Southeast Asia, in which maturation of the erythrocytes does not proceed normally. The most severe form is called Cooley's anemia.
  - Lead exposure from industrial sources or even dust from paint chips of iron-containing paints or pottery that has not been properly glazed may also lead to destruction of the red marrow.
- Various disease processes also can lead to anemias. These include chronic kidney diseases often associated with a decreased production of EPO, hypothyroidism, some forms of cancer, lupus, and rheumatoid arthritis.

In contrast to anemia, an elevated erythrocyte count is called **polycythemia** and is detected in a patient's elevated hematocrit. It can occur transiently in a person who is dehydrated; when water intake is inadequate or water losses are excessive, the plasma volume falls. As a result, the hematocrit rises. For reasons mentioned earlier, a mild form of polycythemia is chronic but normal in people living at high altitudes. Some elite athletes train at high elevations specifically to induce this phenomenon. Finally, a type of red bone marrow disease called polycythemia vera (from the Greek vera =

"true") causes an excessive production of immature erythrocytes. Polycythemia vera can dangerously elevate the viscosity of blood, raising blood pressure and making it more difficult for the heart to pump blood throughout the body. It is a relatively rare disease that occurs more often in men than women, and is more likely to be present in patients over 60 years of age.

Concept Review

The most abundant formed element in blood, erythrocytes are red, biconcave discs packed with an oxygen-carrying compound called hemoglobin. The hemoglobin molecule contains four globin proteins bound to a pigment molecule called heme, which contains an ion of iron. In the bloodstream, iron picks up oxygen in the lungs and drops it off in the tissues; the amino acids in hemoglobin then transport some carbon dioxide from the tissues back to the lungs. Erythrocytes live only 120 days on average, and thus must be continually replaced. Worn-out erythrocytes are phagocytized by macrophages and their hemoglobin is broken down. The breakdown products are recycled or removed as wastes; globin is broken down into amino acids for synthesis of new proteins; iron is stored in the liver or spleen or used by the bone marrow for production of new erythrocytes; and the remnants of heme are converted into bilirubin, or other waste products that are taken up by the liver and excreted in the bile or removed by the kidneys. Anemia is a deficiency of erythrocytes or hemoglobin, whereas polycythemia is an excess of erythrocytes.

Review Questions

Q. Which of the following statements about mature, circulating erythrocytes is true?

A. They have no nucleus.

B. They are packed with mitochondria.

C. They survive for an average of 4 days.

D. All of the above

Answer

Answer: A

Q. A molecule of hemoglobin _____.

A. is shaped like a biconcave disk packed almost entirely with iron

B. contains four glycoprotein units studded with oxygen

C. consists of four globin proteins, each bound to a molecule of heme

D. can carry up to 120 molecules of oxygen

Answer

Answer: C

Q. The production of healthy erythrocytes depends upon the availability of _____.

A. copper

B. zinc

C. vitamin B_{12}

D. copper, zinc, and vitamin B_{12}

Answer

Answer: D

Q. Aging and damaged erythrocytes are removed from the circulation by _____.

A. myeloblasts

B. monocytes

C. macrophages

D. mast cells

Answer

Answer: C

Q. A patient has been suffering for 2 months with a chronic, watery diarrhea. A blood test is likely to reveal _____.

A. a hematocrit below 30 percent

B. hypoxemia

C. anemia

D. polycythemia

Answer

Answer: D

Critical Thinking Questions

Q. A young woman has been experiencing unusually heavy menstrual bleeding for several years. She follows a strict vegan diet (no animal foods). She is at risk for what disorder, and why?

Answer

A. She is at risk for anemia, because her unusually heavy menstrual bleeding results in excessive loss of erythrocytes each month. At the same time, her vegan diet means that she does not have dietary sources of heme iron. The non-heme iron she consumes in plant foods is not as well absorbed as heme iron.

Q. A patient has thalassemia, a genetic disorder characterized by abnormal synthesis of globin proteins and excessive destruction of erythrocytes. This patient is jaundiced and is found to have an excessive level of bilirubin in his blood. Explain the connection.

Answer

A. Bilirubin is a breakdown product of the non-iron component of heme, which is cleaved from globin when erythrocytes are degraded. Excessive erythrocyte destruction would deposit excessive bilirubin in the blood. Bilirubin is a yellowish pigment, and high blood levels can manifest as yellowed skin.

Glossary

anemia
deficiency of red blood cells or hemoglobin

bilirubin
yellowish bile pigment produced when iron is removed from heme and is further broken down into waste products

biliverdin
green bile pigment produced when the non-iron portion of heme is degraded into a waste product; converted to bilirubin in the liver

carbaminohemoglobin
compound of carbon dioxide and hemoglobin, and one of the ways in which carbon dioxide is carried in the blood

deoxyhemoglobin
molecule of hemoglobin without an oxygen molecule bound to it

erythrocyte
(also, red blood cell) mature myeloid blood cell that is composed mostly of hemoglobin and functions primarily in the transportation of oxygen and carbon dioxide

globin
heme-containing globular protein that is a constituent of hemoglobin

heme
red, iron-containing pigment to which oxygen binds in hemoglobin

hemoglobin
oxygen-carrying compound in erythrocytes

hypoxemia
below-normal level of oxygen saturation of blood (typically <95 percent)

macrophage
phagocytic cell of the myeloid lineage; a matured monocyte

oxyhemoglobin
molecule of hemoglobin to which oxygen is bound

polycythemia
elevated level of hemoglobin, whether adaptive or pathological

reticulocyte
immature erythrocyte that may still contain fragments of organelles

sickle cell disease
(also, sickle cell anemia) inherited blood disorder in which hemoglobin molecules are malformed, leading to the breakdown of erythrocytes that take on a characteristic sickle shape

thalassemia
inherited blood disorder in which maturation of erythrocytes does not proceed normally, leading to abnormal formation of hemoglobin and the destruction of erythrocytes

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16.4: Leukocytes and Platelets

By the end of this section, you will be able to:

- Describe the general characteristics of leukocytes
- Classify leukocytes according to their lineage, their main structural features, and their primary functions
- Discuss the most common malignancies involving leukocytes
- Identify the lineage, basic structure, and function of platelets

Leukocytes

The **leukocyte**, commonly known as a white blood cell (or WBC), is a major component of the body's defenses against disease. Leukocytes protect the body against invading microorganisms and body cells with mutated DNA, and they clean up debris. You may find it helpful to reference the image Formed Elements in a Blood Sample (Figure 16.3.1) and the Table 16.2.2 Summary of Formed Elements in Blood along with this content.

Characteristics of Leukocytes

Although leukocytes and erythrocytes both originate from hematopoietic stem cells in the red bone marrow, they are very different from each other in many significant ways. For instance, leukocytes are far less numerous than erythrocytes; typically there are only 5000 to 10,000 per μL. They are also larger than erythrocytes and are the only formed elements that are complete cells in circulation, possessing a nucleus and organelles. Although there is just one type of erythrocyte, there are many types of leukocytes. Most of these types have a much shorter lifespan than that of erythrocytes, some as short as a few hours, or even a few minutes in the case of acute infection.

One of the most distinctive characteristics of leukocytes is their movement. Whereas erythrocytes spend their days circulating within the blood vessels, leukocytes routinely leave the bloodstream to perform their defensive functions in the body's tissues. For leukocytes, the vascular network is often simply a highway they travel and soon exit to reach their true destination. When they arrive, they may differentiate further and be given distinct names, such as macrophage or microglia, depending on their function. As shown in Figure 16.4.1, they leave the capillaries—the smallest blood vessels—or other small vessels through a process known as **emigration** (from the Latin for "removal") or **diapedesis** (dia- = "through"; -pedan = "to leap") in which they squeeze through adjacent cells in a blood vessel wall.

Once they have exited the capillaries, some leukocytes will take up residence in lymphatic tissue, bone marrow, the spleen, the thymus, or other organs. Others will move about through the tissue spaces very much like amoebae, continuously extending their plasma membranes, sometimes wandering freely, and sometimes moving toward the direction in which they are drawn by chemical signals. This attracting of leukocytes occurs because of **positive chemotaxis** (literally "movement in response to chemicals"), a phenomenon in which injured or infected cells and nearby leukocytes emit the equivalent of a chemical "911" call, attracting more leukocytes to the site. In clinical medicine, the differential counts of the types and percentages of leukocytes present are often key indicators in making a diagnosis and selecting a treatment.

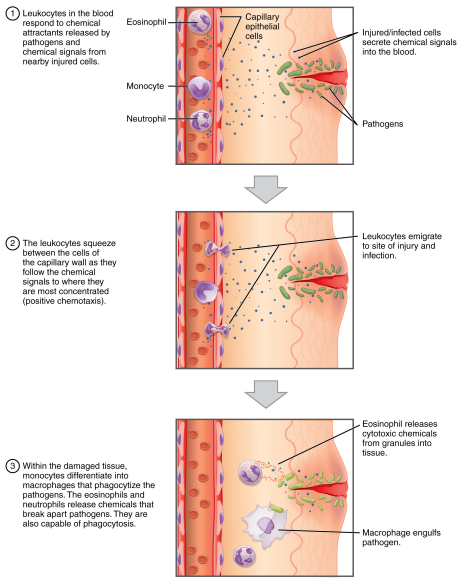

Figure 16.4.1: Emigration or Diapedesis. Injured and/or infected cells secrete chemical signals into the blood. Leukocytes in the blood respond to chemical attractants released by pathogens and chemical signals from nearby injured cells. The leukocytes emigrate or squeeze between the cells of the capillary wall as they follow the chemical signals to where they are most concentrated (positive chemotaxis). Within the damaged tissue, monocytes differentiate into macrophages that phagocytize the pathogens. The eosinophils and neutrophils release cytotoxic chemicals that break apart pathogens from granules into the tissue. They are also capable of phagocytosis. exit the blood vessel and then move through the connective tissue of the dermis toward the site of a wound. Some leukocytes, such as the eosinophil and neutrophil, are characterized as granular leukocytes. They release chemicals from their granules that destroy pathogens; they are also capable of phagocytosis. The monocyte differentiates into a macrophage that then phagocytizes the pathogens. (Image credit: "Emigration" by OpenStax is licensed under CC BY 3.0)

Classification of Leukocytes

When scientists first began to observe stained blood slides, it quickly became evident that leukocytes could be divided into two groups, according to whether their cytoplasm contained highly visible granules:

- **Granular leukocytes** (granulocytes) contain abundant granules within the cytoplasm. They include neutrophils, eosinophils, and basophils (you can view their lineage from myeloid stem cells in Figure 16.5.1 Hemopoietic System of Bone Marrow).
- While granules are not totally lacking in **agranular leukocytes** (agranulocytes), they are far fewer and less obvious. Agranular leukocytes include monocytes, which also arise from myeloid stem cells and mature into macrophages that are phagocytic, and lymphocytes, which arise from the lymphoid stem cell line.

Granular Leukocytes

We will consider the granular leukocytes (granulocytes) in order from most common to least common. All of these are produced in the red bone marrow and have a short lifespan of hours to days. They typically have a lobed nucleus and are classified according to which type of stain best highlights their granules (Figure 16.4.2).

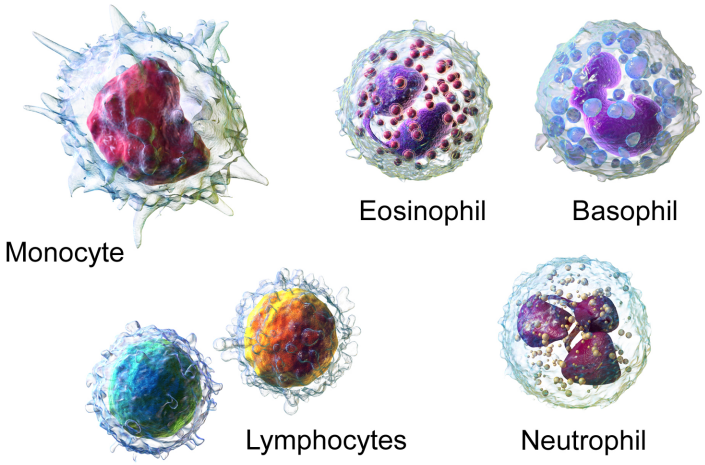

Figure 16.4.2: Leukocytes. A neutrophil has small granules that stain light lilac and a nucleus with two to five lobes. An eosinophil's granules are slightly larger and stain reddish-orange, and its nucleus has two to three lobes. A basophil has large granules that stain dark blue to purple and a two-lobed nucleus. Lymphocytes are the smallest leukocytes, have no visible granules, and are almost entirely filled by a large nucleus. A monocyte is larger than other leukocytes, has no visible granules, and has an indented nucleus. (Image credit: "Blausen 0909 WhiteBloodCells" by Bruce Blaus is licensed under CC BY 3.0)

The most common of all the leukocytes, **neutrophils** will normally comprise 50–70 percent of the total leukocyte count. They are 10–12 μm in diameter, significantly larger than erythrocytes. They are called neutrophils because their granules show up most clearly with stains that are chemically neutral (neither acidic nor basic). The granules are numerous but quite fine and normally appear light lilac. The nucleus has a distinct lobed appearance and may have two to five lobes, the number increasing with the age of the cell. Older neutrophils have increasing numbers of lobes and are often referred to as **polymorphonuclear** (a nucleus with many forms), or simply "polys." Younger and immature neutrophils begin to develop lobes and are known as "bands."

Neutrophils are rapid responders to the site of infection and are efficient phagocytes with a preference for bacteria. Their granules include vesicles filled with substances that help them neutralize infectious agents: **lysozyme**, an enzyme capable of lysing, or breaking down, bacterial cell walls; oxidants such as hydrogen peroxide; and **defensins**, proteins that bind to and puncture bacterial and fungal plasma membranes so that the cell contents leak out. Abnormally high counts of neutrophils indicate infection and/or inflammation, particularly triggered by bacteria, but are also found in burn patients and others experiencing unusual stress. A burn injury increases the proliferation of neutrophils in order to fight off infection that can result from the destruction of the barrier of the skin. Low counts may be caused by drug toxicity and other disorders, and may increase an individual's susceptibility to infection.

Eosinophils typically represent 2–4 percent of the total leukocyte count. They are also 10–12 μm in diameter. The granules of eosinophils stain best with an acidic stain known as eosin. The nucleus of the eosinophil will typically have two to three lobes and, if stained properly, the granules will have a distinct red to orange color.

The granules of eosinophils include vesicles filled with antihistamine molecules, which counteract the activities of histamines, inflammatory chemicals produced by basophils and mast cells. Some eosinophil granules contain molecules toxic to parasitic worms, which can enter the body through the integument, or when an individual consumes raw or undercooked fish or meat. Eosinophils are also capable of phagocytosis and are particularly effective at disposing of antigen-antibody complexes. Antibodies are immunoglobulin proteins produced by certain lymphocytes that carry out several functional aspects of the specific immune response. Antibodies are designed to match-up to a specific molecule, typically a protein called an antigen, on the surface of an invading pathogen such as a parasitic worm, bacterium, or viral particle. Antibodies can also match up with a ubiquitous molecule (such as one on the surface of a pollen granule) and cause an allergic reaction. In this case the antigen is called an allergen, but antibody-antigen complexes are formed during the body's response to the presence of the allergen as if it were the antigen of an invading pathogen. Because it is the function of the eosinophils to use phagocytosis to clear out the debris associated with antibody-antigen complexes, high counts of eosinophils are typical of patients experiencing allergies and some autoimmune diseases, but eosinophils can also be elevated in the case of parasitic worm infestations. Low counts may be due to drug toxicity and stress.

Basophils are the least common leukocytes, typically comprising less than one percent of the total leukocyte count. They are slightly smaller than neutrophils and eosinophils at 8–10 μm in diameter. The granules of basophils stain best with basic (alkaline) stains. Basophils contain large granules that pick up a dark blue stain and are so common they may make it difficult to see the two-lobed nucleus.

In general, basophils intensify the inflammatory response. They share this trait with mast cells of connective tissue proper. In the past, mast cells were considered to be basophils that left the circulation. However, this appears not to be the case, as the two cell types develop from different lineages.

The granules of basophils release histamines, which contribute to inflammation, and heparin, which opposes blood clotting. High counts of basophils are associated with allergies, parasitic infections, and hypothyroidism. Low counts are associated with pregnancy, stress, and hyperthyroidism.

Agranular Leukocytes

Agranular leukocytes (agranulocytes) contain smaller, less-visible granules in their cytoplasm than do granular leukocytes. The nucleus is simple in shape, sometimes with an indentation but without distinct lobes. There are two major types of agranulocytes: lymphocytes and monocytes (Figure 16.4.2).

Lymphocytes are the only formed element of blood that arises from lymphoid stem cells. Although they form initially in the red bone marrow, much of their subsequent development and reproduction occurs in the lymphatic tissues. Lymphocytes are the second most common type of leukocyte, accounting for about 20–30 percent of all leukocytes, and are an essential part of the immune response. The size range of lymphocytes is quite extensive, with some authorities recognizing two size classes and others three. Typically, the large cells are 10–14 μm and have a smaller nucleus-to-cytoplasm ratio and more granules. The smaller cells are typically 6–9 μm with a larger volume of nucleus to cytoplasm, creating a “halo” effect. A few cells may fall outside these ranges, at 14–17 μm. This finding has led to the three size range classification.

The three major groups of lymphocytes include natural killer cells, B cells, and T cells. **Natural killer (NK) cells** are capable of recognizing cells that do not express “self” proteins on their plasma membrane or that contain foreign or abnormal markers. These “non-self” cells include abnormal body cells such as cancer cells, cells infected with a virus, and other cells with atypical surface proteins. Thus, they provide generalized, nonspecific immunity. The larger lymphocytes are typically NK cells.

B cells and T cells, also called **B lymphocytes** and **T lymphocytes**, play prominent roles in defending the body against specific pathogens (disease-causing microorganisms) and are involved in specific immunity. One form of B cells (plasma cells) produces the antibodies or immunoglobulins that bind to specific foreign or abnormal components of plasma membranes. This is also referred to as humoral (body fluid) immunity, since antibodies are proteins dissolved in body fluids. T cells provide cellular-level immunity by physically attacking foreign or diseased cells. A **memory cell** is a variety of both B and T cells that forms after exposure to a pathogen and mounts rapid responses upon subsequent exposures. Unlike other leukocytes, memory cells may live for many years. B cells undergo a maturation process in the bone marrow (B for bone marrow), whereas T cells undergo maturation in the thymus (T for thymus). This site of the maturation process gives rise to the name B and T cells. The functions of lymphocytes are complex and will be covered in detail in the chapter covering the lymphatic system and immunity. Smaller lymphocytes are either B or T cells; they cannot be differentiated in a normal blood smear.

Abnormally high lymphocyte counts are characteristic of viral infections as well as some types of cancer. Abnormally low lymphocyte counts are characteristic of prolonged (chronic) illness or immunosuppression, including that caused by HIV infection and drug therapies that often involve steroids.

Monocytes originate from myeloid stem cells. They normally represent 2–8 percent of the total leukocyte count. They are typically easily recognized by their large size of 12–20 μm and indented or horseshoe-shaped nuclei. Macrophages are monocytes that have left the circulation and further differentiated; macrophages are larger than monocytes and feature many extensions of the plasma membrane spread evenly around their periphery to increase their surface area. Macrophages phagocytize debris, foreign pathogens, worn-out erythrocytes, and many other dead, worn out, or damaged cells. Macrophages also release antimicrobial defensins and chemotactic chemicals that attract other leukocytes to the site of an infection. Some macrophages reside permanently in specific locations of the body, whereas others wander primarily through the matrix of connective tissues patrolling for abnormal cells.

Abnormally high counts of monocytes are associated with viral or fungal infections, tuberculosis, some forms of leukemia, and other chronic diseases. Abnormally low counts are typically caused by suppression of the red bone marrow.

Lifecycle of Leukocytes

Most leukocytes have a relatively short lifespan, typically measured in hours or days. Production of all leukocytes begins in the bone marrow under the influence of CSFs and interleukins. Secondary production and maturation of lymphocytes occurs in specific regions of lymphatic tissue known as germinal centers. Lymphocytes are fully capable of mitosis and may produce clones of cells with identical properties. This capacity enables an individual to maintain immunity throughout life to many threats that have been encountered in the past.

DISORDERS OF THE....

Leukocytes

Leukopenia is a condition in which too few leukocytes are produced. If this condition is pronounced, the individual may be unable to ward off disease. Excessive leukocyte proliferation is known as **leukocytosis**. Although leukocyte counts are high, the cells themselves are often nonfunctional, leaving the individual at increased risk for disease.

Leukemia is a cancer involving an abundance of leukocytes. It may involve only one specific type of leukocyte from either the myeloid line (myelocytic leukemia) or the lymphoid line (lymphocytic leukemia). In chronic leukemia, mature leukocytes accumulate and fail to die. In acute leukemia, there is an overproduction of young, immature leukocytes. In both conditions the cells do not function properly.

Lymphoma is a form of cancer in which masses of malignant T and/or B lymphocytes collect in lymph nodes, the spleen, the liver, and other tissues. As in leukemia, the malignant leukocytes do not function properly, and the patient is vulnerable to infection. Some forms of lymphoma tend to progress slowly and respond well to treatment. Others tend to progress quickly and require aggressive treatment, without which they are rapidly fatal.

Platelets

Platelets are essential for the formation of blood clots to prevent blood loss in the event of damage to a blood vessel wall.

Characteristics and Functions of Platelets

You may occasionally see platelets referred to as **thrombocytes**, but because this name suggests they are a type of cell, it is misleading. A platelet is not a cell but rather a fragment of the cytoplasm of a cell called a **megakaryocyte** that is surrounded by a plasma membrane. Megakaryocytes are descended from myeloid stem cells (see Figure 16.5.1 Hematopoietic System of Bone Marrow) and are large, typically 50–100 μm in diameter, and contain an enlarged, lobed nucleus. Thrombopoietin, a glycoprotein secreted by the kidneys and liver, stimulates the proliferation of megakaryoblasts, which mature into megakaryocytes. These remain within red bone marrow tissue and ultimately form platelet-precursor extensions that extend through the walls of bone marrow capillaries to release into the circulation thousands of cytoplasmic fragments, each enclosed by a bit of plasma membrane. These enclosed fragments are platelets. Each megakarocyte releases 2000–3000 platelets during its lifespan. Following platelet release, megakaryocyte remnants, which are little more than a cell nucleus, are consumed by macrophages.

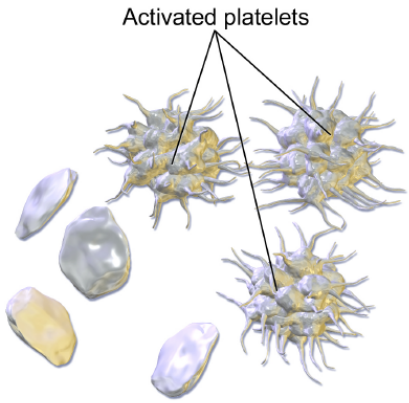

Figure 16.4.3: Platelets. A platelet is a fragment of a cell. When activated, its plasma membrane gains surface area with many hairlike extensions and becomes sticky. (Image credit: "Blausen 0740 Platelets" by Bruce Blaus is licensed under CC BY 3.0)

Platelets are relatively small, 2–4 μm in diameter, but numerous, with typically 150,000–160,000 per μL of blood (Figure 16.4.3). After entering the circulation, approximately one-third migrate to the spleen for storage for later release in response to any rupture in a blood vessel. They then become activated to perform their primary function, which is to limit blood loss. Activated platelets develop hair-like extensions to increase their surface area and become sticky. Platelets remain only about 10 days, then are phagocytized by macrophages.

Platelets are critical to **hemostasis**, the stoppage of blood flow following damage to a vessel. The process of hemostasis involves three steps: vascular spasm, platelet plug formation, and **coagulation** (formation of a blood clot). During vascular spasm, smooth muscle in the wall of the damaged vessel responds to signal chemicals and pain receptors detecting the damage by constricting to restrict blood flow through the damaged area (the body's own way of applying pressure to the bleeding wound). The **platelet plug** is a temporary attempt to seal the damaged vessel wall. It forms when activated platelets clump and attach to the damaged area of the vessel wall. As the platelets form this initial plug, they also release signaling chemicals to initiate a cascade of events that allows the more durable and long-lasting blood clot to form. A **blood clot** is comprised of a mesh of elongated, fibrous **fibrin** proteins (activated from the plasma protein fibrinogen by clotting factors) that trap sticky platelets and red blood cells (Figure 16.4.4). Platelets also secrete a variety of growth factors essential for growth and repair of tissue, particularly connective tissue. Infusions of concentrated platelets are now being used in some therapies to stimulate healing.

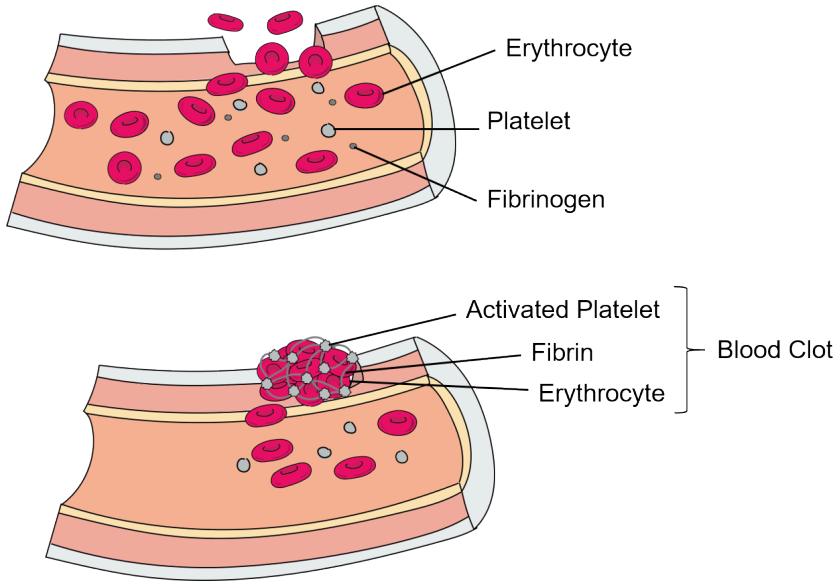

Figure 16.4.4: Blood Clot. A blood clot forms when a vessel wall is damaged. Inactive platelets and fibrinogen circulate in blood and both are activated if a vessel wall is damaged. Activated platelets grow in surface area and stick together, while fibrin becomes fibrous, creating a net-like mesh that sticks to the platelets and traps erythrocytes in the clot as well. ("Blood Clot" by Julie Jenks is a derivative from the original work of Daniel Donnelly and is licensed under CC BY 4.0)

DISORDERS OF THE....

Platelets

Thrombocytosis is a condition in which there are too many platelets. This may trigger formation of unwanted blood clots (thrombosis), a potentially fatal disorder.

If there is an insufficient number of platelets, called **thrombocytopenia**, blood may not clot properly and excessive bleeding may result. **Hemophilia** is a group of genetic disorders also marked by excessive bleeding, but caused by inadequate production of one or more clotting factors, resulting in failure of the blood to properly clot.

Concept Review

Leukocytes function in body defenses. They squeeze out of the walls of blood vessels through emigration or diapedesis, then may move through tissue fluid or become attached to various organs where they fight against pathogenic organisms, diseased cells, or other threats to health. Granular leukocytes, which include neutrophils, eosinophils, and basophils, originate from myeloid stem cells, as do monocytes, one type of agranular leukocyte. The other agranular leukocytes, NK cells, B cells, and T cells, which are all types of lymphocytes, arise from the lymphoid stem cell line. The most abundant leukocytes are the neutrophils, which are first responders to infections, especially with bacteria. About 20–30 percent of all leukocytes are lymphocytes, which are critical to the body's defense against specific threats. Leukemia and lymphoma are malignancies involving leukocytes. Platelets are fragments of cells known as megakaryocytes that dwell within the bone marrow. While many platelets are stored in the spleen, others enter the circulation and are essential for hemostasis; they also produce several growth factors important for repair and healing.

Review Questions

Q. The process by which leukocytes squeeze through adjacent cells in a blood vessel wall is called _____.

A. leukocytosis

B. positive chemotaxis

C. emigration

D. cytoplasmic extending

Answer

Answer: C

Q. Which of the following describes a neutrophil?

A. abundant, agranular, especially effective against cancer cells

B. abundant, granular, especially effective against bacteria

C. rare, agranular, releases antimicrobial defensins

D. rare, granular, contains multiple granules packed with histamine

Answer

Answer: B

Q. T and B lymphocytes _____.

A. are polymorphonuclear

B. are involved with specific immune function

C. proliferate excessively in leukopenia

D. are most active against parasitic worms

Answer

Answer: B

Q. A patient has been experiencing severe, persistent allergy symptoms that are reduced when she takes an antihistamine. Before the treatment, this patient was likely to have had increased activity of which leukocyte?

A. basophils

B. neutrophils

C. monocytes

D. natural killer cells

Answer

Answer: A

Q. Thrombocytes are more accurately called _____.

A. clotting factors

B. megakaryoblasts

C. megakaryocytes

D. platelets

Answer

Answer: D

Critical Thinking Questions

Q. One of the more common adverse effects of cancer chemotherapy is the destruction of leukocytes. Before his next scheduled chemotherapy treatment, a patient undergoes a blood test called an absolute neutrophil count (ANC), which reveals that his neutrophil count is 1900 cells per microliter. Would his healthcare team be likely to proceed with his chemotherapy treatment? Why?

Answer

A. A neutrophil count below 1800 cells per microliter is considered abnormal. Thus, this patient's ANC is at the low end of the normal range and there would be no reason to delay chemotherapy. In clinical practice, most patients are given chemotherapy if their ANC is above 1000.

Q. A patient was admitted to the burn unit the previous evening suffering from a severe burn involving his left upper extremity and shoulder. A blood test reveals that he is experiencing leukocytosis. Why is this an expected finding?

Answer

A. Any severe stress can increase the leukocyte count, resulting in leukocytosis. A burn is especially likely to increase the proliferation of leukocytes in order to ward off infection, a significant risk when the barrier function of the skin is destroyed.

Glossary

agranular leukocytes
leukocytes with few granules in their cytoplasm; specifically, monocytes, lymphocytes, and NK cells

B lymphocytes
(also, B cells) lymphocytes that defend the body against specific pathogens and thereby provide specific immunity

basophils
granulocytes that stain with a basic (alkaline) stain and store histamine and heparin

blood clot
mesh of fibrin proteins and sticky platelets and red blood cells that forms a more durable and long-lasting seal for a damaged blood vessel wall during hemostasis

coagulation
process of forming a blood clot during hemostasis

defensins
antimicrobial proteins released from neutrophils and macrophages that create openings in the plasma membranes to kill cells

diapedesis
(also, emigration) process by which leukocytes squeeze through adjacent cells in a blood vessel wall to enter tissues

emigration
(also, diapedesis) process by which leukocytes squeeze through adjacent cells in a blood vessel wall to enter tissues

eosinophils
granulocytes that stain with eosin; they release antihistamines and are especially active against parasitic worms

fibrin
activated form of the plasma protein fibrinogen; elongated, fibrous protein that forms a mesh framework within a blood clot

granular leukocytes
leukocytes with abundant granules in their cytoplasm; specifically, neutrophils, eosinophils, and basophils

hemophilia
a group of genetic disorders that can result in excessive bleeding related to inadequate production of one or more clotting factors

hemostasis
stoppage of blood flow following damage to a vessel

leukemia
cancer involving leukocytes

leukocyte
(also, white blood cell) colorless, nucleated blood cell, the chief function of which is to protect the body from disease

leukocytosis
excessive leukocyte proliferation

leukopenia
below-normal production of leukocytes

lymphocytes
agranular leukocytes of the lymphoid stem cell line, many of which function in specific immunity

lymphoma
form of cancer in which masses of malignant T and/or B lymphocytes collect in lymph nodes, the spleen, the liver, and other tissues

lysozyme
digestive enzyme with bactericidal properties

megakaryocyte
bone marrow cell that produces platelets

memory cell
type of B or T lymphocyte that forms after exposure to a pathogen

monocytes
agranular leukocytes of the myeloid stem cell line that circulate in the bloodstream; tissue monocytes are macrophages

natural killer (NK) cells
cytotoxic lymphocytes capable of recognizing cells that do not express “self” proteins on their plasma membrane or that contain foreign or abnormal markers; provide generalized, nonspecific immunity

neutrophils
granulocytes that stain with a neutral dye and are the most numerous of the leukocytes; especially active against bacteria

platelet plug
temporary seal for a damaged blood vessel wall during hemostasis; comprised of sticky platelets attached to the damaged vessel wall

polymorphonuclear
having a lobed nucleus, as seen in some leukocytes

positive chemotaxis
process in which a cell is attracted to move in the direction of chemical stimuli

T lymphocytes
(also, T cells) lymphocytes that provide cellular-level immunity by physically attacking foreign or diseased cells

thrombocytes
platelets, one of the formed elements of blood that consists of cell fragments broken off from megakaryocytes

thrombocytopenia
condition in which there are too few platelets, resulting in abnormal bleeding (hemophilia)

thrombocytosis
condition in which there are too many platelets, resulting in abnormal clotting (thrombosis)

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16.5: Production of the Formed Elements

By the end of this section, you will be able to:

- Trace the generation of the formed elements of blood from bone marrow stem cells
- Discuss the role of hemopoietic growth factors in promoting the production of the formed elements

The lifespan of the formed elements is very brief. Although one type of leukocyte called memory cells can survive for years, most erythrocytes, leukocytes, and platelets normally live only a few hours to a few weeks. Thus, the body must form new blood cells and platelets quickly and continuously. When you donate a unit of blood during a blood drive (approximately 475 mL, or about 1 pint), your body typically replaces the donated plasma within 24 hours, but it takes about 4 to 6 weeks to replace the blood cells. This restricts the frequency with which donors can contribute their blood. The process by which this replacement occurs is called **hemopoiesis**, or hematopoiesis (from the Greek root haima- = "blood"; -poiesis = "production").

Sites of Hemopoiesis

Prior to birth, hemopoiesis occurs in a number of tissues, beginning with the yolk sac of the developing embryo, and continuing in the fetal liver, spleen, lymphatic tissue, and eventually the red bone marrow. Following birth, most hemopoiesis occurs in the red marrow, a connective tissue within the spaces of spongy (cancellous) bone tissue. In children, hemopoiesis can occur in the medullary cavity of long bones; in adults, the process is largely restricted to the cranial and pelvic bones, the vertebrae, the sternum, and the proximal epiphyses of the femur and humerus.

Throughout adulthood, the liver and spleen maintain their ability to generate the formed elements. This process is referred to as extramedullary hemopoiesis (meaning hemopoiesis outside the medullary cavity of adult bones). When a disease such as bone cancer destroys the bone marrow, causing hemopoiesis to fail, extramedullary hemopoiesis may be initiated.

Differentiation of Formed Elements from Stem Cells

All formed elements arise from stem cells of the red bone marrow. Recall that stem cells undergo mitosis plus cytokinesis (cellular division) to give rise to new daughter cells; one of these remains a stem cell and the other differentiates into one of any number of diverse cell types. Stem cells may be viewed as occupying a hierarchal system, with some loss of the ability to diversify at each step. The **totipotent stem cell** is the zygote, or fertilized egg. The totipotent (toti- = "all") stem cell gives rise to all cells of the human body. The next level is the **pluripotent stem cell**, which gives rise to multiple types of cells of the body and some of the supporting fetal membranes. Beneath this level, the mesenchymal cell is a stem cell that develops only into types of connective tissue, including fibrous connective tissue, bone, cartilage, and blood, but not epithelium, muscle, and nervous tissue. One step more specific on the hierarchy of stem cells is the **hemopoietic stem cell**, or **hemocytoblast**. All of the formed elements of blood originate from this specific type of cell.

Hemopoiesis begins when the hemopoietic stem cell is exposed to appropriate chemical stimuli collectively called **hemopoietic growth factors**, which prompt it to undergo mitosis (cell division). One daughter cell remains a hemopoietic stem cell, allowing hemopoiesis to continue. The other daughter cell differentiates to become either of two types of more specialized stem cells (Figure 16.5.1):

- **Lymphoid stem cells** give rise to a class of leukocytes known as lymphocytes, which include the various T cells, B cells, and natural killer (NK) cells, all of which function in immunity. However, hemopoiesis of lymphocytes progresses somewhat differently from the process for the other formed elements. In brief, lymphoid stem cells quickly migrate from the bone marrow to lymphatic tissues, including the lymph nodes, spleen, and thymus, where their production and differentiation continues. B cells are so named since they mature in the bone marrow, while T cells mature in the thymus.
- **Myeloid stem cells** give rise to all the other formed elements, including the erythrocytes, megakaryocytes that produce platelets, and a myeloblast lineage that gives rise to monoblasts and three forms of granular leukocytes: neutrophils, eosinophils, and basophils. Monoblasts become agranular monocytes.

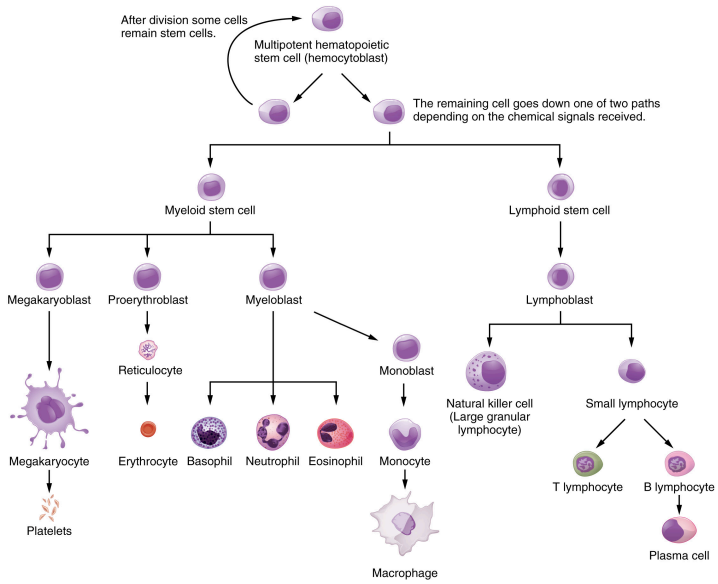

Figure 16.5.1: Hemopoietic System of Bone Marrow. Hemopoiesis, or hematopoiesis, is the proliferation and differentiation of the formed elements of blood. (Image credit: "Hematopoietic System of the Bone Marrow" by Julie Jenks is licensed under CC BY 4.0 / A derivative from the original work)

Lymphoid and myeloid stem cells do not immediately divide and differentiate into mature formed elements. As you can see in Figure 16.5.1, there are several intermediate stages of precursor cells (literally, forerunner cells), many of which can be recognized by their names, which have the suffix "-blast". For instance, megakaryoblasts are the precursors of megakaryocytes, and proerythroblasts become reticulocytes, which eject their nucleus and most other organelles before maturing into erythrocytes.

Lymphoid stem cells give rise to a lymphoblast lineage that gives rise to small lymphocytes and larger, granular natural killer cells (NK cells). Small lymphocytes give rise to T lymphocytes (T cells) and B lymphocytes (B cells).

Hemopoietic Growth Factors

Development from stem cells to precursor cells to mature cells is again initiated by hemopoietic growth factors. These include the following:

- **Erythropoietin (EPO)** is secreted by the interstitial fibroblast cells of the kidneys in response to low oxygen levels. It prompts the production of erythrocytes. Some athletes use synthetic EPO as a performance-enhancing drug (called blood doping) to increase RBC counts and subsequently increase oxygen delivery to tissues throughout the body. EPO is a banned substance in most organized sports, but it is also used medically in the treatment of certain anemia, specifically those triggered by certain types of cancer, and other disorders in which increased erythrocyte counts and oxygen levels are desirable.
- **Thrombopoietin** is produced by the liver and kidneys. It triggers the development of megakaryocytes into platelets.
- **Cytokines** ("cell movers") are secreted by a wide variety of cells, including red bone marrow, leukocytes, macrophages, fibroblasts, and endothelial cells. They act at the site of their secretion to stimulate the proliferation of progenitor cells and help to stimulate both nonspecific and specific resistance to disease. There are two major subtypes of cytokines known as colony-stimulating factors and interleukins.
  - **Colony-stimulating factors (CSFs)** are a family of hormones that trigger the differentiation of myeloblasts into granular leukocytes, namely neutrophils, eosinophils, and basophils, as well as erythrocytes, platelets, and monocytes. Synthetic forms of these hormones are often administered to patients with various forms of cancer who are receiving chemotherapy to revive their leukocyte counts.
  - **Interleukins** are another class of cytokine signaling molecules important in hemopoiesis. They were initially thought to be secreted uniquely by leukocytes and to communicate only with other leukocytes, and were named accordingly, but are now known to be produced by a variety of cells including bone marrow and endothelium. Researchers now suspect that interleukins may play other roles in body functioning, including differentiation and maturation of cells, producing immunity and inflammation. To date, more than a dozen interleukins have been identified, with others likely to follow. They are generally numbered IL-1, IL-2, IL-3, etc.

Bone Marrow Sampling and Transplants

Sometimes, a healthcare provider will order a **bone marrow biopsy**, a diagnostic test of a sample of red bone marrow, or a **bone marrow transplant**, a treatment in which a donor's healthy bone marrow—and its stem cells—replaces the faulty bone marrow of a patient. These tests and procedures are often used to assist in the diagnosis and treatment of various severe forms of anemia, such as thalassemia and sickle cell anemia, as well as some types of cancer, specifically leukemia.

In the past, when a bone marrow sample or transplant was necessary, the procedure would have required inserting a large-bore needle into the region near the iliac crest of the pelvic bones (os coxae). This location was preferred, since its location close to the body surface makes it more accessible, and it is relatively isolated from most vital organs. Unfortunately, the procedure is quite painful.

Now, direct sampling of bone marrow can often be avoided. In many cases, stem cells can be isolated in just a few hours from a sample of a patient's blood. The isolated stem cells are then grown in culture using the appropriate hemopoietic growth factors, and analyzed or sometimes frozen for later use.

For an individual requiring a transplant, a matching donor is essential to prevent the immune system from destroying the donor cells—a phenomenon known as tissue rejection. To treat patients with bone marrow transplants, it is first necessary to destroy the patient's own diseased marrow through radiation and/or chemotherapy. Donor bone marrow stem cells are then intravenously infused. From the bloodstream, they establish themselves in the recipient's bone marrow.

Concept Review

Through the process of hemopoiesis, the formed elements of blood are continually produced, replacing the relatively short-lived erythrocytes, leukocytes, and platelets. Hemopoiesis begins in the red bone marrow, with hemopoietic stem cells that differentiate into myeloid and lymphoid lineages. Myeloid stem cells give rise to most of the formed elements. Lymphoid stem cells give rise only to the various lymphocytes designated as B and T cells, and NK cells. Hemopoietic growth factors, including erythropoietin, thrombopoietin, colony-stimulating factors, and interleukins, promote the proliferation and differentiation of formed elements.

Review Questions

Q. Which of the formed elements arise from myeloid stem cells?

A. B cells

B. natural killer cells

C. platelets

D. all of the above

Answer

Answer: C

Q. Which of the following statements about erythropoietin is true?

A. It facilitates the proliferation and differentiation of the erythrocyte lineage.

B. It is a hormone produced by the thyroid gland.

C. It is a hemopoietic growth factor that prompts lymphoid stem cells to leave the bone marrow.

D. Both a and b are true.

Answer

Answer: A

Q. Interleukins are associated primarily with which of the following?

A. production of various lymphocytes

B. immune responses

C. inflammation

D. all of the above

Answer

Answer: D

Critical Thinking Questions

Q. Myelofibrosis is a disorder in which inflammation and scar tissue formation in the bone marrow impair hemopoiesis. One sign is an enlarged spleen. Why?

Answer

A. When disease impairs the ability of the bone marrow to participate in hemopoiesis, extramedullary hemopoiesis begins in the patient's liver and spleen. This causes the spleen to enlarge.

Q. Would you expect a patient with a form of cancer called acute myelogenous leukemia to experience impaired production of erythrocytes, or impaired production of lymphocytes? Explain your choice.

Answer

A. The adjective myelogenous suggests a condition originating from (generated by) myeloid cells. Acute myelogenous leukemia impairs the production of erythrocytes and other mature formed elements of the myeloid stem cell lineage. Lymphocytes arise from the lymphoid stem cell line.

Glossary

bone marrow biopsy
diagnostic test of a sample of red bone marrow

bone marrow transplant
treatment in which a donor's healthy bone marrow with its stem cells replaces diseased or damaged bone marrow of a patient

colony-stimulating factors (CSFs)
glycoproteins that trigger the proliferation and differentiation of myeloblasts into granular leukocytes (basophils, neutrophils, and eosinophils)

cytokines
class of protein signaling molecules; in the cardiovascular system, they stimulate the proliferation of progenitor cells and help to stimulate both nonspecific and specific resistance to disease

erythropoietin (EPO)
glycoprotein that triggers the bone marrow to produce RBCs; secreted by the kidney in response to low oxygen levels

hemocytoblast
hemopoietic stem cell that gives rise to the formed elements of blood

hemopoiesis
production of the formed elements of blood

hemopoietic growth factors
: chemical signals including erythropoietin, thrombopoietin, colony-stimulating factors, and interleukins that regulate the differentiation and proliferation of particular blood progenitor cells

hemopoietic stem cell
: type of pluripotent stem cell that gives rise to the formed elements of blood (hemocytoblast)

interleukins
: signaling molecules that may function in hemopoiesis, inflammation, and specific immune responses

lymphoid stem cells
: type of hemopoietic stem cells that gives rise to lymphocytes, including various T cells, B cells, and NK cells, all of which function in immunity

myeloid stem cells
: type of hemopoietic stem cell that gives rise to some formed elements, including erythrocytes, megakaryocytes that produce platelets, and a myeloblast lineage that gives rise to monocytes and three forms of granular leukocytes (neutrophils, eosinophils, and basophils)

pluripotent stem cell
: stem cell that derives from totipotent stem cells and is capable of differentiating into many, but not all, cell types

totipotent stem cell
: embryonic stem cell that is capable of differentiating into any and all cells of the body; enabling the full development of an organism

thrombopoietin
: hormone secreted by the liver and kidneys that prompts the development of megakaryocytes into thrombocytes (platelets)

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16.6: Blood Typing

By the end of this section, you will be able to:

- Describe the two basic physiological consequences of transfusion of incompatible blood
- Compare and contrast ABO and Rh blood groups
- Identify which blood groups may be safely transfused into patients with different ABO types

Blood transfusions in humans were risky procedures until the discovery of the major human blood groups by Karl Landsteiner, an Austrian biologist and physician, in 1900. Until that point, physicians did not understand that death sometimes followed blood transfusions, when the type of donor blood infused into the patient was incompatible with the patient's own blood. Blood groups are determined by the presence or absence of specific marker molecules on the plasma membranes of erythrocytes. With their discovery, it became possible for the first time to match patient-donor blood types and prevent transfusion reactions and deaths.

Antigens, Antibodies, and Transfusion Reactions

Antigens are substances that the body does not recognize as belonging to the "self" and that therefore trigger a defensive response from the leukocytes of the immune system (covered more thoroughly in another chapter). Here, we will focus on the role of immunity in blood transfusion reactions.

Recall that all cells have molecules embedded in their plasma membranes that help with cell recognition and identification. Red blood cells have several surface proteins involved in this function; the combination of those present (or absent) determines one's blood type. Because incompatible blood types will trigger a defensive response from the leukocytes, the blood-type related surface proteins are referred to as antigens when discussing blood types.

Following the infusion of incompatible blood, erythrocytes with antigens not present on the person's own erythrocytes appear in the bloodstream and trigger an immune response. Proteins called antibodies (immunoglobulins), which are produced by certain B lymphocytes called plasma cells, attach to the antigens on the plasma membranes of the infused erythrocytes and cause them to adhere to one another. Because the arms of the Y-shaped antibodies attach randomly to more than one non-self erythrocyte surface, they form clumps of erythrocytes. This process is called **agglutination**.

- The clumps of erythrocytes may block small blood vessels throughout the body, depriving tissues of oxygen and nutrients.
- As the erythrocyte clumps are degraded, in a process called **hemolysis**, their hemoglobin is released into the bloodstream. This hemoglobin travels to the kidneys, which are responsible for filtration of the blood. However, the load of hemoglobin released can easily overwhelm the kidney's capacity to clear it, and the patient can quickly develop kidney failure.

More than 50 antigens have been identified on erythrocyte membranes, but the most significant in terms of their potential harm to patients are classified in two groups: the ABO blood group and the Rh blood group.

The ABO Blood Group

Although the **ABO blood group** name consists of three letters, ABO blood typing designates the presence or absence of just two antigens, designated as A and B; both are glycoproteins. People whose erythrocytes have A antigens on their erythrocyte membrane surfaces are designated blood type A, and those whose erythrocytes have B antigens are blood type B. People can also have both A and B antigens on their erythrocytes, in which case they are blood type AB. People with neither A nor B antigens are designated blood type O. ABO blood types are genetically determined.

Normally the body must be exposed to a foreign antigen before an antibody can be produced. This is not the case for the ABO blood group. Individuals with type A blood—without any prior exposure to incompatible blood—have preformed antibodies to the B antigen circulating in their blood plasma. These antibodies, referred to as anti-B antibodies, will cause agglutination and hemolysis if they ever encounter erythrocytes with B antigens. Similarly, an individual with type B blood has pre-formed anti-A antibodies. Individuals with type AB blood, which has both antigens, do not have preformed antibodies to either of these. People with type O blood lack antigens A and B on their erythrocytes, but both anti-A and anti-B antibodies circulate in their blood

plasma.

Rh Blood Groups

The **Rh blood group** is classified according to the presence or absence of a second erythrocyte antigen identified as Rh. (It was first discovered in a type of primate known as a rhesus macaque, often used in research because its blood is similar to that of humans.) Although dozens of Rh antigens have been identified, only one, designated D, is clinically important. Those who have the Rh D antigen present on their erythrocytes—about 85 percent of Americans—are described as Rh positive (Rh^+) and those who lack it are Rh negative (Rh^-). Note that the Rh group is distinct from the ABO group, so any individual, no matter their ABO blood type, may have or lack this Rh antigen. When identifying a patient's blood type, the Rh group is designated by adding the word positive or negative to the ABO type. For example, A positive (A^+) means ABO group A blood with the Rh antigen present, and AB negative (AB^-) means ABO group AB blood without the Rh antigen.

In contrast to the ABO group antibodies, which are preformed, antibodies to the Rh antigen are produced only in Rh^- individuals after exposure to the antigen. This process, called sensitization, occurs following a transfusion with Rh-incompatible blood or, more commonly, with the birth of an Rh^+ baby to an Rh^- mother. Problems are rare in a first pregnancy, since the baby's Rh^+ cells rarely cross the placenta (the organ of gas and nutrient exchange between the baby and the mother). However, during or immediately after birth, the Rh^- mother can be exposed to the baby's Rh^+ red blood cells (Figure 16.6.1). Research has shown that this occurs in about 13–14 percent of such pregnancies. After exposure, the mother's immune system begins to generate anti-Rh antibodies. If the mother should then conceive another Rh^+ baby, the Rh antibodies she has produced can cross the placenta into the fetal bloodstream and destroy the fetal RBCs. This condition, known as **hemolytic disease of the newborn (HDN)** or erythroblastosis fetalis, may cause anemia in mild cases, but the agglutination and hemolysis can be so severe that without treatment the fetus may die in the womb or shortly after birth.

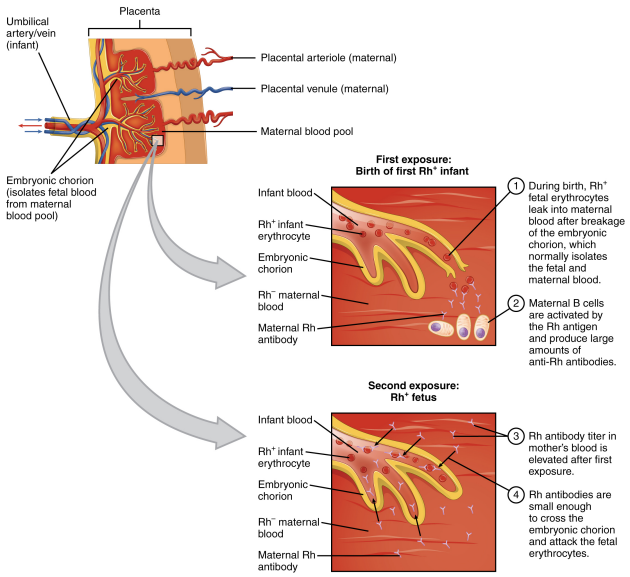


Figure 16.6.1: Hemolytic Disease of the Newborn (HDN). The interface between a pregnant mother and a developing fetus is located within the placenta. Maternal arterioles and venules feed and drain a maternal blood pool, while branches of the umbilical vein and artery are separated from the maternal blood pool by the embryonic chorion. The first exposure of an Rh^- mother to Rh^+ erythrocytes likely occurs during the birth of the first Rh^+ infant, when Rh^+ fetal erythrocytes leak into maternal blood after breakage of the embryonic chorion. Maternal B cells are activated by the Rh antigen and produce large amounts of anti-Rh antibodies, that will circulate in the mother's bloodstream, including the maternal blood pool of the placenta. A second exposure occurs with a subsequent pregnancy with an Rh^+ fetus in the uterus. Maternal anti-Rh antibodies are small enough to cross the embryonic chorion of the placenta and enter the fetal bloodstream, attacking the fetal erythrocytes causing agglutination and hemolysis. (Image credit: "Erythroblastosis Fetalis" by OpenStax is licensed under CC BY 3.0)

A drug known as RhoGAM, short for Rh immune globulin, can temporarily prevent the development of Rh antibodies in the Rh^- mother, thereby averting this potentially serious disease for the fetus. RhoGAM antibodies destroy any fetal Rh^+ erythrocytes that may cross the placental barrier. RhoGAM is normally administered to Rh^- mothers during weeks 26–28 of pregnancy and

within 72 hours following birth. It has proven remarkably effective in decreasing the incidence of HDN. Earlier we noted that the incidence of HDN in an Rh^+ subsequent pregnancy to an Rh^- mother is about 13–14 percent without preventive treatment. Since the introduction of RhoGAM in 1968, the incidence has dropped to about 0.1 percent in the United States.

Determining ABO Blood Types

Clinicians are able to determine a patient's blood type quickly and easily using commercially prepared antibodies. An unknown blood sample is allocated into separate wells. Into one well a small amount of anti-A antibody is added, and to another a small amount of anti-B antibody. If the antigen is present, the antibodies will cause visible agglutination of the cells (Figure 16.6.2). The blood should also be tested for Rh antibodies.

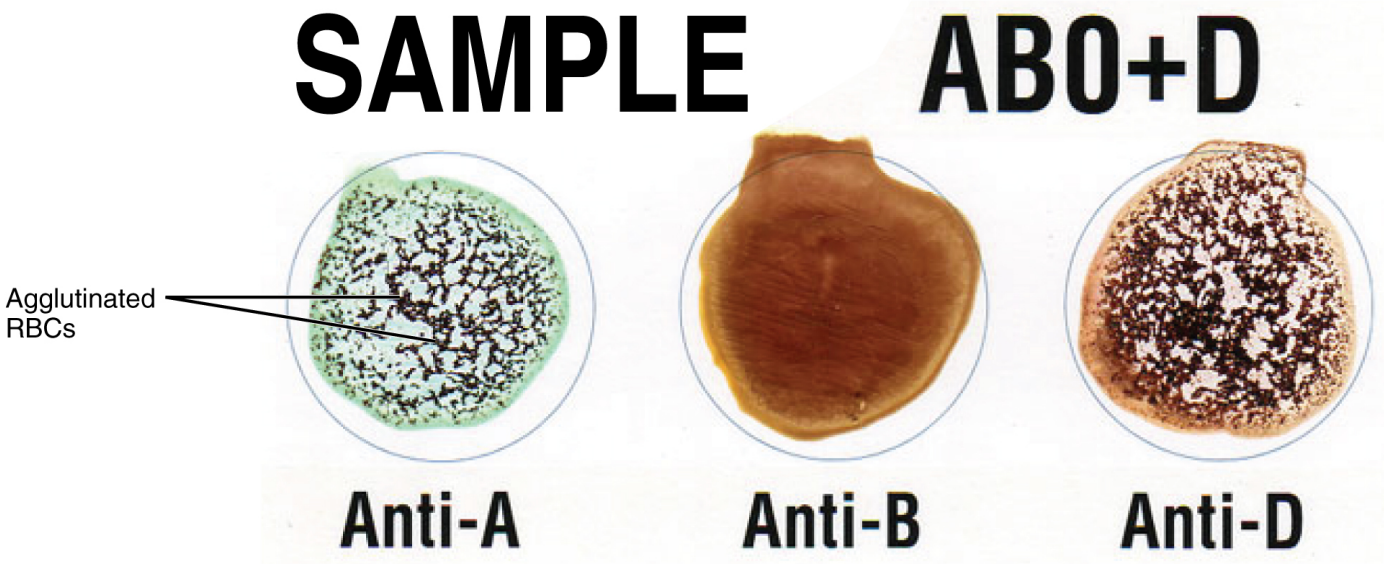


Figure 16.6.2: Cross Matching Blood Types. This sample of a commercially produced "bedside" card enables quick typing of both a recipient's and donor's blood before transfusion. The card contains three reaction sites or wells. One is coated with an anti-A antibody, one with an anti-B antibody, and one with an anti-D antibody (tests for the presence of Rh factor D). Mixing a drop of blood and saline into each well enables the blood to interact with a preparation of type-specific antibodies, also called anti-seras. Agglutination of RBCs in a given site, which changes the solid smear of whole blood to what appears like dark red bubbles in clear or light red fluid, indicates the presence of the corresponding blood antigens, in this case A and Rh antigens for a blood type determination of A^+. For the purpose of transfusion, the donor's and recipient's blood types must match. (Image credit: "Cross Matching Blood Types" by OpenStax is licensed under CC BY 3.0)

ABO Transfusion Protocols

To avoid transfusion reactions, it is best to transfuse only matching blood types; that is, a type B^+ recipient should ideally receive blood only from a type B^+ donor and so on. That said, in emergency situations, when acute hemorrhage threatens the patient's life, there may not be time for cross matching to identify blood type. In these cases, blood from a **universal donor**—an individual with type O^- blood—may be transfused. Recall that type O erythrocytes do not display A or B antigens. Thus, anti-A or anti-B antibodies that might be circulating in the patient's blood plasma will not encounter any erythrocyte surface antigens on the donated blood and therefore will not be provoked into a response. One problem with this designation of universal donor is if the O^- individual had prior exposure to Rh antigen, Rh antibodies may be present in the donated blood. Also, introducing type O blood into an individual with type A, B, or AB blood will nevertheless introduce antibodies against both A and B antigens, as these are always circulating in the type O blood plasma. This may cause problems for the recipient, but because the volume of blood transfused is much lower than the volume of the patient's own blood, the adverse effects of the relatively few infused plasma antibodies are typically limited. Rh factor also plays a role. If Rh^- individuals receiving blood have had prior exposure to Rh antigen, antibodies for this antigen may be present in the blood and trigger agglutination to some degree. Although it is always preferable to cross match a patient's blood before transfusing, in a true life-threatening emergency situation, this is not always possible, and these procedures may be implemented.

Blood banks work to stockpile donated blood for all blood types, especially type O^- blood (the universal donor). Donated blood is

also screened for common and serious blood-bourne illnesses like HIV and hepatitis (among others) to prevent the transmission of disease when a patient receives a blood transfusion from an anonymous donor.

A patient with blood type AB^+ is known as the **universal recipient**. This patient can theoretically receive any type of blood, because the patient's own blood—having both A and B antigens on the erythrocyte surface—does not produce anti-A or anti-B antibodies. In addition, an Rh^+ patient can receive both Rh^+ and Rh^- blood. However, keep in mind that the donor's blood will contain circulating antibodies, again with possible negative implications. Figure 16.6.3 summarizes the characteristics related to each ABO blood type including compatibilities.

At the scene of multiple-vehicle accidents, military engagements, and natural or human-caused disasters, many victims may suffer simultaneously from acute hemorrhage, yet type O blood may not be immediately available. In these circumstances, medics may at least try to replace some of the volume of blood that has been lost. This is done by intravenous administration of a saline solution that provides fluids and electrolytes in proportions equivalent to those of normal blood plasma. Research is ongoing to develop a safe and effective artificial blood that would carry out the oxygen-carrying function of blood without the RBCs, enabling transfusions in the field without concern for incompatibility. These blood substitutes normally contain hemoglobin as well as other types of oxygen carriers.

Blood Type

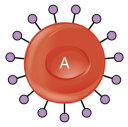
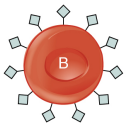
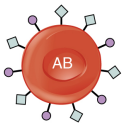
	A	B	AB	O
Red Blood Cell Type				
Antibodies in Plasma	Anti-B	Anti-A	None	Anti-A and Anti-B
Antigens in Red blood Cell	A antigen	B antigen	A and B antigens	None
Blood Types Compatible in an Emergency	A, O	B, O	A, B, AB, O (AB^+ is the universal recipient)	O (O is the universal donor)

Figure 16.6.3: ABO Blood Group Characteristics. This chart summarizes the characteristics of the blood types in the ABO blood group. Type A blood is characterized by A antigens present on the surface of erythrocytes and Anti-B antibodies circulating in the blood plasma. In an emergency, types A and O are compatible for individuals with type A blood. Type B blood is characterized by B antigens present on the surface of erythrocytes and Anti-A antibodies circulating in the blood plasma. In an emergency, types B and O are compatible for individuals with type B blood. Type AB blood is characterized by both A and B antigens present on the surface of erythrocytes and no ABO-specific antibodies circulating in the blood plasma. In an emergency, types A, B, AB, and O are compatible for individuals with type AB blood, so they are known as universal recipients. Type O blood is characterized by no ABO-specific antigens present on the surface of erythrocytes and both Anti-A and Anti-B antibodies circulating in the blood plasma. In an emergency, type O is compatible for individuals with type O blood. While individuals with type O blood can only receive type O, they are able to donate to all ABO blood types, so they are known as universal recipients. Keep in mind that Rh-factor blood type should also be considered for the purposes of compatibility in an emergency. (Image credit: "ABO Blood Groups" by OpenStax is licensed under CC BY 3.0)

Concept Review

Antigens are non-self molecules, usually large proteins, which provoke an immune response. In transfusion reactions, antibodies attach to antigens on the surfaces of erythrocytes and cause agglutination and hemolysis. ABO blood group antigens are designated A and B. People with type A blood have A antigens on their erythrocytes, whereas those with type B blood have B antigens. Those with AB blood have both A and B antigens, and those with type O blood have neither A nor B antigens. The blood plasma contains preformed antibodies against the antigens not present on a person's erythrocytes.

A second group of blood antigens is the Rh group, the most important of which is Rh D. People with Rh^- blood do not have this antigen on their erythrocytes, whereas those who are Rh^+ do. About 85 percent of Americans are Rh^+. When a woman who is Rh^-

becomes pregnant with an Rh^+ fetus, her body may begin to produce anti-Rh antibodies. If she subsequently becomes pregnant with a second Rh^+ fetus and is not treated preventively with RhoGAM, the fetus will be at risk for an antigen-antibody reaction, including agglutination and hemolysis. This is known as hemolytic disease of the newborn.

Cross matching to determine blood type is necessary before transfusing blood, unless the patient is experiencing hemorrhage that is an immediate threat to life, in which case type O^- blood may be transfused.

Review Questions

Q. The process in which antibodies attach to antigens, causing the formation of masses of linked cells, is called _____.

A. sensitization

B. coagulation

C. agglutination

D. hemolysis

Answer

Answer: C

Q. People with ABO blood type O _____.

A. have both antigens A and B on their erythrocytes

B. lack both antigens A and B on their erythrocytes

C. have neither anti-A nor anti-B antibodies circulating in their blood plasma

D. are considered universal recipients

Answer

Answer: B

Q. Hemolytic disease of the newborn is a risk during a subsequent pregnancy in which _____.

A. a type AB mother is carrying a type O fetus

B. a type O mother is carrying a type AB fetus

C. an Rh^+ mother is carrying an Rh^- fetus

D. an Rh^- mother is carrying a second Rh^+ fetus

Answer

Answer: D

Critical Thinking Questions

Q. Following a motor vehicle accident, a patient is rushed to the emergency department with multiple traumatic injuries, causing severe bleeding. The patient's condition is critical, and there is no time for determining his blood type. What type of blood is transfused, and why?

Answer

A. In emergency situations, blood type O^- will be infused until cross matching can be done. Blood type O^- is called the universal donor blood because the erythrocytes have neither A nor B antigens on their surface, and the Rh factor is negative.

Q. In preparation for a scheduled surgery, a patient visits the hospital lab for a blood draw. The technician collects a blood sample and performs a test to determine its type. She places a sample of the patient's blood in two wells. To the first well she adds anti-A antibody. To the second she adds anti-B antibody. Both samples visibly agglutinate. Has the technician made an error, or is this a normal response? If normal, what blood type does this indicate?

Answer

A. The lab technician has not made an error. Blood type AB has both A and B surface antigens, and neither anti-A nor anti-B antibodies circulating in the plasma. When anti-A antibodies (added to the first well) contact A antigens on AB erythrocytes, they will cause agglutination. Similarly, when anti-B antibodies contact B antigens on AB erythrocytes, they will cause agglutination.

References

American Red Cross (US). Blood types [Internet]. c2013 [cited 2013 Apr 3]

Glossary

ABO blood group
blood-type classification based on the presence or absence of A and B glycoproteins on the erythrocyte membrane surface

agglutination
clustering of cells into masses linked by antibodies

cross matching
blood test for identification of blood type using antibodies and small samples of blood

hemolysis
destruction (lysis) of erythrocytes and the release of their hemoglobin into circulation

hemolytic disease of the newborn (HDN)
(also, erythroblastosis fetalis) disorder causing agglutination and hemolysis in an Rh^+ fetus or newborn of an Rh^- mother

Rh blood group
blood-type classification based on the presence or absence of the antigen Rh on the erythrocyte membrane surface

universal donor
individual with type O^- blood

universal recipient
individual with type AB^+ blood

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17: CARDIOVASCULAR SYSTEM - HEART

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17.1: Introduction to the Heart

17.2: Heart Anatomy

17.3: Cardiac Muscle and Electrical Activity

17.4: Coronary Circulation

17.5: Development of the Heart

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17.1: Introduction to the Heart

Chapter Learning Objectives

After studying this chapter, you will be able to:

- Describe the size, shape, and location of the heart
- Identify and describe the interior and exterior parts of the human heart
- Describe the path of blood through the cardiac circuits
- Compare atrial and ventricular systole and diastole
- Explain the cardiac conducting system
- Describe the process and purpose of an electrocardiogram
- Describe fetal heart development

In this chapter, you will explore the remarkable pump that propels the blood into the vessels. The heart functions as a “double pump,” since its contraction develops the pressure that ejects blood into the major vessels for two separate circuits of blood flow: blood from the left side of the heart flows into the aorta for the systemic circuit and blood from the right side of the heart flows into the pulmonary trunk for the pulmonary circuit. From these vessels, blood is distributed to the remainder of the body. Although the connotation of the term “pump” suggests a mechanical device made of steel and plastic, the anatomical structure is a living, sophisticated muscle. As you read this chapter, try to keep these twin concepts in mind: pump and muscle.

Although the term “heart” is an English word, cardiac (heart-related) terminology can be traced back to the Latin term, “kardia.” Cardiology is the study of the heart, and cardiologists are the physicians who deal primarily with the heart.

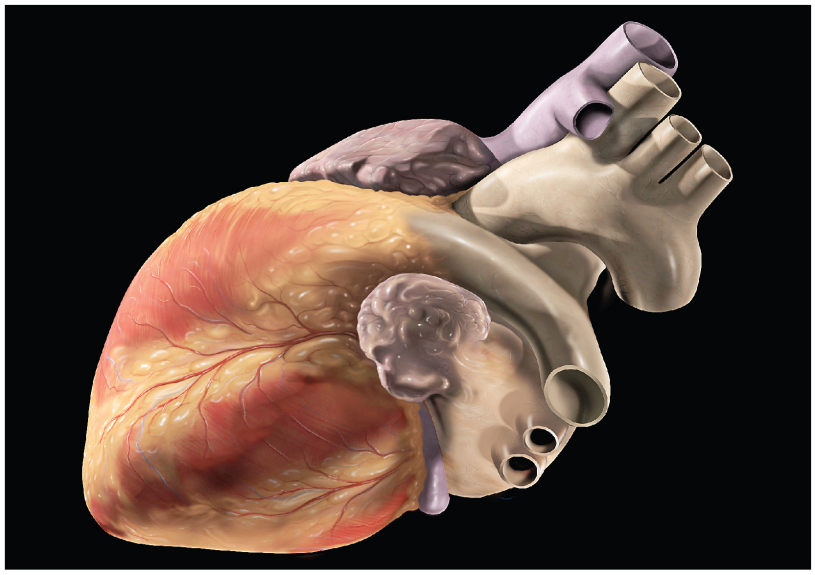

Figure 17.1.1: Human Heart. This artist’s conception of the human heart suggests a powerful engine—not inappropriate for a muscular pump that keeps the body continually supplied with blood. (Image credit: "Human Heart Photo" by Patrick J. Lynch via OpenStax is licensed under CC BY 4.0)

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17.2: Heart Anatomy

By the end of this section, you will be able to:

- Describe the location and position of the heart within the body cavity
- Describe the internal and external anatomy of the heart
- Identify the tissue layers of the heart and pericardium
- Relate the structure of the heart to its function as a double pump
- Compare atrial and ventricular systole and diastole
- Compare systemic circulation to pulmonary circulation
- Trace the pathway of oxygenated and deoxygenated blood through the chambers of the heart

The vital importance of the heart is obvious. If one assumes an average rate of contraction of 75 contractions per minute, a human heart would contract approximately 108,000 times in one day, more than 39 million times in one year, and nearly 3 billion times during a 75-year lifespan. Each of the major pumping chambers of the heart ejects approximately 70 mL of blood per contraction in a resting adult. This would be equal to 5.25 liters of fluid per minute and approximately 14,000 liters per day. Over one year, that would equal 10,000,000 liters or 2.6 million gallons of blood sent through roughly 60,000 miles of vessels.

Location of the Heart

The human heart is located within the thoracic cavity, medially between the lungs in the region known as the mediastinum. The mediastinum also includes the portions of the major blood vessels, the trachea, and the esophagus that are positioned between the lungs medially. Figure 17.2.1 shows the position of the heart within the thoracic cavity. Within the mediastinum, the heart is separated from the other mediastinal structures and is held in place by a tough wrapping known as the pericardium, or pericardial sac. The sac also limits the range of motion of the heart as it beats. The double layered pericardial sac creates a thin space surrounding the heart called the **pericardial cavity** that is filled with serous fluid to prevent friction as the heart beats.

The dorsal surface of the heart lies near the bodies of the vertebrae and its anterior surface sits deep to the sternum and costal cartilages. The great veins, the superior and inferior venae cavae, and the great arteries, the aorta and pulmonary trunk, are attached to the superior surface of the heart, called the base. The base of the heart is located at the level of the third costal cartilage, as seen in Figure 17.2.1. The inferior tip of the heart, the apex, lies just to the left of the sternum between the junction of the fourth and fifth ribs near their articulation with the costal cartilages. The heart is also rotated slightly around its vertical axis such that the more of the right side of the heart is visible in an anterior view while more of the left side is visible in a posterior view. It is important to remember the position and orientation of the heart when placing a stethoscope on the chest of a patient and listening for heart sounds, and also when looking at images taken from a midsagittal perspective. The slight deviation of the apex to the left is reflected in a depression in the medial surface of the inferior lobe of the left lung, called the **cardiac notch**.

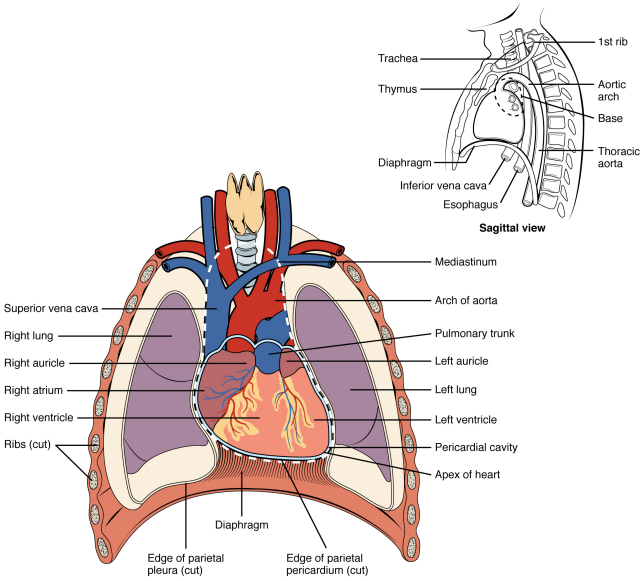


Figure 17.2.1: Position of the Heart in the Thorax. The heart is located within the thoracic cavity, medially between the lungs in the mediastinum. It is about the size of a fist, is broad at the top, and tapers toward the base. (Image credit: "Heart Position in Thorax" by OpenStax is licensed under CC BY 3.0)

EVERYDAY CONNECTION

CPR

The position of the heart in the torso between the vertebrae and sternum (see Figure 17.2.1 for the position of the heart within the thorax) allows for individuals to apply an emergency technique known as cardiopulmonary resuscitation (CPR) if the heart of a patient should stop. If one hand is placed over the other in the middle of the chest about two finger-widths superior to the xiphoid process (Figure 17.2.2), it is possible to manually compress the blood within the heart enough to push some of the blood within it into the pulmonary and systemic circuits. This is particularly critical for the brain, as irreversible damage and death of neurons occur within minutes of loss of blood flow. Current standards call for compression of the chest at least 5 cm deep and at a rate of 100 compressions per minute, a rate equal to the beat in “Staying Alive,” recorded in 1977 by the Bee Gees. If you are unfamiliar with this song, a version is available on www.youtube.com. At this stage, the emphasis is on performing high-quality chest compressions, rather than providing artificial respiration. CPR is generally performed until the patient regains spontaneous contraction or is declared dead by an experienced healthcare professional.

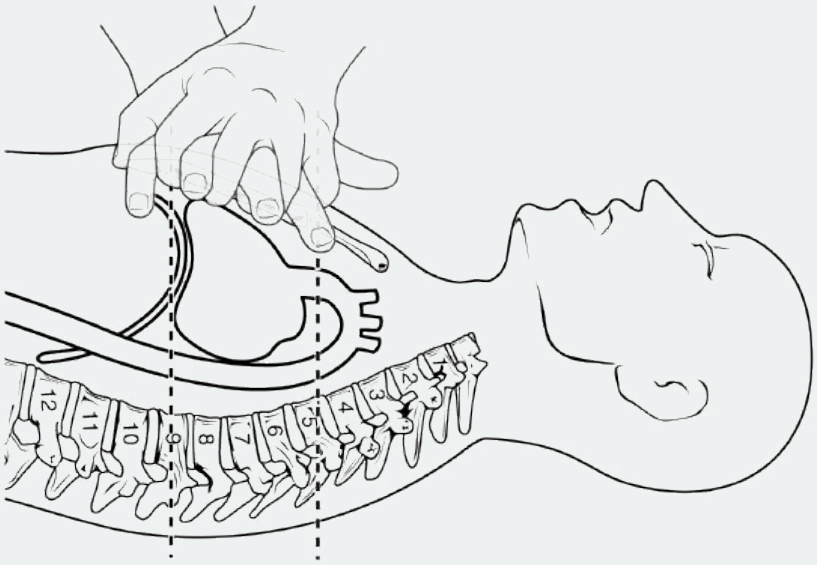


Figure 17.2.2: CPR Technique. If the heart should stop, CPR can maintain the flow of blood until the heart resumes beating. By applying pressure to the sternum, the blood within the heart will be squeezed out of the heart and into the circulation. Proper positioning of the hands on the sternum to perform CPR would be between the lines at T4 and T9, or directly superior to two finger-widths above the xiphoid process. (Image credit: "CPR Technique" by OpenStax College is licensed under CC BY 3.0)

When performed by untrained or overzealous individuals, CPR can result in broken ribs or a broken sternum, and can inflict additional severe damage on the patient. It is also possible, if the hands are placed too low on the sternum, to manually drive the xiphoid process into the liver, a consequence that may prove fatal for the patient. Proper training is essential. This proven life-sustaining technique is so valuable that virtually all medical personnel as well as concerned members of the public should be certified and routinely recertified in its application. CPR courses are offered at a variety of locations, including colleges, hospitals, the American Red Cross, and some commercial companies. They normally include practice of the compression technique on a mannequin.

QR Code representing a URL

Visit the American Heart Association to help locate a course near your home in the United States. There are also many other national and regional heart associations that offer the same service, depending upon the location.

Shape and Size of the Heart

The shape of the heart is similar to a pinecone, rather broad at the superior surface and tapering to the apex (Figure 17.2.1). A typical heart is approximately the size of your fist: 12 cm (5 in) in length, 8 cm (3.5 in) wide, and 6 cm (2.5 in) in thickness. Given the size difference between most members of the sexes, the weight of a female heart is approximately 250–300 grams (9 to 11 ounces), and the weight of a male heart is approximately 300–350 grams (11 to 12 ounces).

The heart of a well-trained athlete, especially one specializing in aerobic sports, can be considerably larger than this. Cardiac muscle responds to exercise in a manner similar to that of skeletal muscle. That is, exercise results in the addition of protein myofilaments that increase the size of the individual cells without increasing their numbers, a concept called hypertrophy. Hearts of athletes can pump blood more effectively at lower rates than those of non-athletes. Enlarged hearts are not always a result of exercise; they can result from pathologies, such as **hypertrophic cardiomyopathy**. The cause of an abnormally enlarged heart muscle is unknown, but hearts with this condition often have mutation(s) in one of the proteins of the sarcomere, such as myosin or troponin (Popa-Fotea *et al*, 2019). The condition can be inherited, is often undiagnosed and can cause sudden death in apparently otherwise healthy young people.

Chambers and Circulation through the Heart

The human heart consists of four chambers: The left side and the right side each have one **atrium** and one **ventricle**. Each of the

upper chambers, the right atrium and the left atrium (plural = atria), acts as a receiving chamber and contracts to push blood into the lower chambers, the right ventricle and the left ventricle. The ventricles serve as the primary pumping chambers of the heart, propelling blood to the lungs or to the rest of the body.

There are two distinct but linked circuits in the human blood circulation called the pulmonary and systemic circuits. Although both circuits transport blood and everything it carries, we can initially view the circuits from the point of view of gases. The **pulmonary circuit** transports blood to and from the lungs, where it picks up oxygen and delivers carbon dioxide for exhalation. The **systemic circuit** transports **oxygenated blood** to virtually all of the tissues of the body and returns relatively deoxygenated blood and carbon dioxide to the heart to be sent back to the pulmonary circulation.

The right ventricle pumps **deoxygenated blood** into the **pulmonary trunk**, which ascends across the anterior surfaces of the ascending aorta and left atrium toward a bifurcation into the left and right **pulmonary arteries**. The right pulmonary artery passes under the aortic arch and delivers blood to the right lung. The left pulmonary artery delivers blood to the left lung. These arteries in turn branch many times in each lung before reaching the **pulmonary capillaries**, where gas exchange occurs: carbon dioxide exits the blood and oxygen enters. The pulmonary trunk, arteries, and their branches are the only arteries in the post-natal body that carry relatively deoxygenated blood. Highly oxygenated blood returning from the pulmonary capillaries in the lungs passes through a series of vessels that join together to form the **pulmonary veins**—the only post-natal veins in the body that carry highly oxygenated blood. The pulmonary veins conduct blood into the right and left sides of the left atrium posteriorly, which pumps the blood into the left ventricle, which in turn pumps oxygenated blood into the aorta, which ascends out of the left ventricle posterior to the pulmonary trunk, arches over the top of the heart and descends posterior to the heart. The aorta branches to deliver oxygenated blood throughout the body via the systemic circuit. Eventually, blood reaches systemic capillaries, where exchange with the tissue fluid and cells of the body occurs. In this case, oxygen and nutrients exit the systemic capillaries to be used by the cells in their metabolic processes, and carbon dioxide and waste products will enter the blood.

The blood exiting the systemic capillaries is lower in oxygen concentration than when it entered. The capillaries will ultimately unite to form venules, joining to form ever-larger veins, eventually flowing into the two major systemic veins, the **superior vena cava** and the **inferior vena cava**, which return blood into the right atrium. The blood in the superior and inferior venae cavae flows into the right atrium, which pumps blood into the right ventricle. This process of blood circulation continues as long as the individual remains alive. Understanding the flow of blood through the pulmonary and systemic circuits is critical to all health professions (Figure 17.2.3).

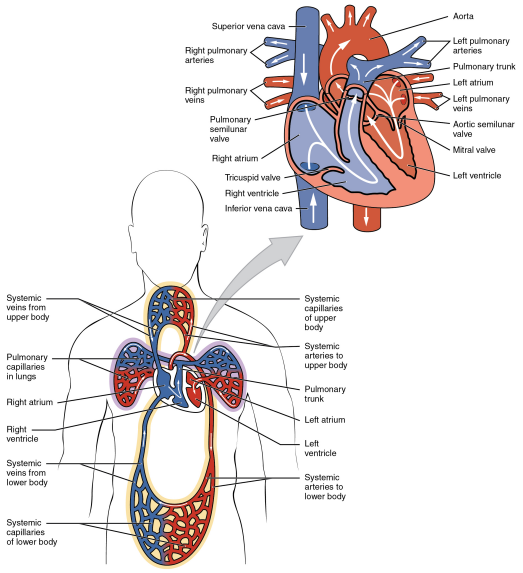


Figure 17.2.3: Dual System of Human Blood Circulation. Blood flows from the right atrium to the right ventricle, where it is pumped into the pulmonary circuit. The blood in the branches of the pulmonary artery is low in oxygen but relatively high in carbon dioxide. Gas exchange occurs in the pulmonary capillaries (oxygen into the blood, carbon dioxide out), and blood high in oxygen and low in carbon dioxide is returned to the left atrium. From here, blood enters the left ventricle, which pumps it into the systemic circuit. Following exchange in the systemic capillaries (oxygen and nutrients out of the capillaries and carbon dioxide and wastes in), blood returns to the right atrium and the cycle is repeated. (Image credit: "Dual System of Human Circulation" by OpenStax is licensed under CC BY 3.0)

Membranes, Surface Features, and Layers

Our exploration of more in-depth heart structures begins by examining the membrane that surrounds the heart, the prominent surface features of the heart, and the layers that form the wall of the heart. Each of these components plays its own unique role in terms of function.

Membranes

The multi-layered membrane that directly surrounds the heart and defines the pericardial cavity is called the **pericardium** or **pericardial sac**. It also surrounds the "roots" of the major vessels, or the areas of closest proximity to the heart. The pericardium, which literally translates as "around the heart," consists of two distinct sublayers: the sturdy outer fibrous pericardium and the inner serous pericardium. The fibrous pericardium is made of tough, dense irregular connective tissue that protects the heart and maintains its position in the thorax while also limiting the heart's motion during the heartbeat. The more delicate serous pericardium consists of two layers: the parietal pericardium, which is fused to the fibrous pericardium, and an inner visceral pericardium, or **epicardium**, which is fused to the heart and is part of the heart wall. The pericardial cavity, filled with lubricating serous fluid, lies between the epicardium and the parietal pericardium.

The serous layers of the pericardium consist of a simple squamous epithelium called a **mesothelium**, reinforced with a layer of areolar connective tissue. The areolar connective tissue connects the parietal pericardium to the fibrous pericardium while it connects the epicardium to the myocardium. The mesothelium secretes the lubricating serous fluid that fills the pericardial cavity and reduces friction as the heart contracts. Figure 17.2.4 illustrates the pericardial membrane and the layers of the heart.

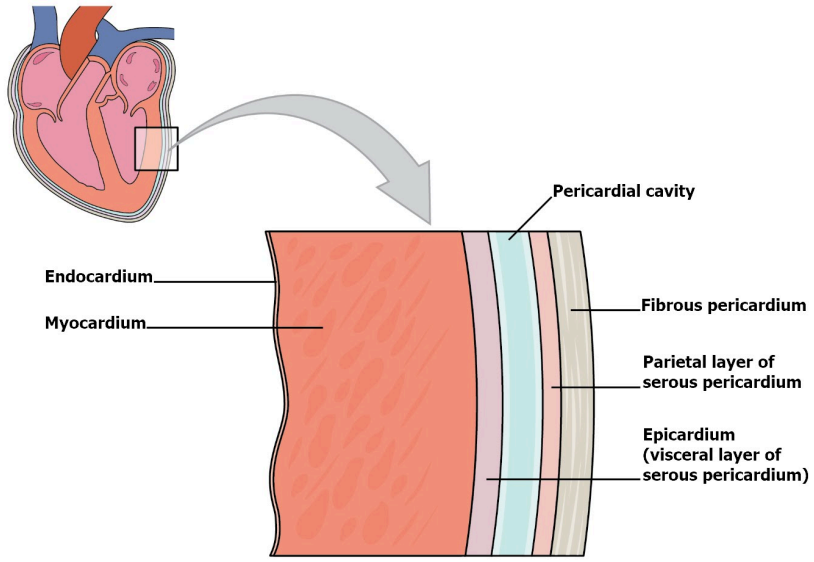


Figure 17.2.4: Pericardial Membranes and Layers of the Heart Wall. A cross-section of the pericardium and heart wall reveal the structure of the layers. The superficial fibrous pericardium is connected to the parietal pericardium that superficially lines the fluid-filled pericardial cavity. The epicardium that lines the deep side of the pericardial cavity is shared by the pericardium and the heart wall. The myocardium is the thickest portion of the heart wall positioned between the epicardium and the endocardium that lines the inside of the heart. (Image Credit: "Heart Wall" by Julie Jenks is licensed under CC BY 4.0 / A derivative from the original work)

DISORDERS OF THE...

Heart: Cardiac Tamponade

If excess fluid builds within the pericardial space, it can lead to a condition called cardiac tamponade, or pericardial tamponade. With each contraction of the heart, more fluid—in most instances, blood—accumulates within the pericardial cavity. In order to fill with blood for the next contraction, the heart must relax. However, the excess fluid in the pericardial cavity puts pressure on the heart and prevents full relaxation, so the chambers within the heart contain slightly less blood as they begin each heart cycle. Over time, less and less blood is ejected from the heart. If the fluid builds up slowly, as in hypothyroidism, the pericardial cavity may be able to expand gradually to accommodate this extra volume. Some cases of

fluid in excess of one liter within the pericardial cavity have been reported. Rapid accumulation of as little as 100 mL of fluid following trauma may trigger cardiac tamponade. Other common causes include myocardial rupture, pericarditis, cancer, or even cardiac surgery. Removal of this excess fluid requires insertion of drainage tubes into the pericardial cavity. Premature removal of these drainage tubes, for example, following cardiac surgery, or clot formation within these tubes are causes of this condition. Untreated, cardiac tamponade can lead to death.

Surface Features of the Heart

Inside the pericardium, the surface features of the heart are visible, including the four chambers. There is a superficial leaf-like extension of each atrium near the superior surface of the heart, one on each side of the pulmonary trunk, called an **auricle**—a name that means “ear like”—because its shape resembles the external ear of a human (Figure 17.2.5). Auricles are relatively thin-walled structures that can fill with blood and empty into the atria or upper chambers of the heart. You may also hear them referred to as atrial appendages. Also prominent along the superficial surfaces of the heart is a series of fat-filled grooves, each of which is known as a **sulcus** (plural = sulci). Major coronary blood vessels are located in these sulci. The deep **coronary sulcus** is located between the atria and ventricles. Located between the left and right ventricles are two additional sulci that are not as deep as the coronary sulcus. The **anterior interventricular sulcus** is visible on the anterior surface of the heart, whereas the **posterior interventricular sulcus** is visible on the posterior surface of the heart. Figure 17.2.5 illustrates anterior and posterior views of the surface of the heart.

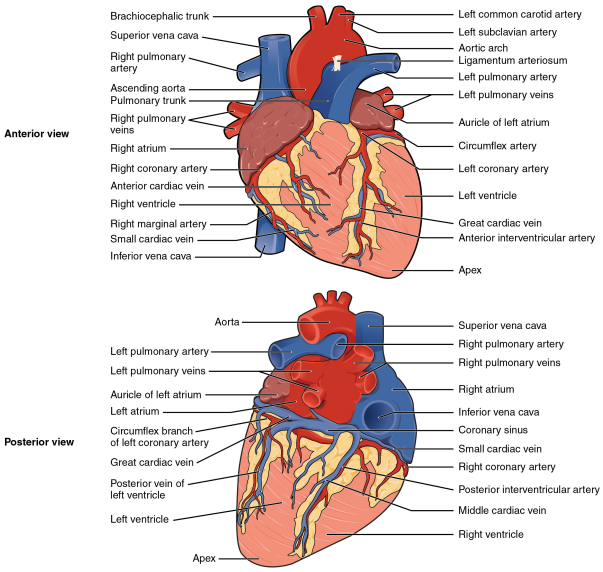


Figure 17.2.5: External Anatomy of the Heart. Deep to the pericardium, the surface features of the heart are visible. (Image credit: "Surface Anatomy of the Heart" by OpenStax is licensed under CC BY 3.0)

Layers

The wall of the heart is composed of three layers of unequal thickness. From superficial to deep, these are the epicardium, the myocardium, and the endocardium (see Figure 17.2.4). The outermost layer of the wall of the heart is also the innermost layer of the pericardium, the epicardium, or the visceral pericardium discussed earlier.

The middle and thickest layer is the **myocardium**, made largely of cardiac muscle cells along with the blood vessels that supply the myocardium and the nerve fibers that help regulate the heart. It is built upon a framework of dense connective tissue called the cardiac skeleton (covered in detail later in this section). It is the contraction of the myocardium that pumps blood through the heart and into the major arteries. The muscle pattern is elegant and complex, as the muscle cells swirl and spiral to form the chambers of the heart. To create this complex 3D structure, cardiac muscle cells approximately follow a figure 8 pattern around the atria and around the roots of the great vessels. Deeper ventricular muscles also form a figure 8 around the two ventricles and proceed toward the apex. More superficial layers of ventricular muscle wrap around both ventricles. This complex swirling pattern allows the heart to pump blood more effectively by decreasing the size of each chamber during contraction. Figure 17.2.6 illustrates the arrangement of muscle cells.

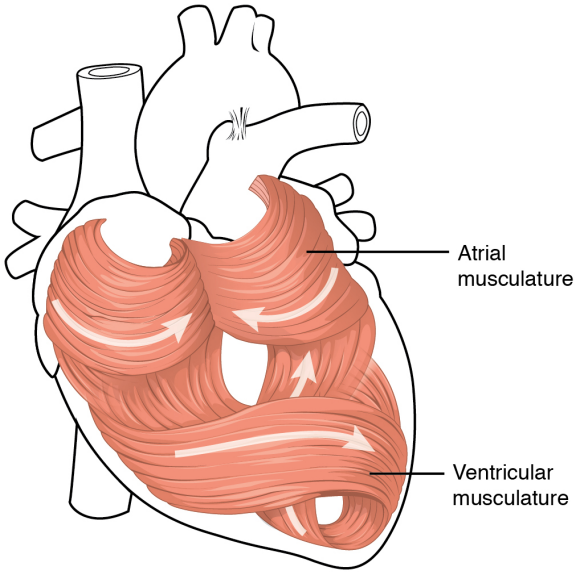


Figure 17.2.6: Cardiac Musculature. The swirling pattern of cardiac muscle tissue contributes significantly to the heart's ability to pump blood effectively. (Image credit: "Heart Musculature" by OpenStax is licensed under CC BY 3.0)

Although the ventricles on the right and left sides pump the same amount of blood per contraction, the muscle of the left ventricle is much thicker and better developed than that of the right ventricle. In order to overcome the high resistance required to pump blood into the long systemic circuit, the left ventricle must generate a great amount of pressure. The right ventricle does not need to generate as much pressure, since the pulmonary circuit is shorter and provides less resistance. Figure 17.2.7 illustrates the differences in muscular thickness needed for each of the ventricles.

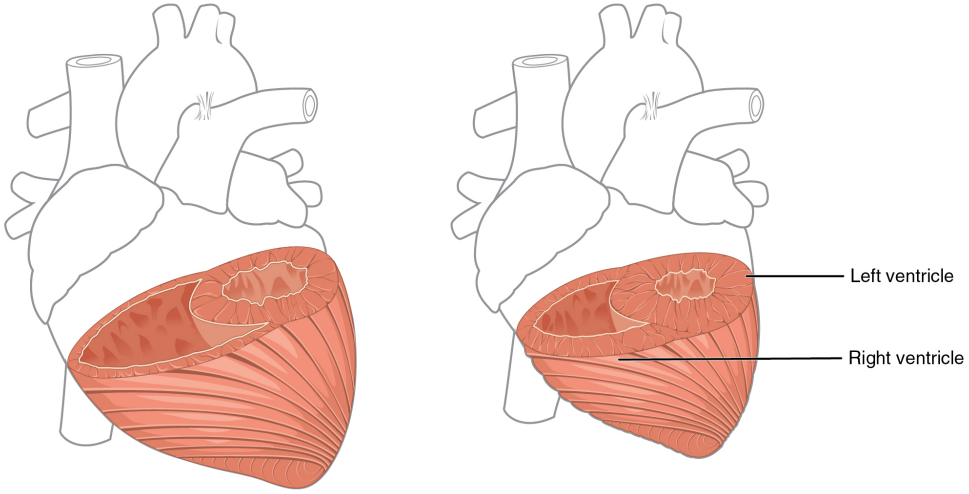


Figure 17.2.7: Differences in Ventricular Muscle Thickness. The myocardium in the left ventricle is significantly thicker than that of the right ventricle. Both ventricles pump the same amount of blood, but the left ventricle must generate a much greater pressure to overcome greater resistance in the systemic circuit. The ventricles are shown in both relaxed and contracting states. Note the differences in the relative size of the lumens, the region inside each ventricle where the blood is contained. (Image credit: "Ventricular Muscle Thickness" by OpenStax is licensed under CC BY 3.0)

The innermost layer of the heart wall, the **endocardium**, is joined to the myocardium with a thin layer of areolar connective tissue. The endocardium lines the chambers where the blood circulates and covers the heart valves. It is made of simple squamous epithelium called **endothelium**, which is continuous with the endothelial lining of the blood vessels (Figure 17.2.4).

Internal Structures of the Heart

Recall that the heart's contraction cycle follows a dual pattern of circulation—the pulmonary and systemic circuits—because of the pairs of chambers that pump blood into the circulation. In order to develop a more precise understanding of cardiac function, it is first necessary to explore the internal anatomical structures in more detail.

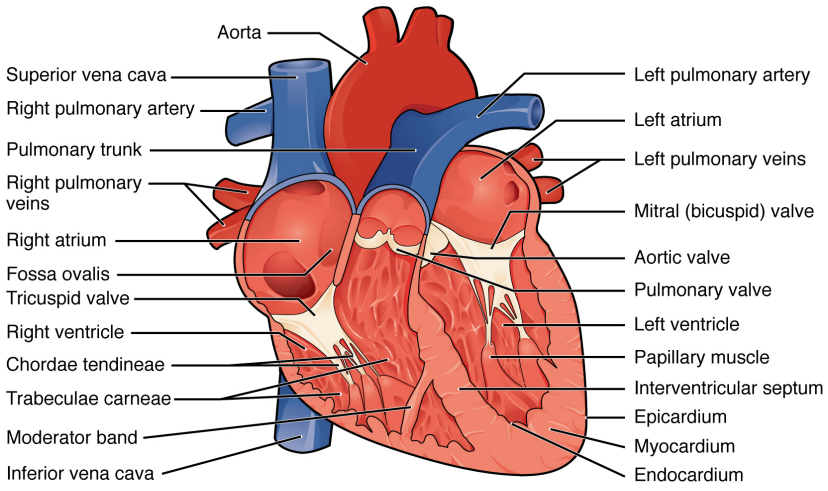
This section explores the anatomy of the septa that divide the heart into four chambers, the cardiac skeleton that provides the supportive internal framework of the heart, and the features of each of the four chambers before describing in more detail the sequence of contractions in a single heart beat—the cardiac cycle—and the structure and function of the heart valves that work to keep blood flowing in one direction through the heart.

Septa of the Heart

The word septum is derived from the Latin for "something that encloses;" in this case, a **septum** (plural = septa) refers to a wall or partition that divides the heart into chambers. The septa are physical extensions of the myocardium lined with endocardium. Located between the two atria is the **interatrial septum**. Normally in an adult heart, the interatrial septum bears an oval-shaped depression known as the **fossa ovalis**, a remnant of an opening in the fetal heart known as the **foramen ovale**. The foramen ovale allowed blood in the fetal heart to pass directly from the right atrium to the left atrium, allowing some blood to bypass the pulmonary circuit. Within seconds after birth, a flap of tissue known as the **septum primum** that previously acted as a valve closes the foramen ovale and establishes the typical cardiac circulation pattern.

Between the two ventricles is a second septum known as the **interventricular septum**. Unlike the interatrial septum, the interventricular septum is normally intact after its formation during fetal development. It is substantially thicker than the interatrial septum, since the ventricles generate far greater pressure when they contract.

The septum between the atria and ventricles is known as the **atrioventricular septum**. It is marked by the presence of four openings that allow blood to move from the atria into the ventricles and from the ventricles into the pulmonary trunk and aorta. Located in each of these openings between the atria and ventricles is a **valve**, a specialized structure that ensures one-way flow of blood. The valves between the atria and ventricles are known generically as **atrioventricular valves**. The valves at the openings that lead to the pulmonary trunk and aorta are known generically as **semilunar valves**. The interventricular septum is visible in Figure 17.2.8. In this figure, the atrioventricular septum has been removed to better show the atrioventricular valves, also known as the bicuspid and tricuspid valves; the interatrial septum is not visible, since its location is covered by the aorta and pulmonary trunk.



Anterior view

Figure 17.2.8: Internal Structures of the Heart. This anterior view of the heart shows the four chambers, the major vessels and their early branches, as well as the valves. The presence of the pulmonary trunk and aorta covers the interatrial septum, and the atrioventricular septum is cut away to show the atrioventricular valves. (Image credit: "Internal Anatomy of the Heart" by OpenStax is licensed under CC BY 3.0)

DISORDERS OF THE...

Heart: Heart Defects

One very common form of interatrial septum pathology is patent foramen ovale, which occurs when the septum primum does not close at birth, and the fossa ovalis is unable to fuse. The word patent is from the Latin root patens for "open." It may be benign or asymptomatic, perhaps never being diagnosed, or in extreme cases, it may require surgical repair to close the opening permanently. As much as 20–25 percent of the general population may have a patent foramen ovale, but fortunately most have the benign, asymptomatic version. Patent foramen ovale is normally detected by auscultation of a heart murmur (an abnormal heart sound) and confirmed by imaging with an echocardiogram. Despite its prevalence in the general population, the causes of patent foramen ovale are unknown, and there are no known risk factors. In nonlife-threatening cases, it is better to monitor the condition than to risk heart surgery to repair and seal the opening.

Coarctation of the aorta is a congenital abnormal narrowing of the aorta that is normally located at the insertion of the ligamentum arteriosum (see Figure 17.2.5), the remnant of the fetal shunt called the ductus arteriosus that connected the pulmonary trunk to the aorta; part of the bypass of the pulmonary circuit. If severe, this condition drastically restricts blood flow through this primary systemic artery, which is life threatening. In some individuals, the condition may be fairly benign and not detected until later in life. Detectable symptoms in an infant include difficulty breathing, poor appetite, trouble feeding, or failure to thrive. In older individuals, symptoms include dizziness, fainting, shortness of breath, chest pain, fatigue, headache, and nosebleeds. Treatment involves surgery to resect (remove) the affected region or angioplasty to open the abnormally narrow passageway. Studies have shown that the earlier the surgery is performed, the better the chance of survival.

A patent ductus arteriosus is a congenital condition in which the ductus arteriosus fails to close. The condition may range from severe to benign. Failure of the ductus arteriosus to close results in blood flowing from the higher pressure aorta into the lower pressure pulmonary trunk. This additional fluid moving toward the lungs increases pulmonary pressure and makes respiration difficult. Symptoms include shortness of breath (dyspnea), tachycardia, enlarged heart, a widened pulse pressure, and poor weight gain in infants. Treatments include surgical closure (ligation), manual closure using platinum coils or specialized mesh inserted via the femoral artery or vein, or nonsteroidal anti-inflammatory drugs to block the synthesis of prostaglandin E2, which maintains the vessel in an open position. If untreated, the condition can result in congestive heart failure.

Septal defects are not uncommon in individuals and may be congenital or caused by various disease processes. Tetralogy of Fallot is a congenital condition that may also occur from exposure to unknown environmental factors; it occurs when there is an opening in the interventricular septum caused by blockage of the pulmonary trunk, normally at the pulmonary semilunar valve. This allows blood that is relatively low in oxygen from the right ventricle to flow into the left ventricle and mix with the blood that is relatively high in oxygen. Symptoms include a distinct heart murmur, low blood oxygen percent saturation, dyspnea or difficulty in breathing, polycythemia, broadening (clubbing) of the fingers and toes, and in children, difficulty in feeding or failure to grow and develop. It is the most common cause of cyanosis following birth. The term "tetralogy" is derived from the four components of the condition, although only three may be present in an individual patient: pulmonary infundibular stenosis (rigidity of the pulmonary valve), overriding aorta (the aorta is shifted above both ventricles), ventricular septal defect (opening), and right ventricular hypertrophy (enlargement of the right ventricle). Other heart defects may also accompany this condition, which is typically confirmed by echocardiography imaging. Tetralogy of Fallot occurs in approximately 400 out of one million live births. Normal treatment involves extensive surgical repair, including the use of stents to redirect blood flow and replacement of valves and patches to repair the septal defect, but the condition has a relatively high mortality. Survival rates are currently 75 percent during the first year of life; 60 percent by 4 years of age; 30 percent by 10 years; and 5 percent by 40 years.

In the case of severe septal defects, including both Tetralogy of Fallot and patent foramen ovale, failure of the heart to develop properly can lead to a condition commonly known as a "blue baby." Regardless of normal skin pigmentation, individuals with this condition have an insufficient supply of oxygenated blood, which leads to cyanosis, a blue or purple coloration of the skin, especially when active.

Septal defects are commonly first detected through auscultation, listening to the chest using a stethoscope. In this case, instead of hearing normal heart sounds attributed to the flow of blood and closing of heart valves, unusual heart sounds may be detected. This is often followed by medical imaging to confirm or rule out a diagnosis. In many cases, treatment may not be needed. Some common congenital heart defects are illustrated in Figure 17.2.9.

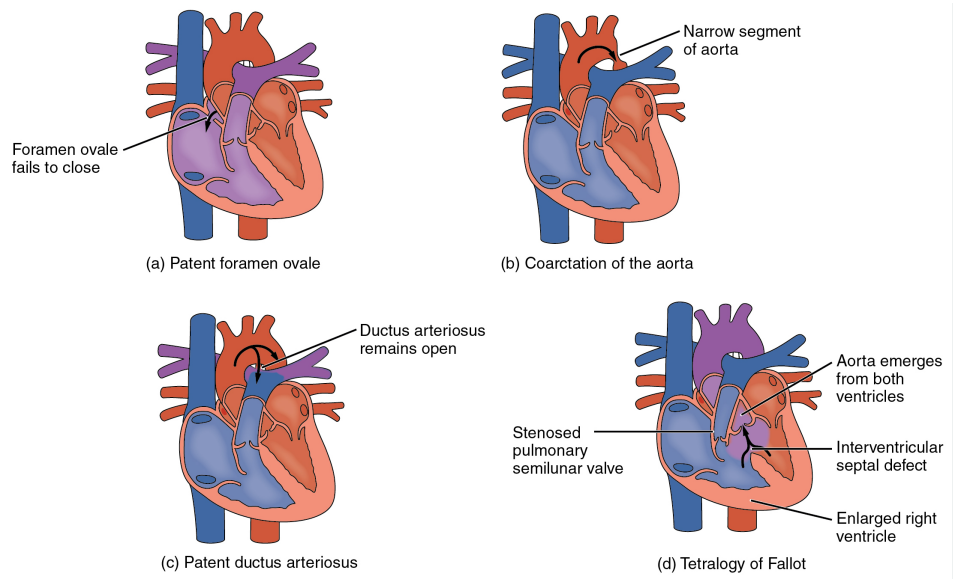


Figure 17.2.9: Congenital Heart Defects. (a) A patent foramen ovale defect is an abnormal opening in the interatrial septum, or more commonly, a failure of the foramen ovale to close. (b) Coarctation of the aorta is an abnormal narrowing of the aorta. (c) A patent ductus arteriosus is the failure of the ductus arteriosus to close. (d) Tetralogy of Fallot includes an abnormal opening in the interventricular septum that causes an enlarged right ventricle, a stenosed (narrowed) pulmonary semilunar valve, and the emergence of the aorta from both ventricles. (Image credit: "Congenital Heart Defects" by OpenStax is licensed under CC BY 3.0)

Cardiac Skeleton

Since these openings and valves structurally weaken the atrioventricular septum, the remaining tissue is heavily reinforced with dense irregular connective tissue of the **cardiac skeleton**, or skeleton of the heart. It includes four rings that surround the openings between the atria and ventricles, and the openings to the pulmonary trunk and aorta, and serve as the point of attachment for the heart valves. The cardiac skeleton also provides the structural framework against which the cardiac muscle contracts and forms an important insulating boundary in the heart's electrical conducting system.

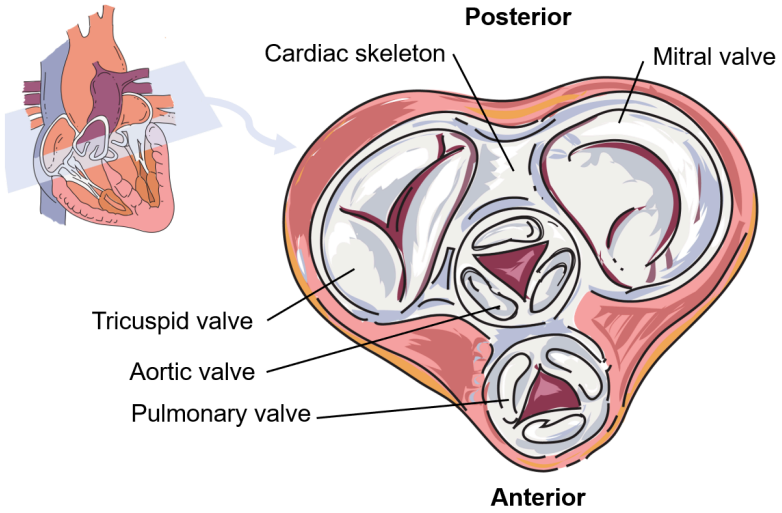


Figure 17.2.10: Cardiac Skeleton. The cardiac skeleton surrounds the four valves positioned in the plane between the atria and ventricles and extends down into the interventricular septum as well. (Image credit: “Cardiac Skeleton" by Julie Jenks is a derivative from the original work of Daniel Donnelly and is licensed under CC BY 4.0)

Right Atrium

The right atrium serves as the receiving chamber for blood returning to the heart from the systemic circulation. The two major systemic veins, the superior and inferior venae cavae, and the large coronary vein called the **coronary sinus** empty into the right atrium. The superior vena cava drains blood from regions superior to the diaphragm: the head, neck, upper limbs, and the thoracic region. It empties into the superior and posterior portions of the right atrium. The inferior vena cava drains blood from areas inferior to the diaphragm: the lower limbs and abdominopelvic region of the body. It, too, empties into the posterior portion of the atria, but inferior to the opening of the superior vena cava. Immediately superior and slightly medial to the opening of the inferior vena cava on the posterior surface of the atrium is the opening of the coronary sinus. This thin-walled vessel drains most of the coronary veins that return systemic blood from the heart into the right atrium. The majority of the internal heart structures discussed in this and subsequent sections are illustrated in Figure 17.2.8.

While the bulk of the internal surface of the right atrium is smooth, the depression of the fossa ovalis is medial, and the anterior surface demonstrates prominent ridges of muscle called the **pectinate muscles**, which are thought to help spread the electrical signals to contract and strengthen the contraction of the atria. The right auricle also has pectinate muscles. The left atrium does not have pectinate muscles except in the auricle.

The atria receive venous blood on a nearly continuous basis, allowing the heart to continue to receive blood even while the ventricles are contracting. While most ventricular filling occurs while the atria are relaxed, they do demonstrate a contractile phase and actively pump blood into the ventricles just prior to ventricular contraction. The opening between the right atrium and right ventricle is guarded by the tricuspid valve.

Right Ventricle

The right ventricle receives blood from the right atrium through the tricuspid valve. Each flap of the valve is attached to strong strands of connective tissue, the **chordae tendineae**, literally “tendinous cords,” or sometimes more poetically referred to as “heart strings.” There are several chordae tendineae associated with each of the flaps. They are composed of approximately 80 percent collagenous fibers with the remainder consisting of elastic fibers and endothelium. They connect each of the flaps to a **papillary muscle**. There are three papillary muscles in the right ventricle, called the anterior, posterior, and septal muscles, which correspond to the three sections of the valves.

When the myocardium of the ventricle contracts, pressure within the ventricular chamber rises. Blood, like any fluid, flows from higher pressure to lower pressure areas, in this case, toward the pulmonary trunk and the atrium. To prevent any potential backflow, the flaps of the tricuspid valve are pushed closed during ventricular contraction. The papillary muscles contract with the ventricular myocardium, generating tension on the chordae tendineae. This prevents the flaps of the valves from being forced into the atria and regurgitation of the blood back into the atria during ventricular contraction. Figure 17.2.11 shows papillary muscles and chordae tendineae attached to the tricuspid valve.

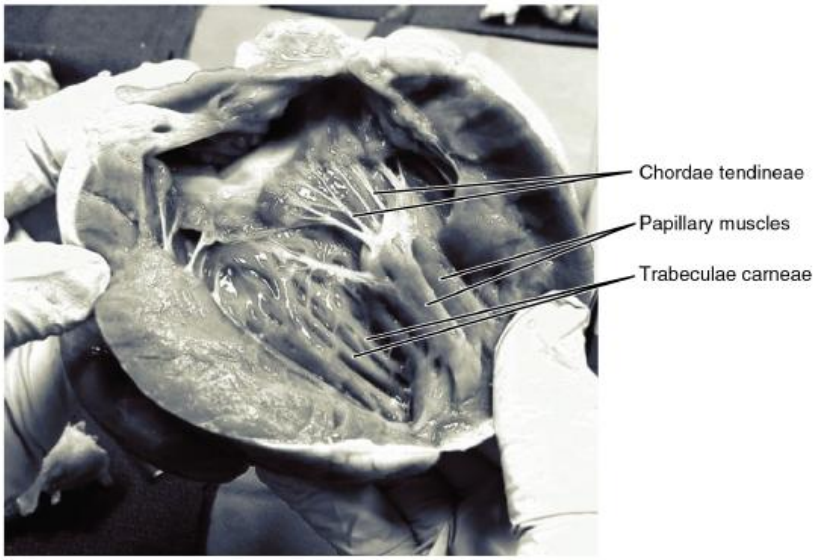


Figure 17.2.11: Chordae Tendineae and Papillary Muscles. In this frontal section, you can see papillary muscles attached to the tricuspid valve on the right as well as the mitral valve on the left via chordae tendineae. (Image credit: "Chordae Tendineae and Papillary Muscles" by CNX is licensed under CC BY 4.0 / A derivative from the original work)

The walls of the ventricle are lined with **trabeculae carneae**, ridges of cardiac muscle covered by endocardium (Figure 17.2.11) that increase the surface area of the ventricular wall. Each papillary muscle is connected to the inferior ventricular myocardium by way of the trabeculae carneae (Axel, 2004). In addition to these muscular ridges, a band of cardiac muscle, also covered by endocardium, known as the **moderator band** (see Figure 17.2.8) reinforces the thin walls of the right ventricle and plays a crucial role in cardiac conduction. It arises from the inferior portion of the interventricular septum and crosses the interior space of the right ventricle to connect with the inferior papillary muscle.

When the right ventricle contracts, it ejects blood into the pulmonary trunk, which branches into the left and right pulmonary arteries that carry deoxygenated blood to each lung. The superior surface of the right ventricle begins to taper as it approaches the pulmonary trunk. At the base of the pulmonary trunk is the pulmonary semilunar valve that prevents backflow from the pulmonary trunk when the ventricle relaxes.

Left Atrium

After exchange of gases in the pulmonary capillaries, freshly oxygenated blood returns to the left atrium via one of the four pulmonary veins. The left atrium does not contain pectinate muscles so its walls are smoother than in the right atrium, but it does have an auricle that includes pectinate ridges. Blood flows nearly continuously from the pulmonary veins back into the atrium, which acts as the receiving chamber, and from here through an open mitral valve, also known as the bicuspid valve, into the left ventricle. Most blood flows passively into the heart while both the atria and ventricles are relaxed, but toward the end of the ventricular relaxation period, the left atrium will contract, pumping blood into the ventricle. This atrial contraction accounts for approximately 20 percent of ventricular filling. The opening between the left atrium and ventricle is guarded by the mitral valve.

Left Ventricle

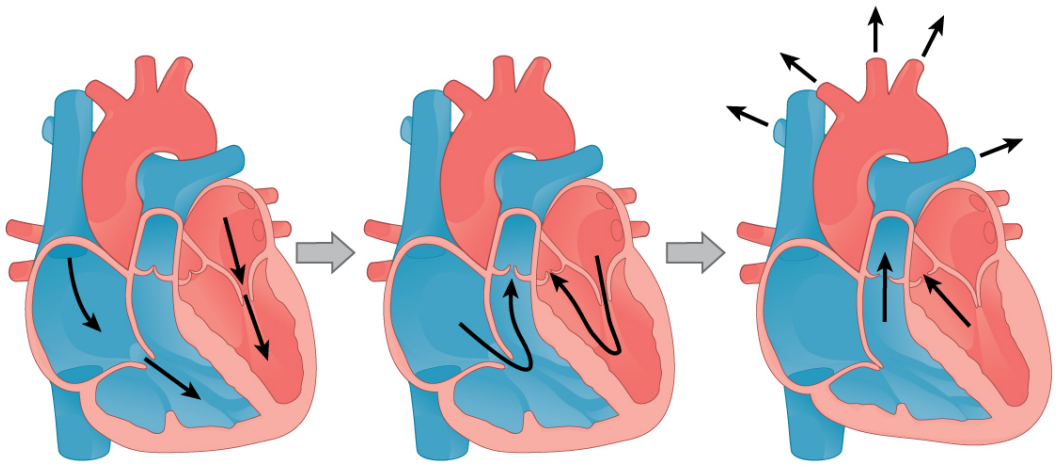
Recall that, although both sides of the heart will pump the same amount of blood, the muscular layer is much thicker in the left ventricle compared to the right (see Figure 17.2.7). Like the right ventricle, the left also has trabeculae carneae, but there is no moderator band. The mitral valve is connected to papillary muscles via chordae tendineae. There are two papillary muscles in the left ventricle—the anterior and posterior—as opposed to three in the right ventricle.

The left ventricle is the major pumping chamber for the systemic circuit; it ejects blood into the aorta through the aortic semilunar valve.

Cardiac Cycle

The period of time that begins with ventricular relaxation and ends after both atria and both ventricles have contracted once is known as the **cardiac cycle** (Figure 17.2.12). The period of contraction that the heart undergoes while it pumps blood into circulation is called **systole**. The period of relaxation that occurs as the chambers fill with blood is called **diastole**. Both the atria and ventricles undergo systole and diastole, and it is essential that these components be carefully regulated and coordinated to ensure blood is pumped efficiently to the body.

The cardiac cycle begins with the atria and ventricles relaxed (cardiac diastole). Blood returns to the right atrium via the superior and inferior venae cavae and coronary sinus and blood returns to the left atrium via four pulmonary veins. With the ventricles relaxed, the tricuspid and mitral valves are open, allowing a majority of blood to passively move inferiorly to begin filling the ventricles. Atrial systole forces the last 30 percent of blood remaining in each atrium into its connected ventricle to finish filling it prior to ventricular systole. The force of ventricular systole forces the blood from the right ventricle through the cusps of the pulmonary semilunar valve into the pulmonary trunk and forces the blood from the left ventricle through the cusps of the aortic semilunar valve into the ascending aorta.



(a) Cardiac diastole: all chambers are relaxed, and blood flows into the heart.

(b) Atrial systole, ventricular diastole: atria contract, pushing blood into the ventricles.

(c) Atrial diastole, ventricular systole: after the atria relax, the ventricles contract, pushing blood out of the heart.

Figure 17.2.12: Cardiac Cycle. The cardiac cycle begins with all chambers of the heart in diastole, during which time the heart fills with blood and blood moves passively from each atrium to the connected ventricle. Then atrial systole pushes the remaining blood from each atrium into the connected ventricle. After the atria relax, ventricular diastole pushes the blood out into the great vessels of each circuit of blood flow. (Image credit: "Figure 40 03 03" by OpenStax is licensed under CC BY 4.0)

Heart Valve Structure and Function

A transverse section through the heart slightly above the level of the atrioventricular septum reveals all four heart valves along the same plane (Figure 17.2.13). The valves ensure unidirectional blood flow through the heart. Between the right atrium and the right ventricle is the **right atrioventricular valve**, or **tricuspid valve**. It typically consists of three flaps, or leaflets, made of endocardium reinforced with additional dense connective tissue. Each flap is connected by several chordae tendineae to a papillary muscle that protrudes from the ventricular wall.

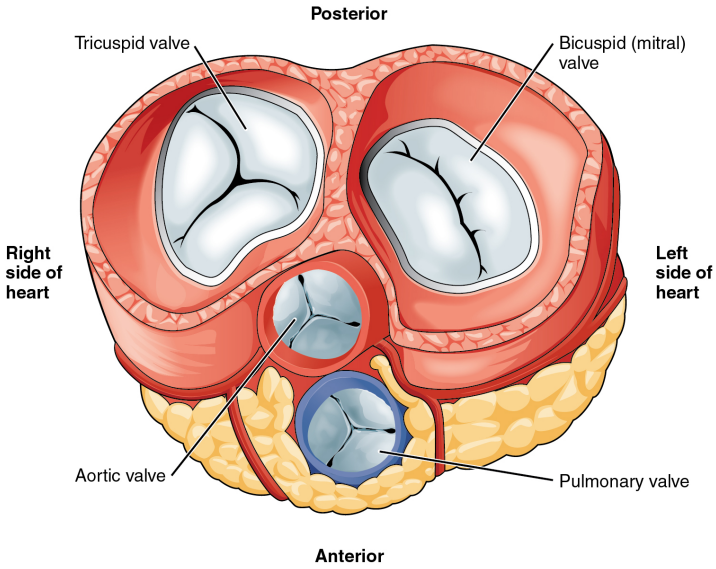


Figure 17.2.13: Heart Valves. With the atria and major vessels removed, all four valves are clearly visible, although it is difficult to distinguish the three separate cusps of the tricuspid valve. (Image credit: "Heart Valves" by OpenStax is licensed under CC BY 3.0)

Located at the opening between the left atrium and left ventricle is the **mitral valve**, also called the **bicuspid valve** or the **left atrioventricular valve**. In a clinical setting, the valve is referred to as the mitral valve, rather than the bicuspid valve, as the actual number of cusps has been found to vary greatly among individuals (Gunnal *et al*, 2012). The cusps of the mitral valve are attached by chordae tendineae to two papillary muscles that project from the trabeculae carneae of the wall of the ventricle.

When the ventricles begin to contract, pressure within the ventricles rises and blood flows toward the area of lowest pressure, which is initially in the atria. This movement of blood causes the cusps of the tricuspid and mitral valves to close. The valve cusps are anchored to the papillary muscles by chordae tendineae. As the myocardium of the ventricle contracts, so do the papillary muscles. This creates tension on the chordae tendineae (see Figure 17.2.15.b), helping to hold the cusps of the atrioventricular valves in place and preventing them from everting into the atria. During the relaxation phase of the cardiac cycle, the papillary muscles are also relaxed and the tension on the chordae tendineae is slight (see Figure 17.2.14.b).

Emerging from the right ventricle at the base of the pulmonary trunk is the pulmonary semilunar valve, or the **pulmonary valve**; it is also known as the pulmonic valve. At the base of the aorta that emerges from the left ventricle is the aortic semilunar valve, or the **aortic valve**. The semilunar valves are both comprised of three small flaps of endothelium reinforced with dense connective tissue.

When the ventricle relaxes, the pressure differential causes blood to flow back towards the ventricle within the pulmonary trunk and aorta. This flow of blood fills the pocket-like flaps of each semilunar valve, causing the valve to close, disrupting the backflow of blood and producing an audible sound. Unlike the atrioventricular valves, there are no papillary muscles or chordae tendineae associated with the semilunar valves.

In Figure 17.2.14.a, the two atrioventricular valves are open and the two semilunar valves are closed. This occurs when both atria and ventricles are relaxed and when the atria contract to pump blood into the ventricles. Figure 17.2.14.b shows a frontal view. Although only the left side of the heart is illustrated, the process is virtually identical on the right.

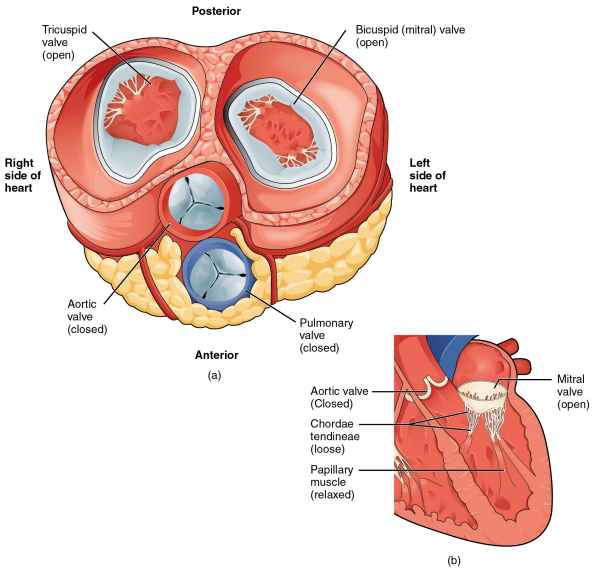


Figure 17.2.14: Positions of Heart Valves during Ventricular Relaxation. (a) A transverse section through the heart illustrates the four heart valves. The two atrioventricular valves are open; the two semilunar valves are closed. The atria and vessels have been removed. (b) A frontal section through the heart illustrates blood flow through the mitral valve. When the mitral valve is open, it allows blood to move from the left atrium to the left ventricle. The aortic semilunar valve is closed to prevent backflow of blood from the aorta to the left ventricle. (Image credit: "Blood Flow Relaxed Ventricles" by OpenStax is licensed under CC BY 3.0)

Figure 17.2.15.a shows the atrioventricular valves closed while the two semilunar valves are open. This occurs when the ventricles contract to eject blood into the pulmonary trunk and aorta. Closure of the two atrioventricular valves prevents blood from being forced back into the atria. This stage can be seen from a frontal view in Figure 17.2.15.b.

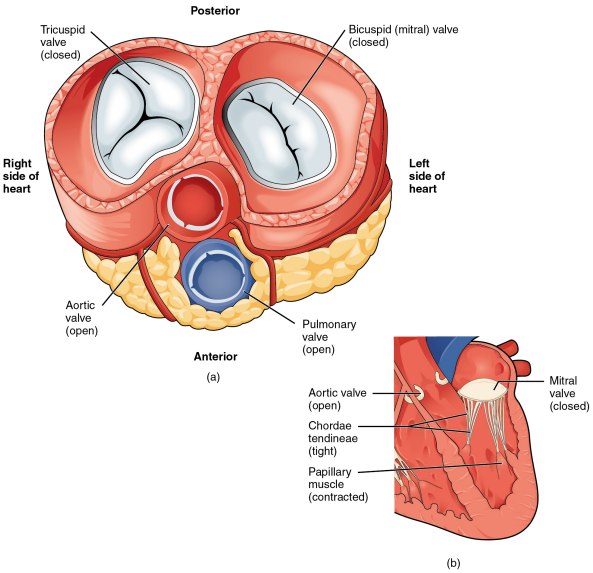


Figure 17.2.15: Positions of Heart Valves during Ventricular Contraction. (a) A transverse section through the heart illustrates the four heart valves during ventricular contraction. The two atrioventricular valves are closed, but the two semilunar valves are open. The atria and vessels have been removed. (b) A frontal view shows the closed mitral (bicuspid) valve that prevents backflow of blood into the left atrium. The aortic semilunar valve is open to allow blood to be ejected into the aorta. (Image credit: "Blood Flow Contracted Ventricles" by OpenStax is licensed under CC BY 3.0)

INTERACTIVE LINK

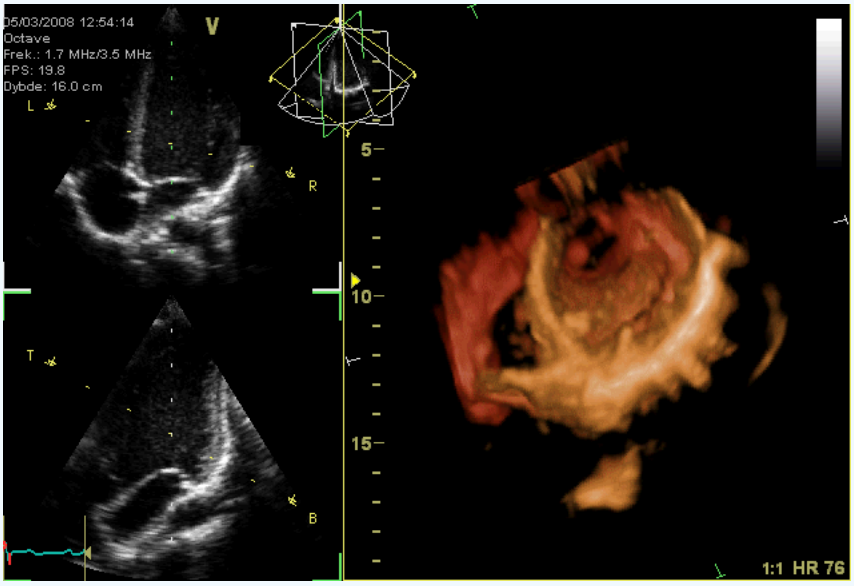


Figure 17.2.16: Echocardiogram of Heart Valves Opening and Closing. GIF-animation showing a moving echocardiogram; a 3D-loop of a heart viewed from the apex, with the apical part of the ventricles removed and the mitral valve clearly visible. Due to missing data the leaflet of the tricuspid and aortic valve is not clearly visible, but the openings are. To the left are two standard two-dimensional views taken from the 3D dataset. If not animated above, visit this site to observe an echocardiogram of actual heart valves opening and closing. (Image and caption credit: "Apikal4D" by Kjetil Lenes is licensed under CC BY-SA 3.0)

Although much of the heart has been "removed" from this gif loop so the chordae tendineae are not visible, why is their presence more critical for the atrioventricular valves (tricuspid and mitral) than the semilunar (aortic and pulmonary) valves?

Answer available at the end of this section.

Heart Sounds

One of the simplest, yet effective, diagnostic techniques applied to assess the state of a patient's heart is auscultation using a stethoscope.

In a normal, healthy heart, there are only two audible **heart sounds**: S_1 and S_2. S_1 is the sound created by the closing of the atrioventricular valves during ventricular contraction and is normally described as a "lub," or first heart sound. The second heart sound, S_2, is the sound of the closing of the semilunar valves during ventricular diastole and is described as a "dub" (Figure 17.2.17). In both cases, as the valves close, the openings within the atrioventricular septum guarded by the valves will become reduced, and blood flow through the opening will become more turbulent until the valves are fully closed. There is a third heart sound, S_3, but it is rarely heard in healthy individuals. It may be the sound of blood flowing into the atria, or blood sloshing back and forth in the ventricle, or even tensing of the chordae tendineae. S_3 may be heard in youth, some athletes, and pregnant women. If the sound is heard later in life, it may indicate congestive heart failure, warranting further tests. Some cardiologists refer to the collective S_1, S_2, and S_3 sounds as the "Kentucky gallop," because they mimic those produced by a galloping horse. The fourth heart sound, S_4, results from the contraction of the atria pushing blood into a stiff or hypertrophic ventricle, indicating failure of the left ventricle. S_4 occurs prior to S_1 and the collective sounds S_4, S_1, and S_2 are referred to by some cardiologists as the "Tennessee gallop," because of their similarity to the sound produced by a galloping horse with a different gait. A few individuals may have both S_3 and S_4, and this combined sound is referred to as S_7.

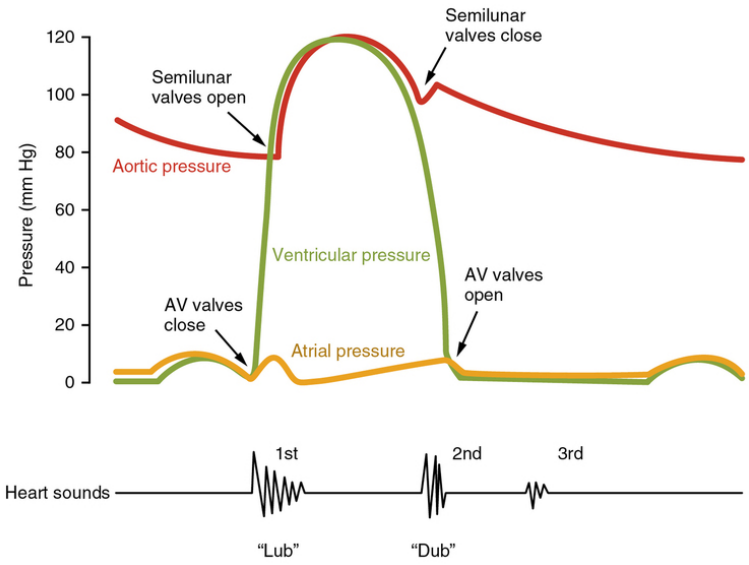


Figure 17.2.17: Heart Sounds and the Cardiac Cycle. In this illustration, the x-axis reflects time with a recording of the heart sounds. The y-axis represents pressure. (Image credit: "Cardiac Cycle vs Heart Sounds" by OpenStax is licensed under CC BY 3.0)

The term **murmur** is used to describe an unusual sound coming from the heart that is caused by the turbulent flow of blood. Murmurs are graded on a scale of 1 to 6, with 1 being the most common, the most difficult sound to detect, and the least serious. The most severe is a 6. Phonocardiograms or auscultograms can be used to record both normal and abnormal sounds using specialized electronic stethoscopes.

During auscultation, it is common practice for the clinician to ask the patient to breathe deeply. This procedure not only allows for listening to airflow, but it may also amplify heart murmurs. Inhalation increases blood flow into the right side of the heart and may increase the amplitude of right-sided heart murmurs. Expiration partially restricts blood flow into the left side of the heart and may amplify left-sided heart murmurs. Placement of the stethoscope in four distinct locations enables optimal ausculation of each valve: near transition of the ascending aorta to the aortic arch for the aortic valve, near the bifurcation of the pulmonary trunk for the pulmonary valve, near the superior portion of the right ventricle for the tricuspid valve, and near the apex of the heart for the mitral valve. Figure 17.2.18 indicates proper placement of the bell of the stethoscope to facilitate auscultation.

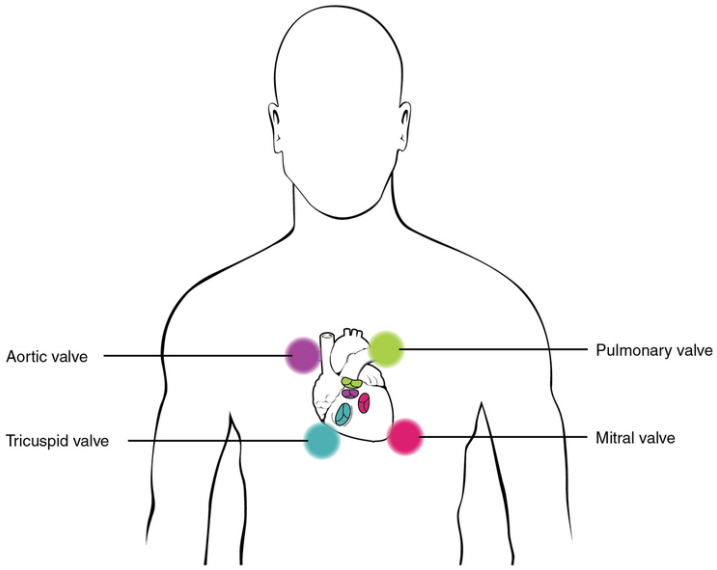


Figure 17.2.18: Stethoscope Placement for Auscultation. Proper placement of the bell of the stethoscope facilitates auscultation. At each of the four locations on the chest, a different valve can be heard. (Image credit: "Stethoscope Placement" by OpenStax is licensed under CC BY 3.0)

DISORDERS OF THE...

Heart Valves

When heart valves do not function properly, they are often described as incompetent and result in valvular heart disease, which can range from benign to lethal. Some of these conditions are congenital, that is, the individual was born with the defect, whereas others may be attributed to disease processes or trauma. Some malfunctions are treated with medications, others require surgery, and still others may be mild enough that the condition is merely monitored since treatment might trigger more serious consequences.

Valvular disorders are often caused by carditis, or inflammation of the heart. One common trigger for this inflammation is rheumatic fever, or scarlet fever, an autoimmune response to the presence of a bacterium, Streptococcus pyogenes, normally a disease of childhood.

While any of the heart valves may be involved in valve disorders, mitral regurgitation is the most common, detected in approximately 2 percent of the population, and the pulmonary semilunar valve is the least frequently involved. When a valve malfunctions, the flow of blood to a region will often be disrupted. The resulting inadequate flow of blood to this region will be described in general terms as an insufficiency. The specific type of insufficiency is named for the valve involved: aortic insufficiency, mitral insufficiency, tricuspid insufficiency, or pulmonary insufficiency.

If one of the cusps of the valve is forced backward by the force of the blood, the condition is referred to as a prolapsed valve. Prolapse may occur if the chordae tendineae are damaged or broken, causing the closure mechanism to fail. The failure of the valve to close properly disrupts the normal one-way flow of blood and results in regurgitation, when the blood flows backward from its normal path. Using a stethoscope, the disruption to the normal flow of blood produces a heart murmur.

Stenosis is a condition in which the heart valves become rigid and may calcify over time. The loss of flexibility of the valve interferes with normal function and may cause the heart to work harder to propel blood through the valve, which eventually weakens the heart. Aortic stenosis affects approximately 2 percent of the population over 65 years of age, and the percentage increases to approximately 4 percent in individuals over 85 years. Occasionally, one or more of the chordae tendineae will tear or the papillary muscle itself may die as a component of a myocardial infarction (heart attack). In this case, the patient's condition will deteriorate dramatically and rapidly, and immediate surgical intervention may be required.

Auscultation, or listening to a patient's heart sounds, is one of the most useful diagnostic tools, since it is proven, safe, and inexpensive. The term auscultation is derived from the Latin for "to listen," and the technique has been used for diagnostic purposes as far back as the ancient Egyptians. Valve and septal disorders will trigger abnormal heart sounds. If a valvular disorder is detected or suspected, a test called an echocardiogram, or simply an "echo," may be ordered. Echocardiograms are sonograms of the heart and can help in the diagnosis of valve disorders as well as a wide variety of heart pathologies.

CAREER CONNECTION

Cardiologist

Cardiologists are medical doctors that specialize in the diagnosis and treatment of diseases of the heart. After completing 4 years of medical school, cardiologists complete a three-year residency in internal medicine followed by an additional three or more years in cardiology. Following this 10-year period of medical training and clinical experience, they qualify for a rigorous two-day examination administered by the Board of Internal Medicine that tests their academic training and clinical abilities, including diagnostics and treatment. After successful completion of this examination, a physician becomes a board-certified cardiologist. Some board-certified cardiologists may be invited to become a Fellow of the American College of Cardiology (FACC). This professional recognition is awarded to outstanding physicians based upon merit, including outstanding credentials, achievements, and community contributions to cardiovascular medicine.

QR Code representing a URL

Visit this site to learn more about cardiologists.

CAREER CONNECTION

Cardiovascular Technologist/Technician

Cardiovascular technologists/technicians are trained professionals who perform a variety of imaging techniques, such as sonograms or echocardiograms, used by physicians to diagnose and treat diseases of the heart. Nearly all of these positions require an associate degree, and these technicians earn a median salary of $68,750 as of 2019. Growth within the field is fast, projected at 12 percent from 2019 - 2029, according to the U.S. Bureau of Labor Statistics.

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Visit this site for more information on cardiovascular technologists/technicians [statistics retrieved 10 Dec 2020].

There is a considerable overlap and complementary skills between cardiac technicians and vascular technicians, and so the term cardiovascular technician is often used. Special certifications within the field require documenting appropriate experience and completing additional and often expensive certification examinations. These subspecialties include Certified Rhythm Analysis Technician (CRAT), Certified Cardiographic Technician (CCT), Registered Congenital Cardiac Sonographer (RCCS), Registered Cardiac Electrophysiology Specialist (RCES), Registered Cardiovascular Invasive Specialist (RCIS), Registered Cardiac Sonographer (RCS), Registered Vascular Specialist (RVS), and Registered Phlebology Sonographer (RPhS).

Concept Review

The heart resides within the pericardial sac and is located in the mediastinal space within the thoracic cavity. The pericardial sac consists of two fused layers: an outer fibrous layer and an inner parietal pericardial serous membrane. Between the pericardial sac and the heart is the pericardial cavity, which is filled with lubricating serous fluid. The walls of the heart are composed of an outer epicardium, a thick myocardium, and an inner lining layer of endocardium. The human heart consists of a pair of atria, which receive blood and pump it into a pair of ventricles, which pump blood into the vessels. The right atrium receives systemic blood relatively low in oxygen and pumps it into the right ventricle, which pumps it into the pulmonary circuit. Exchange of oxygen and carbon dioxide occurs in the lungs, and blood high in oxygen returns to the left atrium, which pumps blood into the left ventricle, which in turn pumps blood into the aorta and the remainder of the systemic circuit. The septa are the partitions that separate the chambers of the heart. They include the interatrial septum, the interventricular septum, and the atrioventricular septum. Two of these openings are guarded by the atrioventricular valves, the right tricuspid valve and the left mitral valve, which prevent the backflow of blood. Each is attached to chordae tendineae that extend to the papillary muscles, which are extensions of the myocardium, to prevent the valves from being blown back into the atria. The pulmonary semilunar valve is located at the base of the pulmonary trunk, and the aortic semilunar valve is located at the base of the aorta.

Review Questions

Q. Which of the following is not important in preventing backflow of blood?

A. chordae tendineae

B. papillary muscles

C. AV valves

D. myocardium

Answer

D

Q. Which valve separates the left atrium from the left ventricle?

A. mitral

B. tricuspid

C. pulmonary

D. aortic

Answer

A

Q. Which of the following lists the valves in the order through which the blood flows from the vena cava through the heart?

A. tricuspid, pulmonary semilunar, bicuspid, aortic semilunar

B. mitral, pulmonary semilunar, bicuspid, aortic semilunar

C. aortic semilunar, pulmonary semilunar, tricuspid, bicuspid

D. bicuspid, aortic semilunar, tricuspid, pulmonary semilunar

Answer

A

Q. Which chamber initially receives blood from the systemic circuit?

A. left atrium

B. left ventricle

C. right atrium

D. right ventricle

Answer

C

Q. The myocardium would be the thickest in the _____.

A. left atrium

B. left ventricle

C. right atrium

D. right ventricle

Answer

B

Q. Most blood enters the ventricle during _____.

A. atrial systole

B. atrial diastole

C. ventricular systole

D. cardiac diastole

Answer

D

Q. The first heart sound represents which portion of the cardiac cycle?

A. atrial systole

B. ventricular systole

C. closing of the atrioventricular valves

D. closing of the semilunar valves

Answer

Answer: C

Q. In which septum is it normal to find openings in the adult?

A. interatrial septum

B. interventricular septum

C. atrioventricular septum

D. all of the above

Answer

C

Critical Thinking Questions

Q. Describe the cardiac cycle, beginning with both atria and ventricles relaxed.

Answer

A. The cardiac cycle comprises a complete relaxation and contraction of both the atria and ventricles, and lasts approximately 0.8 seconds. Beginning with all chambers in diastole, blood flows passively from the veins into the atria and past the atrioventricular valves into the ventricles. The atria begin to contract following depolarization of the atria and pump blood into the ventricles. The ventricles begin to contract, raising pressure within the ventricles. When ventricular pressure rises above the pressure in the two major arteries, blood pushes open the two semilunar valves and moves into the pulmonary trunk and aorta in the ventricular ejection phase. Following ventricular repolarization, the ventricles begin to relax, and pressure within the ventricles drops. When the pressure falls below that of the atria, blood moves from the atria into the ventricles, opening the atrioventricular valves and marking one complete heart cycle.

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Glossary

anterior interventricular sulcus
: sulcus located between the left and right ventricles on the anterior surface of the heart

aortic valve
: (also, aortic semilunar valve) valve located at the base of the aorta

atrioventricular septum
: cardiac septum located between the atria and ventricles; atrioventricular valves are located here

atrioventricular valves
: one-way valves located between the atria and ventricles; the valve on the right is called the tricuspid valve, and the one on the left is the mitral or bicuspid valve

atrium
: (plural = atria) upper or receiving chamber of the heart that pumps blood into the lower chambers just prior to their contraction; the right atrium receives blood from the systemic circuit that flows into the right ventricle; the left atrium receives blood from the pulmonary circuit that flows into the left ventricle

auricle
: extension of an atrium visible on the anterosuperior surface of the heart

bicuspid valve
: (also, mitral valve or left atrioventricular valve) valve located between the left atrium and ventricle; consists of two flaps of tissue

cardiac notch
: depression in the medial surface of the inferior lobe of the left lung where the apex of the heart is located

cardiac skeleton
: (also, skeleton of the heart) reinforced connective tissue located within the atrioventricular septum; includes four rings that surround the openings between the atria and ventricles, and the openings to the pulmonary trunk and aorta; the point of attachment for the heart valves

cardiomyocyte
: muscle cell of the heart

chordae tendineae
: string-like extensions of tough connective tissue that extend from the flaps of the atrioventricular valves to the papillary muscles

coronary arteries
: branches of the ascending aorta that supply blood to the heart; the left coronary artery feeds the left side of the heart, the left atrium and ventricle, and the interventricular septum; the right coronary artery feeds the right atrium, portions of both ventricles, and the heart conduction system

coronary sinus
: large, thin-walled vein on the posterior surface of the heart that lies within the atrioventricular sulcus and drains the heart myocardium directly into the right atrium

coronary sulcus
: sulcus that marks the boundary between the atria and ventricles

endocardium
: innermost layer of the heart lining the heart chambers and heart valves; composed of endothelium reinforced with a thin layer of connective tissue that binds to the myocardium

endothelium
: layer of smooth, simple squamous epithelium that lines the endocardium and blood vessels

epicardium
innermost layer of the serous pericardium and the outermost layer of the heart wall

foramen ovale
opening in the fetal heart that allows blood to flow directly from the right atrium to the left atrium, bypassing the fetal pulmonary circuit

fossa ovalis
oval-shaped depression in the interatrial septum that marks the former location of the foramen ovale

hypertrophic cardiomyopathy
pathological enlargement of the heart, generally for no known reason

inferior vena cava
large systemic vein that returns blood to the heart from the inferior portion of the body

interatrial septum
cardiac septum located between the two atria; contains the fossa ovalis after birth

interventricular septum
cardiac septum located between the two ventricles

mitral valve
(also, left atrioventricular valve or bicuspid valve) valve located between the left atrium and ventricle; consists of two flaps of tissue

mesothelium
simple squamous epithelial portion of serous membranes, such as the superficial portion of the epicardium (the visceral pericardium) and the deepest portion of the pericardium (the parietal pericardium)

mitral valve
(also, left atrioventricular valve or bicuspid valve) valve located between the left atrium and ventricle; consists of two flaps of tissue

moderator band
band of myocardium covered by endocardium that arises from the inferior portion of the interventricular septum in the right ventricle and crosses to the anterior papillary muscle; contains conductile fibers that carry electrical signals followed by contraction of the heart

myocardium
thickest layer of the heart composed of cardiac muscle cells built upon a framework of primarily collagenous fibers and blood vessels that supply it and the nervous fibers that help to regulate it

papillary muscle
extension of the myocardium in the ventricles to which the chordae tendineae attach

pectinate muscles
muscular ridges seen on the anterior surface of the right atrium

pericardial cavity
cavity surrounding the heart filled with a lubricating serous fluid that reduces friction as the heart contracts

pericardial sac
(also, pericardium) membrane that separates the heart from other mediastinal structures; consists of two distinct, fused sublayers: the fibrous pericardium and the parietal pericardium

pericardium
(also, pericardial sac) membrane that separates the heart from other mediastinal structures; consists of two distinct, fused sublayers: the fibrous pericardium and the parietal pericardium

posterior interventricular sulcus
sulcus located between the left and right ventricles on the anterior surface of the heart

pulmonary arteries
left and right branches of the pulmonary trunk that carry deoxygenated blood from the heart to each of the lungs

pulmonary capillaries
capillaries surrounding the alveoli of the lungs where gas exchange occurs: carbon dioxide exits the blood and oxygen enters

pulmonary circuit
blood flow to and from the lungs

pulmonary trunk
large arterial vessel that carries blood ejected from the right ventricle; divides into the left and right pulmonary arteries

pulmonary valve
(also, pulmonary semilunar valve, the pulmonic valve, or the right semilunar valve) valve at the base of the pulmonary trunk that prevents backflow of blood into the right ventricle; consists of three flaps

pulmonary veins
veins that carry highly oxygenated blood into the left atrium, which pumps the blood into the left ventricle, which in turn pumps oxygenated blood into the aorta and to the many branches of the systemic circuit

right atrioventricular valve
(also, tricuspid valve) valve located between the right atrium and ventricle; consists of three flaps of tissue

semilunar valves
valves located at the base of the pulmonary trunk and at the base of the aorta

septum
(plural = septa) walls or partitions that divide the heart into chambers

septum primum
flap of tissue in the fetus that covers the foramen ovale within a few seconds after birth

sulcus
(plural = sulci) fat-filled groove visible on the surface of the heart; coronary vessels are also located in these areas

superior vena cava
large systemic vein that returns blood to the heart from the superior portion of the body

systemic circuit
blood flow to and from virtually all of the tissues of the body

trabeculae carneae
ridges of muscle covered by endocardium located in the ventricles

tricuspid valve
term used most often in clinical settings for the right atrioventricular valve

valve
in the cardiovascular system, a specialized structure located within the heart or vessels that ensures one-way flow of blood

ventricle
one of the primary pumping chambers of the heart located in the lower portion of the heart; the left ventricle is the major pumping chamber on the lower left side of the heart that ejects blood into the systemic circuit via the aorta and receives blood from the left atrium; the right ventricle is the major pumping chamber on the lower right side of the heart that ejects blood into the pulmonary circuit via the pulmonary trunk and receives blood from the right

atrium

Contributors and Attributions

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Answers

INTERACTIVE LINK

Answer

The pressure gradient between the atria and the ventricles is much greater than that between the ventricles and the pulmonary trunk and aorta. Without the presence of the chordae tendineae and papillary muscles, the valves would be blown back (prolapsed) into the atria and blood would regurgitate.

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17.3: Cardiac Muscle and Electrical Activity

By the end of this section, you will be able to:

- Describe the structure of cardiac muscle tissue and cells
- Identify and describe the components of the conducting system that distributes electrical impulses through the heart

Recall that cardiac muscle shares a few characteristics with both skeletal muscle and smooth muscle, but it has some unique properties of its own. Not the least of these exceptional properties is its ability to initiate an electrical potential at a fixed rate that spreads rapidly from cell to cell to trigger the contractile mechanism. This property is known as **autorhythmicity**. Skeletal muscle can not do this. Even though cardiac muscle has autorhythmicity, heart rate is modulated by the endocrine and nervous systems.

Structure of Cardiac Muscle Tissue and Cells

Compared to the giant cylinders of skeletal muscle, cardiac muscle cells, or cardiomyocytes, are considerably shorter with much smaller diameters. Cardiac muscle also demonstrates striations, the alternating pattern of dark A bands and light I bands attributed to the precise arrangement of the myofilaments and fibrils that are organized in sarcomeres along the length of the cell (Figure 17.3.1.a). These contractile elements are virtually identical to skeletal muscle. T (transverse) tubules penetrate from the surface plasma membrane, the sarcolemma, to the interior of the cell, allowing the electrical impulse to reach the interior. The T tubules are only found at the Z discs, whereas in skeletal muscle, they are found at the junction of the A and I bands. Therefore, there are one-half as many T tubules in cardiac muscle as in skeletal muscle. In addition, the sarcoplasmic reticulum of cardiomyocytes stores few calcium ions, so most of the calcium ions must come from outside the cells. The result is a slower onset of contraction. Mitochondria are plentiful, providing energy for the cross-bridge cycling responsible for contractions of the heart. Typically, cardiomyocytes have a single, central nucleus, but two or more nuclei may be found in some cells. Cardiac muscle undergoes aerobic respiration patterns, primarily metabolizing lipids and carbohydrates. Myoglobin, lipids, and glycogen are all stored within the cytoplasm.

Cardiac muscle cells branch freely. A junction between two adjoining cells is marked by a critical structure called an **intercalated disc**, which helps support the synchronized contraction of the muscle and structurally links the cells together (Figure 17.3.1). Intercalated discs are formed by regions of sarcolemma with specialized integral membrane proteins. These form desmosomes, fasciae adherens, and large numbers of gap junctions. Desmosomes and fasciae adherens anchor the cells together. Fasciae adherens also anchor actin filaments of the sarcomere directly to the sarcolemma. Gap junctions allow the passage of ions from cell-to-cell through their sarcoplasm, a feature essential to producing synchronized contractions (Figure 17.3.1.c). Intercellular connective tissue also helps to bind the cells together. The importance of strongly binding these cells together is necessitated by the forces exerted by contraction; unlike skeletal muscle in which cells are the length of the organ to pull collectively on a bone via collagenous connective tissue attachments, smaller cardiac muscle cells pull on each other and ultimately on the dense connective tissue of the cardiac skeleton when they contract.

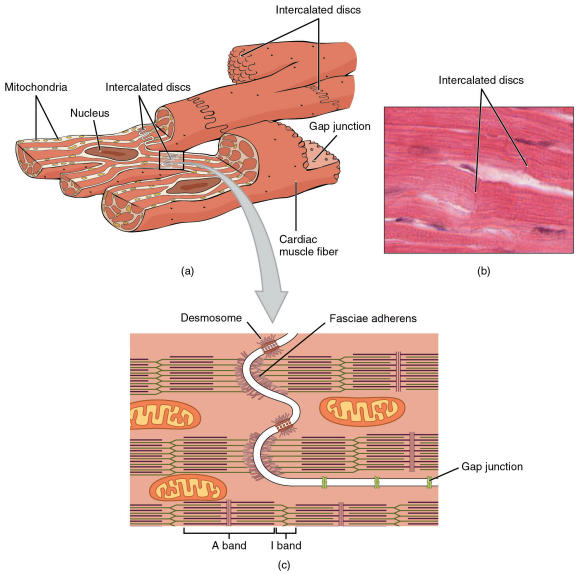

Figure 17.3.1: Cardiac Muscle. (a) Cardiac muscle cells have myofibrils composed of myofilaments arranged in sarcomeres, T tubules to transmit the impulse from the sarcolemma to the interior of the cell, numerous mitochondria for energy, and intercalated discs that are found at the junction of different cardiac muscle cells. (b) A photomicrograph of cardiac muscle cells shows the nuclei and intercalated discs. LM × 1600. (c) An intercalated disc connects cardiac muscle cells and consists of desmosomes, fasciae adherens, and gap junctions. (Image credit: "Cardiac Muscle" by Julie Jenks is licensed under CC BY 4.0 / A derivative from the original work / Micrograph provided by the Regents of the University of Michigan Medical School © 2012)

There are two major types of cardiac muscle cells: myocardial contractile cells and myocardial conducting cells. The **myocardial contractile cells** constitute the bulk (99 percent) of the cells in the myocardium of the atria and ventricles. Myocardial contractile cells are autorhythmic, but they are primarily responsible for the strong, synchronized contractions necessary to pump blood through the body. The **myocardial conducting cells** (1 percent of the cells) are generally much smaller than the contractile cells and have fewer myofibrils for contraction. Myocardial conducting cells are specialized to initiate and propagate the electrical activity that travels throughout the heart and triggers the contractions of the myocardial contractile cells that propel the blood. If embryonic heart cells are separated into a Petri dish and kept alive, each is capable of generating its own electrical impulse (also referred to as a wave of depolarization or an action potential) that is followed by contraction (the capability that is described as autorhythmicity). When two independently beating embryonic cardiac muscle cells are placed together, the cell with the faster inherent rate sets the pace, and the impulse spreads from the faster to the slower cell to trigger a contraction in such rapid succession that they appear to contract in unison. As more cells are joined together, the fastest cell continues to assume control of the rate. A fully developed adult heart maintains the capability to generate its own electrical activity, triggered by the fastest cells. The fastest cells are the myocardial conducting cells. The slower cells (which are also stronger) are the myocardial contractile cells.

EVERYDAY CONNECTION

Repair and Replacement of Cardiac Muscle

Damaged cardiac muscle cells have extremely limited abilities to repair themselves or to replace dead cells via mitosis. Recent evidence indicates that at least some stem cells remain within the heart that continue to divide and at least potentially replace these dead cells. However, newly formed or repaired cells are rarely as functional as the original cells, and cardiac function is reduced. In the event of a heart attack or myocardial infarction (MI), dead cells are often replaced by patches of scar tissue in a process called fibrosis. Autopsies performed on individuals who had successfully received heart transplants show some proliferation of original cells. If researchers can unlock the mechanism that generates new cells and restore full mitotic capabilities to heart muscle, the prognosis for heart attack survivors will be greatly enhanced. To date, myocardial cells produced within the patient (*in situ*) by cardiac stem cells seem to be nonfunctional, although those grown in Petri dishes (*in vitro*) do beat. Perhaps soon this mystery will be solved, and new advances in treatment will be commonplace.

Conducting System of the Heart

The myocardial conducting cells are concentrated in specific areas of the heart that make up the Conducting System. The components of the cardiac conducting system include the sinoatrial node, the atrioventricular node, the atrioventricular bundle, the atrioventricular bundle branches, and the Purkinje fibers (Figure 17.3.2).

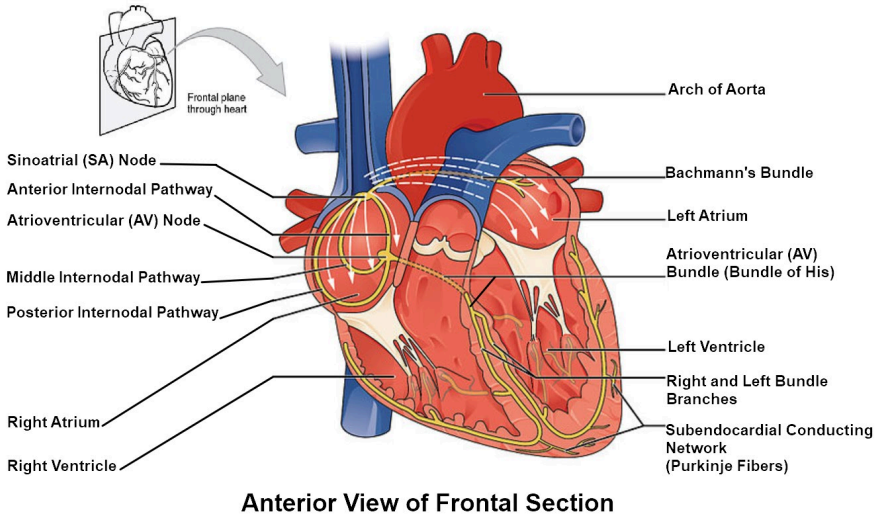

Figure 17.3.2: Conducting System of the Heart. Specialized conducting components of the heart include the sinoatrial node, the internodal pathways, the atrioventricular node, the atrioventricular bundle, the right and left bundle branches, and the Purkinje fibers. (Image credit: "Conducting System of the Heart" by Julie Jenks is licensed under CC BY 4.0 / A derivative from the original work)

Sinoatrial (SA) Node

Normal cardiac rhythm is established by the **sinoatrial (SA) node**, a specialized clump of myocardial conducting cells located in the posterosuperior walls of the right atrium in close proximity to the orifice of the superior vena cava. The myocardial conducting cells of the SA node have the highest inherent rate of electrical signal initiation, so the SA node is known as the **pacemaker** of the heart. It initiates the **sinus rhythm**, or normal electrical pattern followed by contraction of the heart.

This impulse spreads from its initiation in the SA node throughout the atria through specialized **internodal pathways**, to the atrial myocardial contractile cells and the atrioventricular node. The internodal pathways consist of three bands (anterior, middle, and posterior) of myocardial conducting cells that lead directly from the SA node to the next node in the conducting system, the atrioventricular node (see Figure 17.3.2). The impulse takes approximately 50 ms (milliseconds, thousandths of a second) to travel between these two nodes. The relative importance of this pathway has been debated since the impulse would reach the atrioventricular node simply following the cell-by-cell pathway through the contractile cells of the myocardium in the atria. In addition, there is a specialized pathway called **Bachmann's bundle** or the **interatrial band** that conducts the impulse directly from the right atrium to the left atrium. Regardless of the pathway, as the impulse reaches the atrioventricular septum, the insulating connective tissue of the cardiac skeleton prevents the impulse from spreading into the myocardial cells in the ventricles except at the atrioventricular node. Figure 17.3.3 illustrates the initiation of the impulse in the SA node that then spreads the impulse throughout the atria to the atrioventricular node.

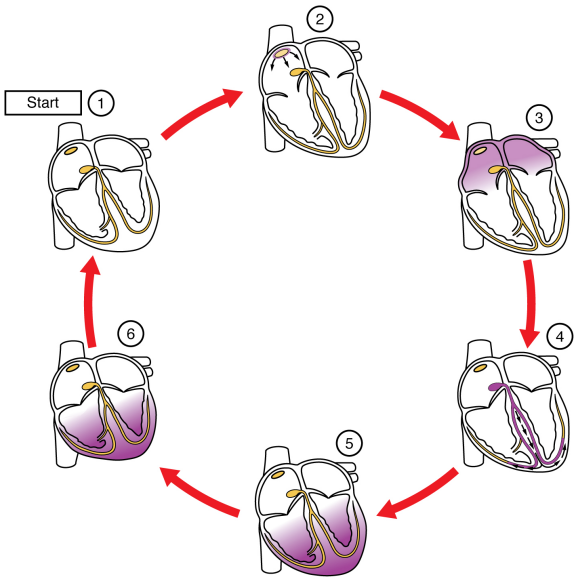

Figure 17.3.3: Cardiac Conduction. (1) The sinoatrial (SA) node and the remainder of the conducting system are at rest. (2) The SA node initiates the action potential, which sweeps across the atria. (3) After reaching the atrioventricular node, there is a delay of approximately 100 ms that allows the atria to complete pumping blood before the impulse is transmitted to the atrioventricular bundle. (4) Following the delay, the impulse travels through the atrioventricular bundle and bundle branches to the Purkinje fibers, and also reaches the right papillary muscle via the moderator band. (5) The impulse spreads to the contractile fibers of the ventricle. (6) Ventricular contraction begins. (Image credit: "Cardiac Conduction" by OpenStax is licensed under CC BY 3.0)

The electrical event (the wave of electrical signal) spreads the signal through the conducting system, but it is also the trigger for muscular contraction of the atria. The wave of electrical signal begins in the right atrium, and the impulse spreads across the superior portions of both atria and then down through the contractile cells. The contractile cells then begin contraction from the superior to the inferior portions of the atria, efficiently pumping blood into the ventricles.

Atrioventricular (AV) Node

The **atrioventricular (AV) node** is a second clump of specialized myocardial conducting cells, located in the inferior portion of the right atrium within the atrioventricular septum. The septum contains the dense irregular connective tissue of the cardiac skeleton that prevents the impulse from spreading directly to the ventricles without passing through the AV node. There is a critical pause before the AV node activates and transmits the electrical impulse to the atrioventricular bundle (see Figure 17.3.3, step 3). This delay in transmission is partially attributable to the small diameter of the cells of the node, which slow the impulse. Also, conduction between nodal cells is less efficient than between conducting cells. These factors mean that it takes the impulse approximately 100 ms to pass through the node. This pause is critical to heart function, as it allows the atrial cardiomyocytes to complete their contraction that pumps blood into the ventricles before the impulse is transmitted to the cells of the ventricle itself. With extreme stimulation by the SA node, the AV node can transmit impulses maximally at 220 per minute. This establishes the typical maximum heart rate in a healthy young individual. Damaged hearts or those stimulated by drugs can contract at higher rates, but at these rates, the heart can no longer effectively pump blood.

Atrioventricular Bundle (Bundle of His), Bundle Branches, and Subendocardial Conducting Network (Purkinje Fibers)

Arising from the AV node, the **atrioventricular bundle**, or **bundle of His**, proceeds into the interventricular septum before dividing into two **atrioventricular bundle branches**, commonly called the left and right bundle branches. The left bundle branch supplies the left ventricle, and the right bundle branch the right ventricle. Since the left ventricle is much larger than the right, the left bundle branch is also considerably larger than the right. Portions of the right bundle branch are found in the moderator band and supply the right papillary muscles. Because of this connection, each papillary muscle receives the impulse at approximately the same time, so they begin to contract simultaneously just prior to the remainder of the myocardial contractile cells of the ventricles. This is believed to allow tension to develop on the chordae tendineae prior to right ventricular contraction. There is no corresponding moderator band on the left. Both bundle branches descend and reach the apex of the heart where they connect with the subendocardial conducting network, or Purkinje fibers (see Figure 17.3.3, step 4). This passage takes approximately 25

ms.

The **subendocardial conducting network**, or **Purkinje fibers,** are additional myocardial conducting fibers that spread the impulse to the myocardial contractile cells in the ventricles. They extend throughout the myocardium from the apex of the heart toward the atrioventricular septum and the base of the heart at the top of the ventricles. The subendocardial conducting network has a fast inherent conduction rate, and the electrical impulse reaches all of the ventricular muscle cells in about 75 ms (see Figure 17.3.3, step 5). Since the electrical stimulus begins at the apex, the contraction also begins at the apex and travels toward the base of the heart, similar to squeezing a tube of toothpaste from the bottom. This allows the blood to be pumped out of the ventricles and into the aorta and pulmonary trunk. The total time elapsed from the initiation of the impulse in the SA node until initiation of impulse in the ventricles is approximately 225 ms.

Electrocardiogram

By careful placement of surface electrodes on the body, it is possible to record the complex, compound electrical signal of the heart. This tracing of the electrical signal is the **electrocardiogram (ECG)**, also commonly abbreviated EKG (K coming from kardiology, the German spelling of cardiology). Careful analysis of the ECG reveals a detailed picture of both normal and abnormal heart function, and is an indispensable clinical diagnostic tool. The standard electrocardiograph (the instrument that generates an ECG) uses 3, 5, or 12 leads. The greater the number of leads an electrocardiograph uses, the more information the ECG provides. The term “lead” may be used to refer to the cable from the electrode to the electrical recorder, but it typically describes the voltage difference between two of the electrodes. The 12-lead electrocardiograph uses 10 electrodes placed in standard locations on the patient’s skin (Figure 17.3.4). In continuous ambulatory electrocardiographs, the patient wears a small, portable, battery-operated device known as a Holter monitor, or simply a Holter, that continuously monitors heart electrical activity, typically for a period of 24 hours during the patient’s normal routine.

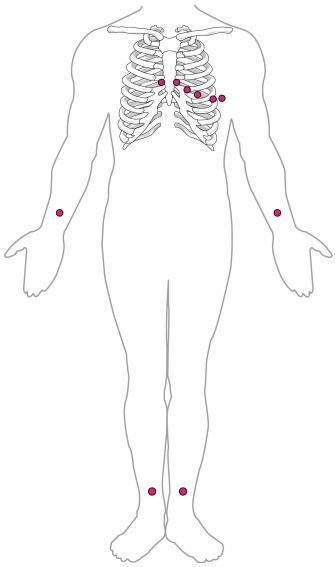

Figure 17.3.4: Standard Placement of ECG Leads. In a 12-lead ECG, six electrodes are placed on the chest, and four electrodes are placed on the limbs. (Image credit: "ECG Placement of Electrodes" by OpenStax is licensed under CC BY 3.0)

The ECG measures and graphs electrical activity over the time of each cardiac cycle that visually represents the spread of the electrical impulse through the conducting system (Figure 17.3.5). The spread of electrical impulse from the SA node that initiates the cardiac cycle and causes atrial systole is visible in the P wave. The spread of electrical impulse from the AV node through the AV bundle and bundle branches is visible as the portion of the ECG with the largest amplitude (height), the QRS complex. The T wave (and a portion of the QRS complex) measure the electrical activity associated with repolarization, the physiological reset required to prepare for the next cardiac cycle.

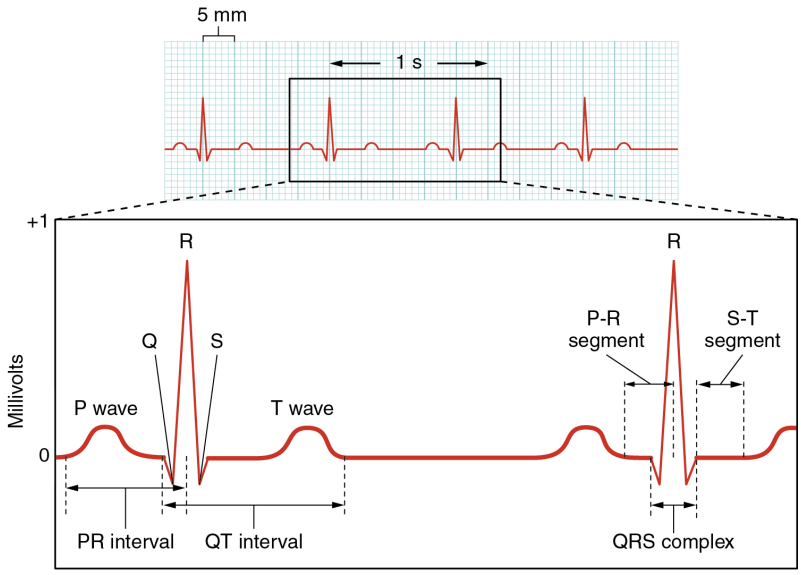

Figure 17.3.5: Electrocardiogram. A normal tracing shows the P wave, QRS complex, and T wave. Also indicated are the PR, QT, QRS, and ST intervals, plus the P-R and S-T segments. (Image credit: "Electrocardiogram" by OpenStax is licensed under CC BY 3.0)

EVERYDAY CONNECTION

ECG Abnormalities

Occasionally, an area of the heart other than the SA node will initiate an impulse that will be followed by a premature contraction. Such an area, which may actually be a component of the conducting system or some other contractile cells, is known as an ectopic focus or ectopic pacemaker. An ectopic focus may be stimulated by localized ischemia (reduced blood flow to an area, depriving it of nutrients); exposure to certain drugs, including caffeine, digitalis, or acetylcholine; elevated stimulation by both sympathetic or parasympathetic divisions of the autonomic nervous system; or a number of disease or pathological conditions. Occasional occurrences are generally transitory and nonlife-threatening, but if the condition becomes chronic, it may lead to either an arrhythmia, a deviation from the normal pattern of impulse conduction and contraction, or to fibrillation, an uncoordinated beating of the heart.

While interpretation of an ECG is possible and extremely valuable after some training, a full understanding of the complexities and intricacies generally requires several years of experience. In general, the size of the electrical variations, the duration of the events, and detailed vector analysis provide the most comprehensive picture of cardiac function. For example, an amplified P wave may indicate enlargement of the atria, an enlarged Q wave may indicate a myocardial infarction (MI, heart attack), and an enlarged suppressed or inverted Q wave often indicates enlarged ventricles. T waves often appear flatter when insufficient oxygen is being delivered to the myocardium. An elevation of the ST segment above baseline is often seen in patients with an acute MI, and may appear depressed below the baseline when hypoxia is occurring.

As useful as analyzing these electrical recordings may be, there are limitations. For example, not all areas suffering a MI may be obvious on the ECG. Additionally, it will not reveal the effectiveness of the pumping, which requires further testing, such as an ultrasound test called an echocardiogram or nuclear medicine imaging. It is also possible for there to be pulseless electrical activity, which will show up on an ECG tracing, although there is no corresponding pumping action. Common abnormalities that may be detected by the ECGs are shown in Figure 17.3.6.

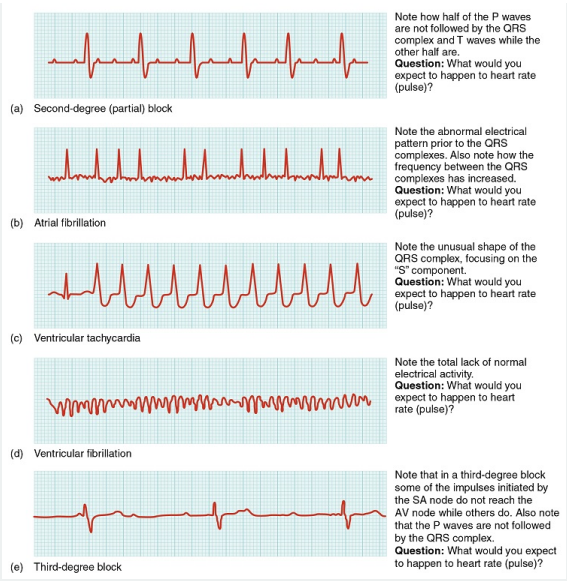

Figure 17.3.6: Common ECG Abnormalities. (a) In a second-degree or partial block, one-half of the P waves are not followed by the QRS complex and T waves while the other half are. (b) In atrial fibrillation, the electrical pattern is abnormal prior to the QRS complex, and the frequency between the QRS complexes has increased. (c) In ventricular tachycardia, the shape of the QRS complex is abnormal. (d) In ventricular fibrillation, there is no normal electrical activity. (e) In a third-degree block, there is no correlation between atrial activity (the P wave) and ventricular activity (the QRS complex). (Image credit: "Cardiac Arrhythmias" by OpenStax is licensed under CC BY 3.0)

EVERYDAY CONNECTION

Automated External Defibrillators (AEDs)

In the event that the electrical activity of the heart is severely disrupted, cessation of electrical activity or fibrillation may occur. In fibrillation, the heart beats in a wild, uncontrolled manner, which prevents it from being able to pump effectively. Atrial fibrillation (see Figure 17.3.6.b) is a serious condition, but as long as the ventricles continue to pump blood, the patient's life may not be in immediate danger. Ventricular fibrillation (see Figure 17.3.6.d) is a medical emergency that requires life support, because the ventricles are not effectively pumping blood. In a hospital setting, it is often described as "code blue." If untreated for as little as a few minutes, ventricular fibrillation may lead to brain death. The most common treatment is defibrillation, which uses special paddles to apply a charge to the heart from an external electrical source in an attempt to establish a normal sinus rhythm (Figure 17.3.7). A defibrillator effectively stops the heart so that the SA node can trigger a normal conduction cycle. Because of their effectiveness in reestablishing a normal sinus rhythm, external automated defibrillators (EADs) are being placed in areas frequented by large numbers of people, such as schools, restaurants, and airports. These devices contain simple and direct verbal instructions that can be followed by nonmedical personnel in an attempt to save a life.

(a)

(b)

Figure 17.3.7: Defibrillators. (a) An external automatic defibrillator can be used by nonmedical personnel to reestablish a normal sinus rhythm in a person with fibrillation. (b) Defibrillator paddles are more commonly used in hospital settings. (Image credit: "Defibrillators" by OpenStax is licensed under CC BY 4.0 / (b) is a derivative of the original work)

Disorders of the Conducting System

A **heart block** refers to an interruption in the normal conduction pathway. The nomenclature for these is very straightforward. SA nodal blocks occur within the SA node. AV nodal blocks occur within the AV node. Infra-Hisian blocks involve the bundle of His. Bundle branch blocks occur within either the left or right atrioventricular bundle branches. Hemiblocks are partial and occur within one or more fascicles of the atrioventricular bundle branch. Clinically, the most common types are the AV nodal and infra-Hisian blocks.

AV blocks are often described by degrees. A first-degree or partial block indicates a delay in conduction between the SA and AV nodes. This can be recognized on the ECG as an abnormally long PR interval. A second-degree or incomplete block occurs when some impulses from the SA node reach the AV node and continue, while others do not. In this instance, the ECG would reveal some P waves not followed by a QRS complex, while others would appear normal. In the third-degree or complete block, there is no correlation between atrial activity (the P wave) and ventricular activity (the QRS complex). Even in the event of a total SA block, the AV node will assume the role of pacemaker and continue initiating contractions at 40–60 contractions per minute, which is adequate to maintain consciousness. Second- and third-degree blocks are demonstrated on the ECG presented in Figure 17.3.6.

When arrhythmias become a chronic problem, the heart maintains a junctional rhythm, which originates in the AV node. In order to speed up the heart rate and restore full sinus rhythm, a cardiologist can implant an **artificial pacemaker**, which delivers electrical impulses to the heart muscle to ensure that the heart continues to contract and pump blood effectively. These artificial pacemakers are programmable by the cardiologists and can either provide stimulation temporarily upon demand or on a continuous basis. Some devices also contain built-in defibrillators.

Heart Rates

Heart rates (HRs) vary considerably, not only with exercise and fitness levels, but also with age. Newborn resting HRs may be 120 bpm. Resting HR gradually decreases until young adulthood and then gradually increases again with age.

Maximum HRs are normally in the range of 200–220 bpm, although there are some extreme cases in which they may reach higher levels. As one ages, the ability to generate maximum rates decreases. This may be estimated by taking the maximal value of 220 bpm and subtracting the individual's age. So a 40-year-old individual would be expected to hit a maximum rate of approximately 180 bpm, and a 60-year-old person would achieve 160 bpm.

Heart rate is adjusted by chemical signals from the endocrine system as well as nervous signals that emerge from the medulla oblongata in the brainstem and travel to the heart via the vagus nerve (parasympathetic nervous system) to slow down the heart

rate or via the sympathetic cardiac nerve (sympathetic nervous system) to speed up the heart rate. Both nerve pathways send branches to both the SA and AV nodes, and the sympathetic nervous system also sends neurons to portions of both the atria and ventricles. Without any nervous stimulation, the SA node would establish a sinus rhythm of approximately 100 bpm. Since resting rates are considerably less than this, it becomes evident that parasympathetic stimulation normally slows HR. Reducing the parasympathetic stimulation allows the heart rate to approach 100 bpm. Increasing the heart rate above 100 bpm involves sympathetic stimulation.

DISORDERS OF THE...

Heart: Abnormal Heart Rates

For an adult, normal resting HR will be in the range of 60–100 bpm. Bradycardia is the condition in which resting rate drops below 60 bpm, and tachycardia is the condition in which the resting rate is above 100 bpm. Trained athletes typically have very low HRs. If the patient is not exhibiting other symptoms, such as weakness, fatigue, dizziness, fainting, chest discomfort, palpitations, or respiratory distress, bradycardia is not considered clinically significant. However, if any of these symptoms are present, they may indicate that the heart is not providing sufficient oxygenated blood to the tissues. The term relative bradycardia may be used with a patient who has a HR in the normal range but is still suffering from these symptoms. Most patients remain asymptomatic as long as the HR remains above 50 bpm.

Bradycardia may be caused by either inherent factors or causes external to the heart. While the condition may be inherited, typically it is acquired in older individuals. Inherent causes include abnormalities in either the SA or AV node. If the condition is serious, a pacemaker may be required. Other causes include ischemia to the heart muscle or diseases of the heart vessels or valves. External causes include metabolic disorders, pathologies of the endocrine system often involving the thyroid, electrolyte imbalances, neurological disorders including inappropriate autonomic responses, autoimmune pathologies, over-prescription of beta blocker drugs that reduce HR, recreational drug use, or even prolonged bed rest. Treatment relies upon establishing the underlying cause of the disorder and may necessitate supplemental oxygen.

Tachycardia is not normal in a resting patient but may be detected in pregnant women or individuals experiencing extreme stress. In the latter case, it would likely be triggered by stimulation from the limbic system or disorders of the autonomic nervous system. In some cases, tachycardia may involve only the atria. Some individuals may remain asymptomatic, but when present, symptoms may include dizziness, shortness of breath, lightheadedness, rapid pulse, heart palpitations, chest pain, or fainting (syncope). While tachycardia is defined as a HR above 100 bpm, there is considerable variation among people. Further, the normal resting HRs of children are often above 100 bpm, but this is not considered to be tachycardia. Many causes of tachycardia may be benign, but the condition may also be correlated with fever, anemia, hypoxia, hyperthyroidism, hypersecretion of catecholamines, some cardiomyopathies, some disorders of the valves, and acute exposure to radiation. Elevated rates in an exercising or resting patient are normal and expected. Resting rate should always be taken after recovery from exercise. Treatment depends upon the underlying cause but may include medications, implantable cardioverter defibrillators, ablation, or surgery.

Concept Review

The heart is regulated by both neural and endocrine control, yet it initiates its own electrical impulse at an intrinsic rate followed by muscular contraction. The myocardial conducting cells within the heart establish the heart rate and transmit it through the myocardium. The myocardial contractile cells contract and propel the blood. The normal path of transmission for the conductive cells is the sinoatrial (SA) node, internodal pathways, atrioventricular (AV) node, atrioventricular (AV) bundle, bundle branches, and Purkinje fibers. Normal resting heart rate is in the range of 60 to 100 bpm.

Review Questions

Q. Which of the following distinguishes cardiac muscle cells from skeletal muscle cells?

A. Only cardiac muscle contains a sarcoplasmic reticulum.

B. Only cardiac muscle has striations.

C. Only cardiac muscle is capable of autorhythmicity.

D. Only cardiac muscle has a high concentration of mitochondria.

Answer

Answer: C

Q. Which component of the heart's conducting system would have the slowest rate of firing?

A. atrioventricular node

B. atrioventricular bundle

C. bundle branches

D. subendocardial conducting network

Answer

Answer: D

Critical Thinking Questions

Q. How does the delay of the impulse at the atrioventricular node contribute to cardiac function?

Answer

A. It ensures sufficient time for the atrial muscle to contract and pump blood into the ventricles prior to the impulse being conducted into the lower chambers.

Q. How do intercalated discs aid contraction of the heart?

Answer

A. Intercalated discs consist of desmosomes, fasciae adherens, and gap junctions. Desmosomes and fasciae adherens create strong connections between adjacent cardiac muscle cells that will contract against one another. Gap junctions within the intercalated discs allow impulses to spread from one cardiac muscle cell to another, allowing ions to flow between adjacent cells, propagating the electrical impulse to contract, and ensuring coordinated contractions.

Q. Why is it important that the conducting system initiates ventricular systole from the apex of the heart?

Answer

A. Initiation of ventricular systole at the apex of heart allows the blood to be squeezed from the bottom-up toward the semilunar valves into the ascending aorta and pulmonary trunk.

Glossary

artificial pacemaker
medical device that transmits electrical signals to the heart to ensure that it contracts and pumps blood to the body

atrioventricular bundle
(also, bundle of His) group of specialized myocardial conductile cells that transmit the impulse from the AV node through the interventricular septum; form the left and right atrioventricular bundle branches

atrioventricular bundle branches
(also, left or right bundle branches) specialized myocardial conductile cells that arise from the bifurcation of the atrioventricular bundle and pass through the interventricular septum; lead to the Purkinje fibers and also to the

right papillary muscle via the moderator band

atrioventricular (AV) node
clump of myocardial cells located in the inferior portion of the right atrium within the atrioventricular septum; receives the impulse from the SA node, pauses, and then transmits it into specialized conducting cells within the interventricular septum

autorhythmicity
ability of cardiac muscle to initiate its own electrical impulse that triggers the mechanical contraction that pumps blood at a fixed pace without nervous or endocrine control

Bachmann's bundle
(also, interatrial band) group of specialized conducting cells that transmit the impulse directly from the SA node in the right atrium to the left atrium

bundle of His
(also, atrioventricular bundle) group of specialized myocardial conductile cells that transmit the impulse from the AV node through the interventricular septum; form the left and right atrioventricular bundle branches

electrocardiogram (ECG)
surface recording of the electrical activity of the heart that can be used for diagnosis of irregular heart function; also abbreviated as EKG

heart block
interruption in the normal conduction pathway

interatrial band
(also, Bachmann's bundle) group of specialized conducting cells that transmit the impulse directly from the SA node in the right atrium to the left atrium

intercalated disc
physical junction between adjacent cardiac muscle cells; consisting of desmosomes, specialized linking proteoglycans, and gap junctions that allow passage of ions between the two cells

internodal pathways
specialized conductile cells within the atria that transmit the impulse from the SA node throughout the myocardial cells of the atrium and to the AV node

myocardial conducting cells
specialized cells that transmit electrical impulses throughout the heart and trigger contraction by the myocardial contractile cells

myocardial contractile cells
bulk of the cardiac muscle cells in the atria and ventricles that conduct impulses and contract to propel blood

P wave
component of the electrocardiogram that represents the initiation of electrical signal of the atria

pacemaker
cluster of specialized myocardial cells known as the SA node that initiates the sinus rhythm

Purkinje fibers
(also, subendocardial conducting network) specialized myocardial conducting fibers that arise from the bundle branches and spread the impulse to the myocardial contraction fibers of the ventricles

QRS complex
component of the electrocardiogram that represents the initiation of electrical signal of the ventricles

sinoatrial (SA) node
known as the pacemaker, a specialized clump of myocardial conducting cells located in the superior portion of the right atrium that has the highest inherent rate of depolarization that then spreads throughout the heart

sinus rhythm
: normal contractile pattern of the heart

subendocardial conducting network
: (also, Purkinje fibers) specialized myocardial conducting fibers that arise from the bundle branches and spread the impulse to the myocardial contraction fibers of the ventricles

T wave
: component of the electrocardiogram that represents the repolarization of the ventricles

Contributors and Attributions

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17.4: Coronary Circulation

By the end of this section, you will be able to:

- Identify the veins and arteries of the coronary circulation system
- Describe how atherosclerosis impacts blood flow in coronary arteries

You will recall that the heart is a remarkable pump composed largely of cardiac muscle cells that are incredibly active throughout life. Like all other cells, a **cardiomyocyte** requires a reliable supply of oxygen and nutrients, and a way to remove wastes, so it needs a dedicated, complex, and extensive coronary circulation. And because of the critical and nearly ceaseless activity of the heart throughout life, this need for a blood supply is even greater than for a typical cell. However, coronary circulation is not continuous; rather, it cycles, reaching a peak when the heart muscle is relaxed and nearly ceasing while it is contracting.

Coronary Arteries

Coronary arteries supply blood to the myocardium and other components of the heart. The first portion of the aorta after it arises from the left ventricle gives rise to the coronary arteries. There are three dilations in the wall of the aorta just superior to the aortic semilunar valve. Two of these, the left posterior aortic sinus and anterior aortic sinus, give rise to the left and right coronary arteries, respectively. The third sinus, the right posterior aortic sinus, typically does not give rise to a vessel. Coronary vessel branches that remain on the surface of the heart and follow the sulci are called **epicardial coronary arteries**.

The left coronary artery distributes blood to the left side of the heart, the left atrium and ventricle, and the interventricular septum. It runs posterior to the pulmonary trunk and almost immediately branches into two vessels: the circumflex and anterior interventricular arteries. The **circumflex artery** follows the coronary sulcus to the left and eventually fuses with the small branches of the right coronary artery. The larger **anterior interventricular artery**, also known as the left anterior descending artery (LAD), follows the anterior interventricular sulcus around the pulmonary trunk. Along the way it gives rise to numerous smaller branches that interconnect with the branches of the posterior interventricular artery, forming anastomoses. An **anastomosis** is an area where vessels unite to form interconnections that normally allow blood to circulate to a region even if there may be partial blockage in another branch. The anastomoses in the heart are very small. Therefore, this ability is somewhat restricted in the heart so a coronary artery blockage often results in death of the cells (myocardial infarction) supplied by the particular vessel.

The right coronary artery proceeds along the coronary sulcus and distributes blood to the right atrium, portions of both ventricles, and the cardiac conducting system. Normally, one or more marginal arteries arise from the right coronary artery inferior to the right atrium. The **marginal arteries** supply blood to the superficial portions of the right ventricle. On the posterior surface of the heart, the right coronary artery abruptly dips inferiorly and becomes the **posterior interventricular artery**, also known as the posterior descending artery. It runs along the posterior portion of the interventricular sulcus toward the apex of the heart, giving rise to branches that supply the posterior aspects of the interventricular septum and portions of both ventricles. Figure 17.4.1 presents the major vessels of coronary circulation from both the anterior and posterior views.

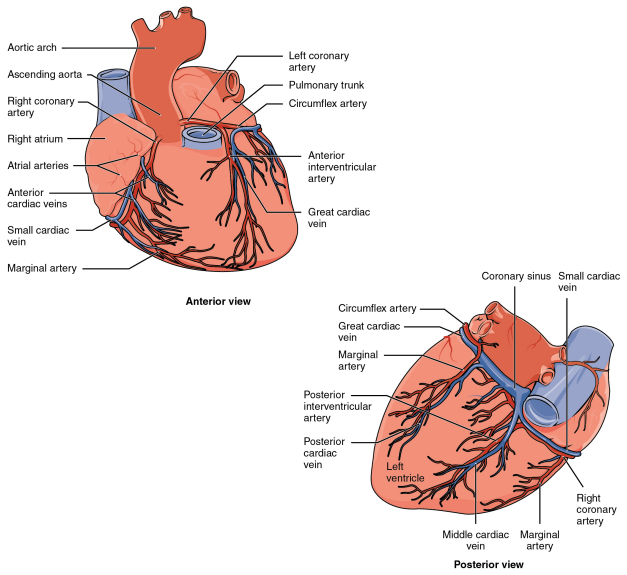

Figure 17.4.1: Coronary Circulation. The anterior view of the heart shows the prominent coronary surface vessels. The posterior view of the heart shows the prominent coronary surface vessels. (Image credit: "Coronary Blood Vessels" by OpenStax is licensed under CC BY 3.0)

DISORDERS OF THE...

Heart: Coronary Artery Disease

Coronary artery disease is the leading cause of death worldwide. It occurs when the buildup of plaque—a fatty material including cholesterol, connective tissue, white blood cells, and some smooth muscle cells—within the walls of the arteries obstructs the flow of blood and decreases the flexibility or compliance of the vessels. This condition is called atherosclerosis, a hardening of the arteries that involves the accumulation of plaque. As the coronary blood vessels become occluded, the flow of blood to the tissues will be restricted, a condition called ischemia that causes the cells to receive insufficient amounts of oxygen, called hypoxia. Figure 17.4.2 shows the blockage of coronary arteries highlighted by the injection of dye. Some individuals with coronary artery disease report pain radiating from the chest called angina pectoris, but others remain asymptomatic. If untreated, coronary artery disease can lead to MI or a heart attack.

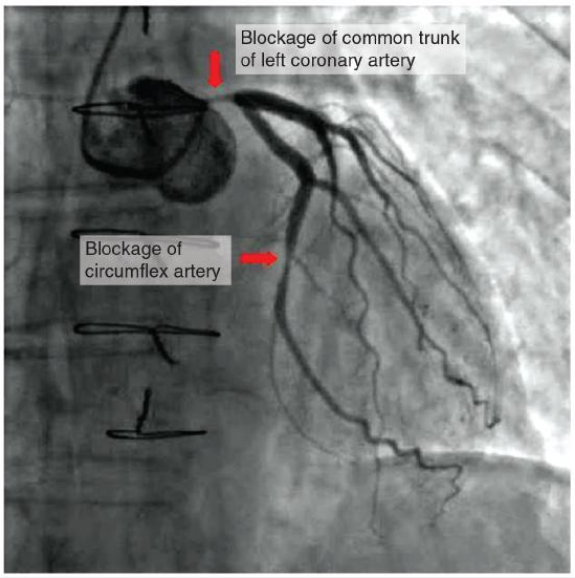

Figure 17.4.2: Atherosclerotic Coronary Arteries. In this coronary angiogram (X-ray), the dye makes visible two occluded coronary arteries, with noticeable narrowing pointed out in the circumflex artery and the common trunk of the left coronary artery. Such blockages can lead to decreased blood flow (ischemia) and insufficient oxygen (hypoxia) delivered to the cardiac tissues. If uncorrected, this can lead to cardiac muscle death (myocardial infarction). (Image credit: "Occluded Coronay Arteries [sic]" by OpenStax is licensed under CC BY 3.0)

The disease progresses slowly and often begins in children and can be seen as fatty “streaks” in the vessels. It then gradually progresses throughout life. Well-documented risk factors include smoking, family history, hypertension, obesity, diabetes, high alcohol consumption, lack of exercise, stress, and hyperlipidemia or high circulating levels of lipids in the blood. Treatments may include medication, changes to diet and exercise, angioplasty with a balloon catheter, insertion of a stent, or coronary bypass procedure.

Angioplasty is a procedure in which the occlusion is mechanically widened with a balloon. A specialized catheter with an expandable tip is inserted into a superficial vessel, normally in the leg, and then directed to the site of the occlusion. At this point, the balloon is inflated to compress the plaque material and to open the vessel to increase blood flow. Then, the balloon is deflated and retracted. A stent consisting of a specialized mesh is typically inserted at the site of occlusion to reinforce the weakened and damaged walls. Stent insertions have been routine in cardiology for more than 40 years.

Coronary bypass surgery may also be performed. This surgical procedure grafts a replacement vessel obtained from another, less vital portion of the body to bypass the occluded area. This procedure is clearly effective in treating patients experiencing a MI, but overall does not increase longevity. Nor does it seem advisable in patients with stable although diminished cardiac capacity since frequently loss of mental acuity occurs following the procedure. Long-term changes to behavior, emphasizing diet and exercise plus a medicine regime tailored to lower blood pressure, lower cholesterol and lipids, and reduce clotting are equally as effective.

DISORDERS OF THE...

Heart: Myocardial Infarction

Myocardial infarction (MI) is the formal term for what is commonly referred to as a heart attack. It normally results from a lack of blood flow (ischemia) and oxygen (hypoxia) to a region of the heart, resulting in death of the cardiac muscle cells. An MI often occurs when a coronary artery is blocked by the buildup of atherosclerotic plaque consisting of lipids, cholesterol and fatty acids, and white blood cells, primarily macrophages. It can also occur when a portion of an unstable atherosclerotic plaque travels through the coronary arterial system and lodges in one of the smaller vessels. The resulting blockage restricts the flow of blood and oxygen to the myocardium and causes death of the tissue. MIs may be triggered by excessive exercise, in which the partially occluded artery is no longer able to pump sufficient quantities of blood, or severe stress, which may induce spasm of the smooth muscle in the walls of the vessel.

In the case of acute MI, there is often sudden pain beneath the sternum (retrosternal pain) called angina pectoris, often radiating down the left arm in males but not in female patients. Until this anomaly between the sexes was discovered, many female patients suffering MIs were misdiagnosed and sent home. In addition, patients typically present with difficulty breathing and shortness of breath (dyspnea), irregular heartbeat (palpitations), nausea and vomiting, sweating (diaphoresis), anxiety, and fainting (syncope), although not all of these symptoms may be present. Many of the symptoms are shared with other medical conditions, including anxiety attacks and simple indigestion, so differential diagnosis is critical. It is estimated that between 22 and 64 percent of MIs present without any symptoms.

An MI can be confirmed by examining the patient’s ECG, which frequently reveals alterations in the ST and Q components. Some classification schemes of MI are referred to as ST-elevated MI (STEMI) and non-elevated MI (non-STEMI). In addition, echocardiography or cardiac magnetic resonance imaging may be employed. Common blood tests indicating an MI include elevated levels of creatine kinase MB (an enzyme that catalyzes the conversion of creatine to phosphocreatine, consuming ATP) and cardiac troponin (the regulatory protein for muscle contraction), both of which are released by damaged cardiac muscle cells.

Immediate treatments for MI are essential and include administering supplemental oxygen, aspirin that helps to break up clots, and nitroglycerine administered sublingually (under the tongue) to facilitate its absorption. Despite its unquestioned success in treatments and use since the 1880s, the mechanism of nitroglycerine is still incompletely understood but is believed to involve the release of nitric oxide, a known vasodilator, and endothelium-derived releasing factor, which also relaxes the smooth muscle in the tunica media of coronary vessels. Longer-term treatments include injections of thrombolytic agents such as streptokinase that dissolve the clot, the anticoagulant heparin, balloon angioplasty and stents to open blocked vessels, and bypass surgery to allow blood to pass around the site of blockage. If the damage is extensive, coronary

replacement with a donor heart or coronary assist device, a sophisticated mechanical device that supplements the pumping activity of the heart, may be employed. Despite the attention, development of artificial hearts to augment the severely limited supply of heart donors has proven less than satisfactory but will likely improve in the future.

MIs may trigger cardiac arrest, but the two are not synonymous. Important risk factors for MI include cardiovascular disease, age, smoking, high blood levels of the low-density lipoprotein (LDL, often referred to as “bad” cholesterol), low levels of high-density lipoprotein (HDL, or “good” cholesterol), hypertension, diabetes mellitus, obesity, lack of physical exercise, chronic kidney disease, excessive alcohol consumption, and use of illegal drugs.

Coronary Veins

Coronary veins drain the heart and generally parallel the large surface arteries (see Figure 17.4.1). The **great cardiac vein** can be seen initially on the surface of the heart following the interventricular sulcus, but it eventually flows along the coronary sulcus into the coronary sinus on the posterior surface. The great cardiac vein initially parallels the anterior interventricular artery and drains the areas supplied by this vessel. It receives several major branches, including the posterior cardiac vein, the middle cardiac vein, and the small cardiac vein. The **posterior cardiac vein** parallels and drains the areas supplied by the marginal artery branch of the circumflex artery. The **middle cardiac vein** parallels and drains the areas supplied by the posterior interventricular artery. The **small cardiac vein** parallels the right coronary artery and drains the blood from the posterior surfaces of the right atrium and ventricle. The coronary sinus is a large, thin-walled vein on the posterior surface of the heart lying within the atrioventricular sulcus and emptying directly into the right atrium. The **anterior cardiac veins** parallel the small cardiac arteries and drain the anterior surface of the right ventricle. Unlike these other cardiac veins, it bypasses the coronary sinus and drains directly into the right atrium.

Concept Review

The right and left coronary arteries are the first to branch off the aorta and arise from two of the three sinuses located near the base of the aorta and are generally located in the sulci. Cardiac veins parallel the small cardiac arteries and generally drain into the coronary sinus. Coronary artery disease is caused by the build up of plaque in the walls of coronary arteries that causes ischemia and hypoxia in downstream tissues.

Review Questions

Q. Which of the following branches from the right coronary artery?

A. coronary sinus

B. anterior interventricular artery

C. posterior interventricular artery

D. circumflex artery

Answer

C

Q. Which of the following drains blood most directly from the anterior of the heart?

A. great cardiac vein

B. middle cardiac vein

C. small cardiac vein

D. coronary sinus

Answer

A

Critical Thinking Questions

Q. How can coronary artery disease lead to a myocardial infarction?

Answer

Coronary artery disease is marked by plaques of atherosclerosis that harden the walls of one or more coronary arteries, reducing their flexibility and eventually blocking the passage of blood (a condition referred to as ischemia). When less oxygen and nutrients are supplied to myocardium of the heart, cardiac muscle cells may die (referred to as myocardial infarction).

Glossary

anastomosis
(plural = anastomoses) area where vessels unite to allow blood to circulate even if there may be partial blockage in another branch

anterior cardiac veins
vessels that parallel the small cardiac arteries and drain the anterior surface of the right ventricle; bypass the coronary sinus and drain directly into the right atrium

anterior interventricular artery
(also, left anterior descending artery or LAD) major branch of the left coronary artery that follows the anterior interventricular sulcus

circumflex artery
branch of the left coronary artery that follows coronary sulcus

coronary veins
vessels that drain the heart and generally parallel the large surface arteries

epicardial coronary arteries
surface arteries of the heart that generally follow the sulci

great cardiac vein
vessel that follows the interventricular sulcus on the anterior surface of the heart and flows along the coronary sulcus into the coronary sinus on the posterior surface; parallels the anterior interventricular artery and drains the areas supplied by this vessel

marginal arteries
branches of the right coronary artery that supply blood to the superficial portions of the right ventricle

middle cardiac vein
vessel that parallels and drains the areas supplied by the posterior interventricular artery; drains into the great cardiac vein

posterior cardiac vein
vessel that parallels and drains the areas supplied by the marginal artery branch of the circumflex artery; drains into the great cardiac vein

posterior interventricular artery
(also, posterior descending artery) branch of the right coronary artery that runs along the posterior portion of the interventricular sulcus toward the apex of the heart and gives rise to branches that supply the interventricular septum and portions of both ventricles

small cardiac vein
: parallels the right coronary artery and drains blood from the posterior surfaces of the right atrium and ventricle; drains into the great cardiac vein

cardiac cycle
: period of time between the onset of atrial contraction (atrial systole) and ventricular relaxation (ventricular diastole)

diastole
: period of time when the heart muscle is relaxed and the chambers fill with blood

end diastolic volume (EDV)
: (also, preload) the amount of blood in the ventricles at the end of atrial systole just prior to ventricular contraction

end systolic volume (ESV)
: amount of blood remaining in each ventricle following systole

heart sounds
: sounds heard via auscultation with a stethoscope of the closing of the atrioventricular valves (“lub”) and semilunar valves (“dub”)

isovolumetric contraction
: (also, isovolumic contraction) initial phase of ventricular contraction in which tension and pressure in the ventricle increase, but no blood is pumped or ejected from the heart

isovolumetric ventricular relaxation phase
: (also, isovolumic ventricular relaxation phase) initial phase of the ventricular diastole when pressure in the ventricles drops below pressure in the two major arteries, the pulmonary trunk, and the aorta, and blood attempts to flow back into the ventricles, closing the two semilunar valves

murmur
: unusual heart sound detected by auscultation; typically related to septal or valve defects

preload
: (also, end diastolic volume) amount of blood in the ventricles at the end of atrial systole just prior to ventricular contraction

systole
: period of time when the heart muscle is contracting

ventricular ejection phase
: second phase of ventricular systole during which blood is pumped from the ventricle

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17.5: Development of the Heart

By the end of this section, you will be able to:

- Describe the embryological development of heart structures
- Identify five regions of the fetal heart
- Relate fetal heart structures to adult counterparts

The human heart is the first functional organ to develop. It begins beating and pumping blood around day 21 or 22, a mere three weeks after fertilization. This emphasizes the critical nature of the heart in distributing blood through the vessels and the vital exchange of nutrients, oxygen, and wastes both to and from the developing baby. The critical early development of the heart is reflected by the prominent **heart bulge** that appears on the anterior surface of the embryo.

The heart forms from an embryonic tissue called **mesoderm** around 18 to 19 days after fertilization. Mesoderm is one of the three primary germ layers that differentiates early in development that collectively gives rise to all subsequent tissues and organs. The heart begins to develop near the head of the embryo in a region known as the **cardiogenic area**. Following chemical signals called factors from the underlying endoderm (another of the three primary germ layers), the cardiogenic area begins to form two strands called the **cardiogenic cords** (Figure 17.5.1). As the cardiogenic cords develop, a lumen rapidly develops within them. At this point, they are referred to as **endocardial tubes**. The two tubes migrate together and fuse to form a single **primitive heart tube**. The primitive heart tube quickly forms five distinct regions. From head to tail, these include the truncus arteriosus, bulbus cordis, primitive ventricle, primitive atrium, and the sinus venosus. Initially, all venous blood flows into the sinus venosus, and contractions propel the blood from tail to head, or from the sinus venosus to the truncus arteriosus. This is a very different pattern from that of an adult.

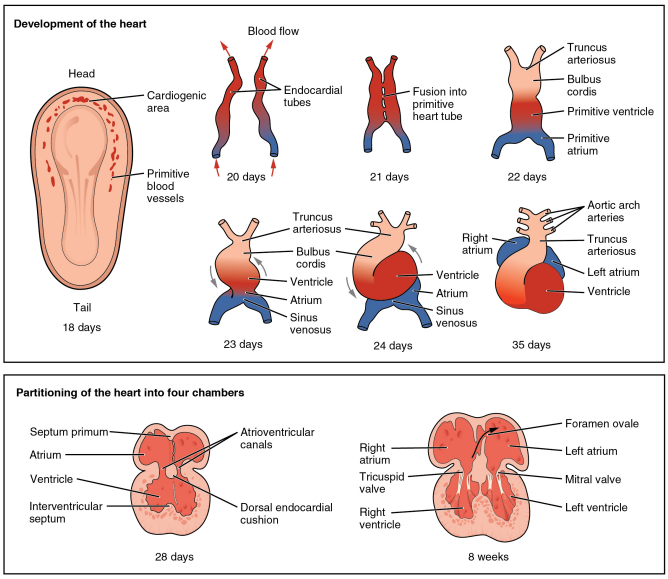

Figure 17.5.1: Development of the Human Heart. This diagram outlines the embryological development of the human heart during the first eight weeks and the subsequent formation of the four heart chambers. (Image credit: "Embryonic Development of Heart" by OpenStax is licensed under CC BY 3.0)

The five regions of the primitive heart tube develop into recognizable structures in a fully developed heart. The **truncus arteriosus** will eventually divide and give rise to the ascending aorta and pulmonary trunk. The **bulbus cordis** develops into the right ventricle. The **primitive ventricle** forms the left ventricle. The **primitive atrium** becomes the anterior portions of both the right and left atria, and the two auricles. The **sinus venosus** develops into the posterior portion of the right atrium, the SA node, and the coronary sinus.

As the primitive heart tube elongates, it begins to fold within the pericardium, eventually forming an S shape, which places the chambers and major vessels into an alignment similar to the adult heart. This process occurs between days 23 and 28. The

remainder of the cardiac development pattern includes development of septa and valves, and remodeling of the actual chambers. Partitioning of the atria and ventricles by the interatrial septum, interventricular septum, and atrioventricular septum is complete by the end of the fifth week, although the fetal blood shunts remain until birth or shortly after. The atrioventricular valves form between weeks five and eight, and the semilunar valves form between weeks five and nine.

Concept Review

The heart is the first organ to form and become functional, emphasizing the importance of transport of material to and from the developing infant. It originates about day 18 or 19 from the mesoderm and begins beating and pumping blood about day 21 or 22. It forms from the cardiogenic region near the head and is visible as a prominent heart bulge on the surface of the embryo. Originally, it consists of a pair of strands called cardiogenic cords that quickly form hollow lumens and are referred to as endocardial tubes. These then fuse into a single heart tube and differentiate into the truncus arteriosus, bulbus cordis, primitive ventricle, primitive atrium, and sinus venosus, starting about day 22. The primitive heart begins to form an S shape within the pericardium between days 23 and 28. The internal septa begin to form about day 28, separating the heart into the atria and ventricles, although the foramen ovale persists until shortly after birth. Between weeks five and eight, the atrioventricular valves form. The semilunar valves form between weeks five and nine.

Review Questions

Q. The earliest organ to form and begin function within the developing human is the _____.

A. brain

B. stomach

C. lungs

D. heart

Answer

Answer: D

Q. Of the three germ layers that give rise to all adult tissues and organs, which gives rise to the heart?

A. ectoderm

B. endoderm

C. mesoderm

D. placenta

Answer

Answer: C

Q. The two tubes that eventually fuse to form the heart are referred to as the _____.

A. primitive heart tubes

B. endocardial tubes

C. cardiogenic region

D. bulbus cordis

Answer

Answer: B

Q. Which primitive area of the heart will give rise to the right ventricle?

A. bulbus cordis

B. primitive ventricle

C. sinus venosus

D. truncus arteriosus

Answer

Answer: A

Q. The pulmonary trunk and aorta are derived from which primitive heart structure?

A. bulbus cordis

B. primitive ventricle

C. sinus venosus

D. truncus arteriosus

Answer

Answer: D

Critical Thinking Questions

Q. Why is it so important for the human heart to develop early and begin functioning within the developing embryo?

Answer

A. The human embryo is rapidly growing and has great demands for nutrients and oxygen, while producing waste products including carbon dioxide. All of these materials must be received from or delivered to the mother for processing. Without an efficient early circulatory system, this would be impossible.

Q. Describe how the major pumping chambers, the ventricles, form within the developing heart.

Answer

A. After fusion of the two endocardial tubes into the single primitive heart, five regions quickly become visible. From the head, these are the truncus arteriosus, bulbus cordis, primitive ventricle, primitive atrium, and sinus venosus. Contractions propel the blood from the sinus venosus to the truncus arteriosus. About day 23, the heart begins to form an S-shaped structure within the pericardium. The bulbus cordis develops into the right ventricle, whereas the primitive ventricle becomes the left ventricle. The interventricular septum separating these begins to form about day 28. The atrioventricular valves form between weeks five to eight. At this point, the heart ventricles resemble the adult structure.

Glossary

bulbus cordis
portion of the primitive heart tube that will eventually develop into the right ventricle

cardiogenic area
: area near the head of the embryo where the heart begins to develop 18–19 days after fertilization

cardiogenic cords
: two strands of tissue that form within the cardiogenic area

endocardial tubes
: stage in which lumens form within the expanding cardiogenic cords, forming hollow structures

heart bulge
: prominent feature on the anterior surface of the heart, reflecting early cardiac development

mesoderm
: one of the three primary germ layers that differentiate early in embryonic development

primitive atrium
: portion of the primitive heart tube that eventually becomes the anterior portions of both the right and left atria, and the two auricles

primitive heart tube
: singular tubular structure that forms from the fusion of the two endocardial tubes

primitive ventricle
: portion of the primitive heart tube that eventually forms the left ventricle

sinus venosus
: develops into the posterior portion of the right atrium, the SA node, and the coronary sinus

truncus arteriosus
: portion of the primitive heart that will eventually divide and give rise to the ascending aorta and pulmonary trunk

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18: CARDIOVASCULAR SYSTEM - BLOOD VESSELS AND CIRCULATION

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18.1: Introduction to Blood Vessels and Circulation

18.2: Structure and Function of Blood Vessels

18.3: Circulatory Pathways

18.4: Development of Blood Vessels and Fetal Circulation

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18.1: Introduction to Blood Vessels and Circulation

Chapter Learning Objectives:

After studying this chapter, you will be able to:

- Compare and contrast the anatomical structure of arteries, arterioles, capillaries, venules, and veins
- Describe how blood flow, blood pressure, and resistance interrelate
- Describe the interaction of the cardiovascular system with other body systems
- Label the major blood vessels of the pulmonary and systemic circulations
- Identify and describe the hepatic portal system
- Describe the development of blood vessels and fetal circulation
- Compare fetal circulation to that of an individual after birth

Figure 18.1.1: Blood Vessels. While most blood vessels are located deep from the surface and are not visible, the superficial veins of the upper limb provide an indication of the extent, prominence, and importance of these structures to the body. In some individuals, contraction of the forearm muscles by squeezing a fist may cause the larger superficial veins to distend such that they are more prominent and easily located. (Image credit: "Arm veins" by Colin Davis is licensed under CC BY 2.0)

In this chapter, you will learn about the vascular part of the cardiovascular system, that is, the vessels that transport blood throughout the body and provide the physical site where gases, nutrients, and other substances are exchanged with body cells. When vessel functioning is reduced, blood-borne substances do not circulate effectively throughout the body. As a result, tissue injury occurs, metabolism is impaired, and the functions of every body system are threatened.

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18.2: Structure and Function of Blood Vessels

By the end of this section, you will be able to:

- Compare and contrast the three tunics that make up the walls of most blood vessels
- Distinguish between elastic arteries, muscular arteries, and arterioles on the basis of structure, location, and function
- Compare and contrast the three types of capillaries on the basis of structure, location, and function
- Describe the basic structure of a capillary bed, from the supplying metarteriole to the venule into which it drains
- Compare and contrast veins, venules, and venous sinuses on the basis of structure, location, and function
- Discuss several factors affecting blood flow in the venous system

Blood is carried through the body via blood vessels. An artery is a blood vessel that carries blood away from the heart, where it branches into ever-smaller vessels. Eventually, the smallest arteries, vessels called arterioles, further branch into tiny capillaries, where nutrients and wastes are exchanged, and then combine with other vessels that exit capillaries to form venules, small blood vessels that carry blood to a vein, a larger blood vessel that returns blood to the heart.

Blood flow is the movement of blood through a vessel, tissue, or organ. The slowing or blocking of blood flow is called resistance. **Blood pressure** is the force that blood exerts upon the walls of the blood vessels or chambers of the heart. The components of blood pressure include systolic pressure, which results from ventricular contraction, and diastolic pressure, which results from ventricular relaxation. Pulse, the expansion and recoiling of an artery, reflects the heartbeat. In the arterial system, vasodilation and vasoconstriction of the arterioles is a significant factor in systemic blood pressure: slight vasodilation greatly decreases resistance and increases flow, whereas slight vasoconstriction greatly increases resistance and decreases flow. In the arterial system, as resistance increases, blood pressure increases and flow decreases. In the venous system, constriction increases blood pressure as it does in arteries; the increasing pressure helps to return blood to the heart. In addition, constriction causes the vessel lumen to become more rounded, decreasing resistance and increasing blood flow.

Arteries and veins transport blood in two distinct circuits: the systemic circuit and the pulmonary circuit (Figure 18.2.1). The systemic circuit begins in the left atrium of the heart and ends in the venae cavae and coronary sinus that drain into the right atrium. Systemic arteries provide blood rich in oxygen to the body's tissues; this blood is often referred to as oxygenated blood. The blood returned to the heart through systemic veins has less oxygen, since much of the oxygen carried by the arteries has been delivered to the cells; this blood is often referred to as deoxygenated blood. In contrast, the pulmonary circuit begins in the right atrium and ends in the pulmonary veins that drain into the left atrium. Pulmonary arteries carry blood low in oxygen exclusively to the lungs for gas exchange. Pulmonary veins then return freshly oxygenated blood from the lungs to the heart to be pumped back out into systemic circulation. Although arteries and veins differ structurally and functionally, they share certain features.

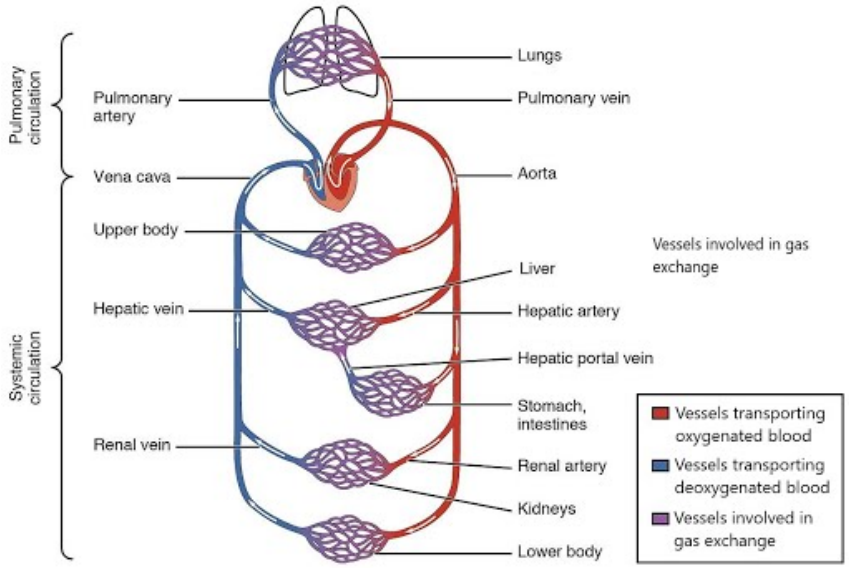

Figure 18.2.1: Cardiovascular Circulation in Pulmonary and Systemic Circuits. The pulmonary circuit moves blood from the right side of the heart to the lungs and back to the heart. The systemic circuit moves blood from the left side of the heart to the head and body and returns it to the right side of the heart to repeat the cycle. Blood flows in one direction to and from capillary beds, each with a network of interconnected capillaries, that are positioned between the arterial and venous sides of circulation throughout the body to allow for gas and nutrient exchange. In the pulmonary circuit, deoxygenated blood flows on the arterial side of the circuit while oxygenated blood flows on the venous side. In the systemic circuit, oxygenated blood flows on the arterial side of the circuit while deoxygenated blood flows on the venous side. In the figure, the arrows indicate the direction of blood flow and the colors show the relative levels of oxygen concentration. (Image credit: "Cardiovascular Circulation in Pulmonary and Systemic Circuits" by Julie Jenks / A derivative from the original work)

Structural Characteristics of Vessels

Different types of blood vessels vary slightly in their structures, but they share the same general features. Arteries and arterioles have thicker walls than veins and venules because they are closer to the heart and receive blood that is surging at a far greater pressure (Figure 18.2.2). Each type of vessel has a **lumen**—a hollow passageway through which blood flows. Arteries have smaller lumens than veins, a characteristic that helps to maintain the pressure of blood moving through the system. Together, their thicker walls and smaller diameters give arterial lumens a more rounded appearance in cross section than the lumens of veins.

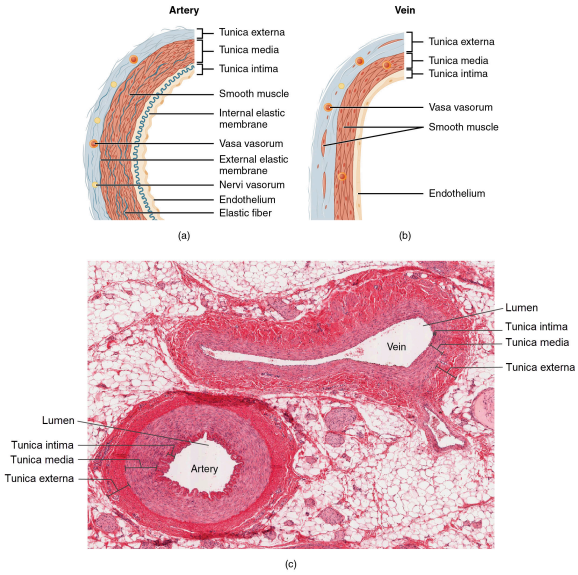

Figure 18.2.2: Structure of Blood Vessels. (a) Arteries and (b) veins share the same general features, but the walls of arteries are much thicker because of the higher pressure of the blood that flows through them. (c) A micrograph shows a similarly sized artery and vein. Note the relative differences in wall thickness and compare the round lumen of the artery to the flattened lumen of the vein. LM × 160. (Image credit: "Comparison of Artery and Vein" by Julie Jenks / A derivative from the original work / Micrograph provided by the Regents of the University of Michigan Medical School © 2012)

By the time blood has passed through capillaries and entered venules, the pressure initially exerted upon it by heart contractions has diminished. In other words, in comparison to arteries, venules and veins withstand a much lower pressure from the blood that flows through them. Their walls are considerably thinner and their lumens are correspondingly larger in diameter, allowing more blood to flow with less vessel resistance. In addition, many veins of the body, particularly those of the limbs, contain valves that assist the unidirectional flow of blood toward the heart. This is critical because blood flow becomes sluggish in the extremities, as a result of the lower pressure and the effects of gravity.

The walls of arteries and veins are largely composed of living cells and their products (including collagen and elastic fibers); the cells require nourishment and produce waste. Since blood passes through the larger vessels relatively quickly, there is limited opportunity for blood in the lumen of the vessel to provide nourishment to or remove waste from the vessel's cells. Further, the walls of the larger vessels are too thick for nutrients to diffuse through to all of the cells. Larger arteries and veins contain small blood vessels within their walls known as the **vasa vasorum**—literally "vessels of the vessel"—to provide them with this critical exchange. Since the pressure within arteries is relatively high, the vasa vasorum must function in the outer layers of the vessel (see Figure 18.2.2) or the pressure exerted by the blood passing through the vessel would collapse it, preventing any exchange from occurring. The lower pressure within veins allows the vasa vasorum to be located closer to the lumen. The restriction of the vasa vasorum to the outer layers of arteries is thought to be one reason that arterial diseases are more common than venous diseases, since their location makes it more difficult to nourish the cells of the arteries and remove waste products. There are also minute nerves within the walls of both types of vessels that control the contraction and dilation of smooth muscle. These minute nerves are known as the **nervi vasorum**.

Both arteries and veins have the same three distinct tissue layers, called tunics (from the Latin term tunica, for the garments first worn by ancient Romans). From the most interior layer to the outer, these tunics are the tunica intima, the tunica media, and the tunica externa (see Figure 18.2.2). Table 18.2.1 compares and contrasts the tunics of the arteries and veins.

Table 18.2.1: Comparison of Tunics in Arteries and Veins

Tunic (Layer)	Arteries	Veins
General Appearance	Thick walls with small lumens Generally appear rounded	Thin walls with large lumens Generally appear flattened
Tunica Intima	Endothelium usually appears wavy due to constriction of smooth muscle Internal elastic membrane present in larger vessels	Endothelium appears smooth Internal elastic membrane absent

Tunic (Layer)	Arteries	Veins
Tunica Media	Normally the thickest layer in arteries Smooth muscle cells and elastic fibers predominate (the proportions of these vary with distance from the heart) Nervi vasorum and vasa vasorum present External elastic membrane present in larger vessels	Normally thinner than the tunica externa Smooth muscle cells with elastic and collagen fibers Nervi vasorum and vasa vasorum present External elastic membrane absent
Tunica Externa	Normally thinner than the tunica media in all but the largest arteries Collagen and elastic fibers Nervi vasorum and vasa vasorum present	Normally the thickest layer in veins Collagen and smooth fibers predominate Some smooth muscle fibers Nervi vasorum and vasa vasorum present

Tunica Intima

The **tunica intima** (also called the tunica interna) is composed of epithelial and connective tissue layers. Lining the tunica intima is the specialized simple squamous epithelium called the endothelium, which is continuous throughout the entire vascular system, including the lining of the chambers of the heart. Damage to this endothelial lining and exposure of blood to the collagen fibers beneath is one of the primary causes of clot formation. Until recently, the endothelium was viewed simply as the boundary between the blood in the lumen and the walls of the vessels. Recent studies, however, have shown that it is physiologically critical to such activities as helping to regulate capillary exchange and altering blood flow. The endothelium releases local chemicals called endothelins that can constrict the smooth muscle within the walls of the vessel to increase blood pressure. Uncompensated overproduction of endothelins may contribute to hypertension (high blood pressure) and cardiovascular disease.

Next to the endothelium is the basement membrane, or basal lamina, that effectively binds the endothelium to the connective tissue. The basement membrane provides strength while maintaining flexibility, and it is permeable, allowing materials to pass through it. The thin outer layer of the tunica intima contains a small amount of areolar connective tissue that consists primarily of elastic fibers to provide the vessel with additional flexibility; it also contains some collagen fibers to provide additional strength.

In larger arteries, there is also a thick, distinct layer of elastic connective tissue known as the **internal elastic membrane** (also called the internal elastic lamina) at the boundary with the tunica media. Like the other components of the tunica intima, the internal elastic membrane provides structure while allowing the vessel to stretch. It is permeated with small openings that allow exchange of materials between the tunics. The internal elastic membrane is not apparent in veins. In addition, many veins, particularly in the lower limbs, contain one-way valves formed by sections of thickened endothelium that are reinforced with connective tissue, extending into the lumen.

Under the microscope, the lumen and the entire tunica intima of a vein will appear smooth, whereas those of an artery will normally appear wavy because of the partial constriction of the smooth muscle in the tunica media, the next layer of blood vessel walls.

Tunica Media

The **tunica media** is the substantial middle layer of the vessel wall (see Figure 18.2.2). It is generally the thickest layer in arteries, and it is much thicker in arteries than it is in veins. The tunica media consists of layers of smooth muscle supported by connective tissue that is primarily made up of elastic fibers, most of which are arranged in circular sheets. Toward the outer portion of the tunic, there are also layers of longitudinal smooth muscle. Contraction and relaxation of the circular muscles decrease and increase the diameter of the vessel lumen, respectively. Specifically in arteries, **vasoconstriction** decreases blood flow as the smooth muscle in the walls of the tunica media contracts, making the lumen narrower and increasing blood pressure. Similarly, **vasodilation** increases blood flow as the smooth muscle relaxes, allowing the lumen to widen and blood pressure to drop. Both vasoconstriction and vasodilation are regulated in part by small vascular nerves, known as **nervi vasorum**, or “nerves of the vessel,” that run within the walls of blood vessels. Neural and chemical mechanisms reduce or increase blood flow in response to changing body conditions, from exercise to hydration.

The smooth muscle layers of the tunica media are supported by a framework of collagen fibers that also binds the tunica media to the inner and outer tunics. Along with the collagen fibers are large numbers of elastic fibers that appear as wavy lines in prepared slides. Separating the tunica media from the outer tunica externa in larger arteries is the **external elastic membrane** (also called the external elastic lamina), which also appears wavy in slides. This structure is not usually seen in smaller arteries, nor is it seen in veins.

Tunica Externa

The outer tunic, the **tunica externa** (also called the tunica adventitia), is a substantial sheath of dense irregular connective tissue composed primarily of collagen fibers. Some bands of elastic fibers are found here as well. The tunica externa in veins also contains groups of smooth muscle fibers. This is normally the thickest tunic in veins and may be thicker than the tunica media in some larger arteries. The outer layers of the tunica externa are not distinct but rather blend with the surrounding connective tissue outside the vessel, helping to hold the vessel in relative position. If you are able to palpate some of the superficial veins on your upper limbs and try to move them, you will find that the tunica externa prevents this. If the tunica externa did not hold the vessel in place, any movement would likely result in disruption of blood flow.

Arteries

An **artery** is a blood vessel that conducts blood away from the heart. All arteries have relatively thick walls that can withstand the high pressure of blood ejected from the heart. However, those close to the heart have the thickest walls, containing a high percentage of elastic fibers in all three of their tunics. This type of artery is known as an **elastic artery** (Figure 18.2.3). Vessels larger than 10 mm in diameter are typically elastic. Their abundant elastic fibers allow them to expand, as blood pumped from the ventricles passes through them, and then to recoil after the surge has passed. If artery walls were rigid and unable to expand and recoil, their resistance to blood flow would greatly increase and blood pressure would rise to even higher levels, which would in turn require the heart to pump harder to increase the volume of blood expelled by each pump and maintain adequate pressure and flow. Artery walls would have to become even thicker in response to this increased pressure. The elastic recoil of the vascular wall helps to maintain the pressure gradient that drives the blood through the arterial system. An elastic artery is also known as a conducting artery, because the large diameter of the lumen gives it a low resistance and enables it to accept a large volume of blood from the heart which is conducted to smaller branches within regions of the body.

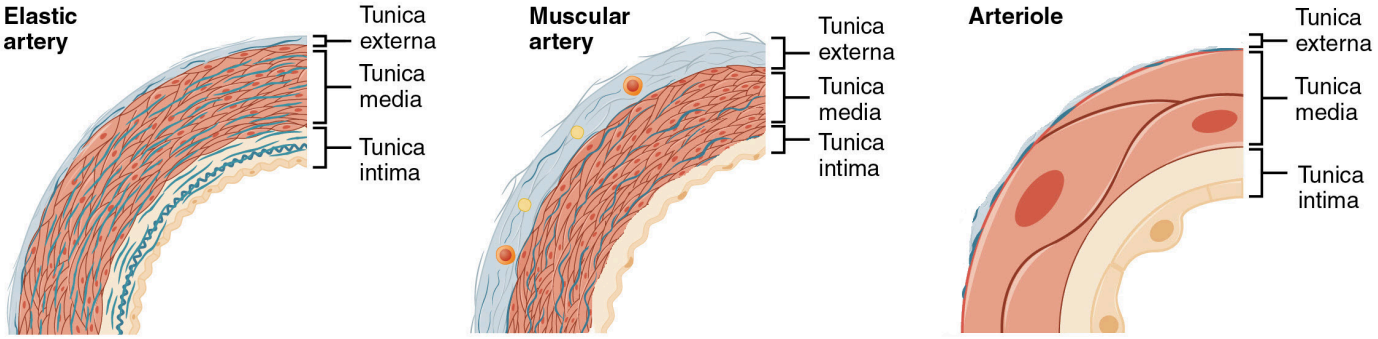

Figure 18.2.3: Types of Arteries and Arterioles. A comparison of the walls of an elastic artery, a muscular artery, and an arteriole is shown. The scale of each vessel's wall has been adjusted for comparison in this illustration. The tunica media is thickest in muscular arteries in proportion to the diameter of the lumen. Tunica externa is very thin and incomplete in arterioles. (Image credit: "Types of Arteries and Arterioles" by Julie Jenks / A derivative from the original work)

Farther from the heart, where the surge of blood has dampened, the percentage of elastic fibers in an artery's tunica intima decreases and the amount of smooth muscle in its tunica media increases. The artery at this point is described as a **muscular artery**. The diameter of muscular arteries typically ranges from 0.1 mm to 10 mm. Their thick tunica media allows muscular arteries to play a leading role in vasoconstriction which controls blood flow to individual organs. In contrast, their decreased quantity of elastic fibers limits their ability to expand. Fortunately, because the blood pressure has eased by the time it reaches these more distant vessels, elasticity has become less important.

Notice that although the distinctions between elastic and muscular arteries are important, there is no "line of demarcation" where an elastic artery suddenly becomes muscular. Rather, there is a gradual transition as the vascular tree repeatedly branches. In turn, muscular arteries branch to distribute blood to the vast network of arterioles that deliver blood to capillaries within specific organs and tissues. For this reason, a muscular artery is also known as a distributing artery.

Arterioles

An **arteriole** is a very small artery that leads to a capillary. Arterioles have the same three tunics as the larger vessels, but the thickness of each is greatly diminished. The critical endothelial lining of the tunica intima is intact. The tunica media is restricted to one or two smooth muscle cell layers in thickness. The tunica externa remains but is very thin as arterioles are supported and held in place by their positioning within organs and tissues (see Figure 18.2.3).

With a lumen averaging 30 micrometers or less in diameter, arterioles are critical in slowing down—or resisting—blood flow and, thus, causing a substantial drop in blood pressure. Because of this, you may see them referred to as resistance vessels. The muscle fibers in arterioles are normally slightly contracted, causing arterioles to maintain a consistent muscle tone—in this case referred to as vascular tone—in a similar manner to the muscular tone of skeletal muscle. In reality, all blood vessels exhibit vascular tone due to the partial contraction of smooth muscle. The importance of the arterioles is that they will be the primary site of both resistance and regulation of blood pressure. The precise diameter of the lumen of an arteriole at any given moment is determined by neural and chemical controls, and vasoconstriction and vasodilation in the arterioles are the primary mechanisms for distribution of blood flow to capillary beds as well as regulation of systemic blood pressure.

DISORDERS OF THE...

Cardiovascular System: Arteriosclerosis

Compliance allows an artery to expand when blood is pumped through it from the heart, and then to recoil after the surge has passed. This helps promote blood flow. In arteriosclerosis, compliance is reduced, and pressure and resistance within the vessel increase. This is a leading cause of hypertension and coronary heart disease, as it causes the heart to work harder to generate a pressure great enough to overcome the resistance.

Arteriosclerosis begins with injury to the endothelium of an artery, which may be caused by irritation from high blood glucose, infection, tobacco use, excessive blood lipids, and other factors. Artery walls that are constantly stressed by blood flowing at high pressure are also more likely to be injured—which means that hypertension can promote arteriosclerosis, as well as result from it.

Recall that tissue injury causes inflammation. As inflammation spreads into the artery wall, it weakens and scars it, leaving it stiff (sclerotic). As a result, compliance is reduced. Moreover, circulating triglycerides and cholesterol can seep between the damaged lining cells and become trapped within the artery wall, where they are frequently joined by leukocytes, calcium, and cellular debris. Eventually, this buildup, called plaque, can narrow arteries enough to impair blood flow. The term for this condition, atherosclerosis (athero- = “porridge”) describes the mealy deposits (Figure 18.2.4).

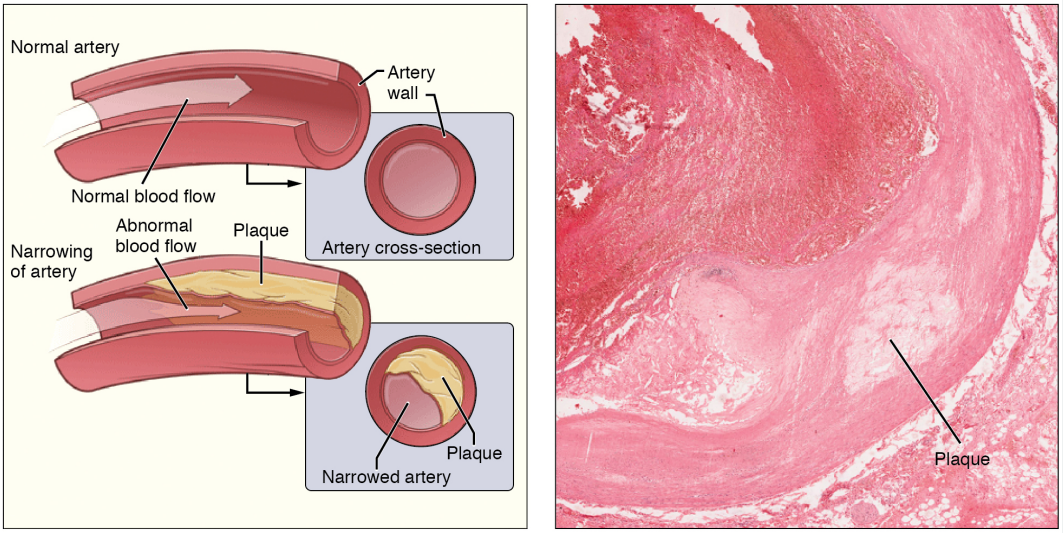

Figure 18.2.4: Atherosclerosis. (a) Atherosclerosis can result from plaques formed by the buildup of fatty, calcified deposits in an artery. (b) Plaques can also take other forms, as shown in this micrograph of a coronary artery that has a buildup of connective tissue within the artery wall. LM × 40. (Image credit: "Atherosclerosis" by OpenStax is licensed under CC BY 3.0; Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Sometimes a plaque can rupture, causing microscopic tears in the artery wall that allow blood to leak into the tissue on the other side. When this happens, platelets rush to the site to clot the blood. This clot can further obstruct the artery and—if it occurs in a coronary or cerebral artery—cause a sudden heart attack or stroke. Alternatively, plaque can break off and travel through the bloodstream as an embolus until it blocks a more distant, smaller artery.

Even without total blockage, vessel narrowing leads to ischemia—reduced blood flow—to the tissue region "downstream" of the narrowed vessel. Ischemia in turn leads to hypoxia—decreased supply of oxygen to the tissues. Hypoxia involving cardiac muscle or brain tissue can lead to cell death and severe impairment of brain or heart function.

A major risk factor for both arteriosclerosis and atherosclerosis is advanced age, as the conditions tend to progress over time. Arteriosclerosis is normally defined as the more generalized loss of compliance, "hardening of the arteries," whereas atherosclerosis is a more specific term for the build-up of plaque in the walls of the vessel and is a specific type of arteriosclerosis. There is also a distinct genetic component, and pre-existing hypertension and/or diabetes also greatly increase the risk. However, obesity, poor nutrition, lack of physical activity, and tobacco use all are major risk factors.

Treatment includes lifestyle changes, such as weight loss, smoking cessation, regular exercise, and adoption of a diet low in sodium and saturated fats. Medications to reduce cholesterol and blood pressure may be prescribed. For blocked coronary arteries, surgery is warranted. In angioplasty, a catheter is inserted into the vessel at the point of narrowing, and a second catheter with a balloon-like tip is inflated to widen the opening. To prevent subsequent collapse of the vessel, a small mesh tube called a stent is often inserted. In an endarterectomy, plaque is surgically removed from the walls of a vessel. This operation is typically performed on the carotid arteries of the neck, which are a prime source of oxygenated blood for the brain. In a coronary bypass procedure, a non-vital superficial vessel from another part of the body (often the great saphenous vein) or a synthetic vessel is inserted to create a path around the blocked area of a coronary artery.

Capillaries

A **capillary** is a microscopic channel that supplies blood to the tissues, through a process called **perfusion**. Exchange of gases and other substances occurs in the capillaries between the blood and the surrounding cells and their tissue fluid (interstitial fluid). The diameter of a capillary lumen ranges from 5–10 micrometers; the smallest are just barely wide enough for an erythrocyte to squeeze through. Flow through capillaries is often described as **microcirculation**.

The wall of a capillary consists of the endothelial layer surrounded by a basement membrane with occasional smooth muscle fibers. Some variation in wall structure is seen depending on the size of the capillary. In a large capillary, several endothelial cells

bordering each other may line the lumen, while in a small capillary, there may be only a single cell layer that wraps around to contact itself.

For capillaries to function, their walls must be leaky, or **permeable**, allowing some substances to pass through. There are three major types of capillaries, which differ according to their degree of permeability: continuous, fenestrated, and sinusoid capillaries (Figure 18.2.5).

Continuous Capillaries

The most common type of capillary, the **continuous capillary**, is found in almost all vascularized tissues. Continuous capillaries are characterized by a complete endothelial lining with tight junctions between endothelial cells. Although a tight junction is usually impermeable and only allows for the passage of water and ions, they are often incomplete in capillaries, leaving intercellular clefts that allow for exchange of water and other very small molecules between the blood plasma and the interstitial fluid. Substances that can pass between cells include metabolic products, such as glucose, water, and small hydrophobic molecules like gases and hormones, as well as various leukocytes. Continuous capillaries not associated with the brain are rich in transport vesicles, contributing to either endocytosis or exocytosis. Those in the brain are part of the blood-brain barrier. Here, there are tight junctions and no intercellular clefts, plus a thick basement membrane and astrocyte extensions called end feet; these structures combine to prevent the movement of nearly all substances.

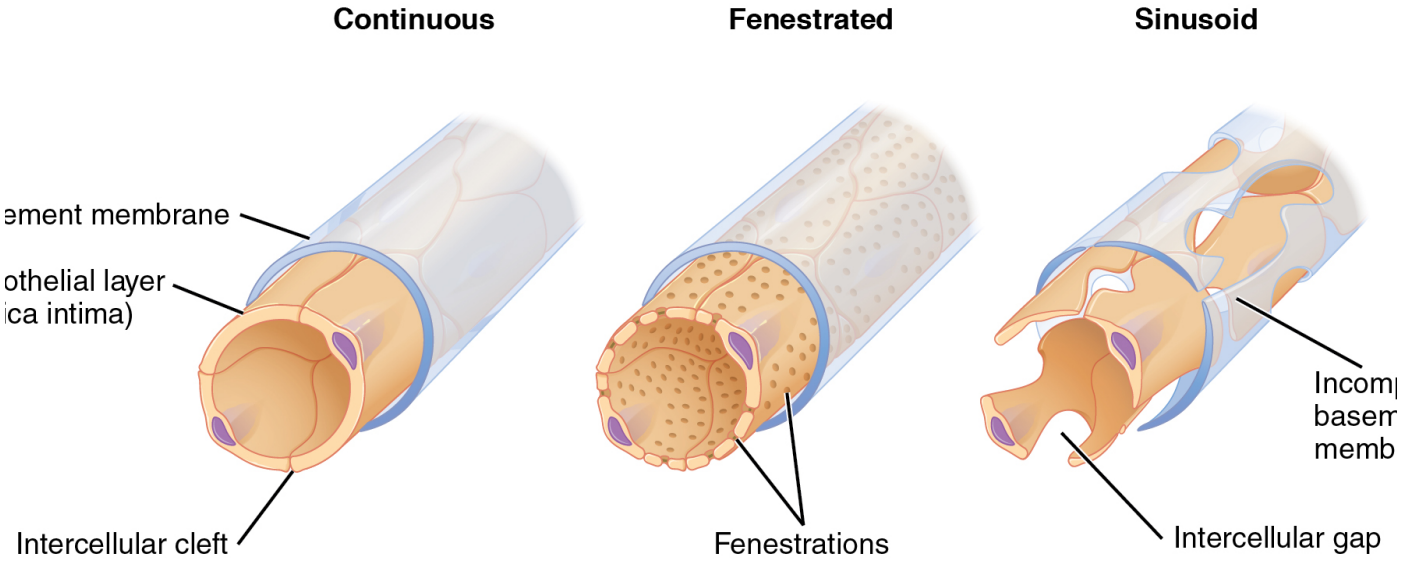

Figure 18.2.5: Types of Capillaries. The three major types of capillaries: continuous, fenestrated, and sinusoid. (Image credit: "Three Major Capillary Types" by OpenStax is in the Public Domain)

Fenestrated Capillaries

A **fenestrated capillary** is one that has pores (or fenestrations) in addition to tight junctions in the endothelial lining. These make the capillary permeable to larger molecules. The number of fenestrations and their degree of permeability vary according to their location. Fenestrated capillaries are common in the small intestine, which is the primary site of nutrient absorption, as well as in the kidneys, which filter the blood. They are also found in the choroid plexus of the brain and many endocrine structures, including the hypothalamus, pituitary, pineal, and thyroid glands.

Sinusoid Capillaries

A **sinusoid capillary** (or sinusoid) is the least common type of capillary and the most permeable. Sinusoid capillaries are flattened, and they have extensive intercellular gaps and incomplete basement membranes, in addition to intercellular clefts and fenestrations. This gives them an appearance similar to Swiss cheese. These very large openings allow for the passage of the largest molecules, including plasma proteins and even cells. Blood flow through sinusoids is very slow, allowing more time for exchange of gases, nutrients, and wastes. Sinusoids are found in the liver and spleen, bone marrow, lymph nodes (where they carry lymph, not blood), and many endocrine glands including the pituitary and adrenal glands. Without these specialized capillaries,

these organs would not be able to provide their myriad functions. For example, when bone marrow forms new blood cells, the cells must enter the blood supply and can only do so through the large openings of a sinusoid capillary; they cannot pass through the small openings of continuous or fenestrated capillaries. The liver also requires extensive specialized sinusoid capillaries in order to process the materials brought to it by the hepatic portal vein from both the digestive tract and spleen, and to release plasma proteins into circulation.

Metarterioles and Capillary Beds

A **metarteriole** is a type of vessel that has structural characteristics of both an arteriole and a capillary. Slightly larger than the typical capillary, the smooth muscle of the tunica media of the metarteriole is not continuous but forms rings of smooth muscle (sphincters) prior to the entrance of the capillaries. Each metarteriole arises from a terminal arteriole and branches to supply blood to a **capillary bed** that may consist of 10–100 capillaries depending on the metabolic needs of the surrounding tissues.

The **precapillary sphincters**, circular smooth muscle cells that surround the capillary at its origin with the metarteriole, tightly regulate the flow of blood from a metarteriole to the capillaries it supplies. Their function is critical: If all of the capillary beds in the body were to open simultaneously, they would collectively hold every drop of blood in the body and there would be none in the arteries, arterioles, venules, veins, or the heart itself. Normally, the precapillary sphincters are closed. When the surrounding tissues need oxygen and have excess waste products, the precapillary sphincters open, allowing blood to flow through and exchange to occur before closing once more (Figure 18.2.6). If all of the precapillary sphincters in a capillary bed are closed, blood will flow from the metarteriole directly into a **thoroughfare channel** and then into the venous circulation, bypassing the capillary bed entirely. This creates what is known as a **vascular shunt**. In addition, some regions contain one or more **arteriovenous anastomoses**, which can be opened to bypass the capillary bed, skipping perfusion and leading directly to the venous system.

Although you might expect blood flow through a capillary bed to be smooth, in reality, it moves with an irregular, pulsating flow. This pattern is called **vasomotion** and is regulated by chemical signals that are triggered in response to changes in internal conditions, such as oxygen, carbon dioxide, hydrogen ion, and lactic acid levels. For example, during strenuous exercise when oxygen levels decrease and carbon dioxide, hydrogen ion, and lactic acid levels all increase, the capillary beds in skeletal muscle are open, as they would be in the digestive system when nutrients are present in the digestive tract. During sleep or rest periods, vessels in both areas are largely closed; they open only occasionally to allow oxygen and nutrient supplies to travel to the tissues to maintain basic life processes.

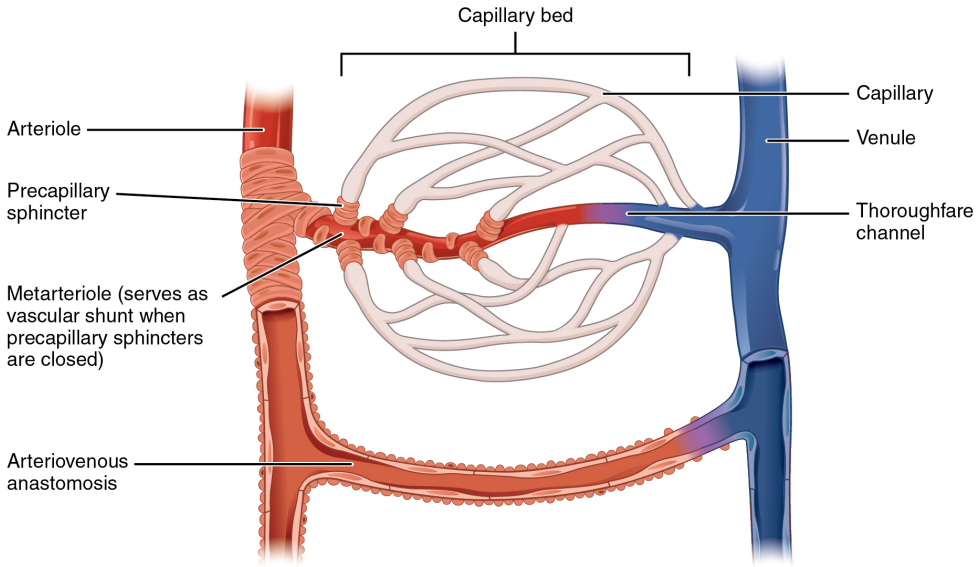

Figure 18.2.6: Capillary Bed. In a capillary bed, arterioles give rise to metarterioles. Precapillary sphincters located at the junction of a metarteriole with a capillary regulate blood flow. A thoroughfare channel connects the metarteriole to a venule. An arteriovenous anastomosis, which directly connects the arteriole with the venule, is shown at the bottom. (Image credit: "Capillary Bed" by OpenStax is licensed under CC BY 3.0)

Venules

A **venule** is an extremely small vein, generally 8–100 micrometers in diameter. Postcapillary venules drain multiple capillaries exiting from a capillary bed. Multiple venules join to form veins. The walls of venules consist of endothelium, a thin or non-existent middle layer with a few smooth muscle cells and elastic fibers, plus an outer layer of connective tissue fibers that constitute a very thin tunica externa (Figure 18.2.7). Venules as well as capillaries are the primary sites of emigration or diapedesis, in which the white blood cells adhere to the endothelial lining of the vessels and then squeeze between adjacent cells to enter the tissue fluid.

Veins

A **vein** is a blood vessel that conducts blood toward the heart. Compared to arteries, veins are thin-walled vessels with large and irregular lumens (see Figure 18.2.2). Because they are low-pressure vessels, larger veins are commonly equipped with valves that promote the unidirectional flow of blood toward the heart and prevent backflow toward the capillaries caused by the inherent low blood pressure in veins as well as the pull of gravity (Figure 18.2.7).

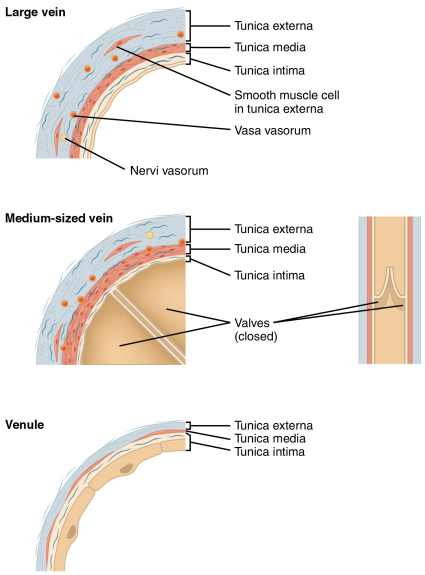

Figure 18.2.7: Comparison of Veins and Venules. Many veins have valves to prevent back flow of blood, whereas venules do not. In terms of scale, the diameter of a venule is measured in micrometers compared to millimeters for veins. (Image credit: "Large Medium Vein Venule" by OpenStax is licensed under CC BY 3.0)

Table 18.2.2 compares the features of arteries and veins.

Table 18.2.2: Comparison of General Features of Arteries and Veins

	Arteries	Veins
Direction of blood flow	Conducts blood away from the heart	Conducts blood toward the heart
General appearance	Rounded	Irregular, often collapsed
Pressure	High	Low
Wall thickness	Thick	Thin
Relative oxygen concentration	Higher in systemic arteries Lower in pulmonary arteries	Lower in systemic veins Higher in pulmonary veins

	Arteries	Veins
Valves	Not present	Present most commonly in limbs and in veins inferior to the heart

Venous System

The pumping action of the heart propels the blood into the arteries, from an area of higher pressure toward an area of lower pressure. If blood is to flow from the veins back into the heart, the pressure in the veins must be greater than the pressure in the atria of the heart. Two factors help maintain this pressure gradient between the veins and the heart. First, the pressure in the atria during diastole is very low, often approaching zero when the atria are relaxed (atrial diastole). Second, two physiologic "pumps" increase pressure in the venous system. The use of the term "pump" implies a physical device that speeds flow. These physiological pumps are less obvious.

Skeletal Muscle Pump

In many body regions, the pressure within the veins can be increased by the contraction of the surrounding skeletal muscle. This mechanism, known as the **skeletal muscle pump** (Figure 18.2.8), helps the lower-pressure veins counteract the force of gravity, increasing pressure to move blood back to the heart. As leg muscles contract, for example during walking or running, they exert pressure on nearby veins with their numerous one-way valves. This increased pressure causes blood to flow upward, opening valves superior to the contracting muscles so blood flows through. Simultaneously, valves inferior to the contracting muscles close; thus, blood should not seep back downward toward the feet. Military recruits are trained to flex their legs slightly while standing at attention for prolonged periods. Failure to do so may allow blood to pool in the lower limbs rather than returning to the heart. Consequently, the brain will not receive enough oxygenated blood, and the individual may lose consciousness.

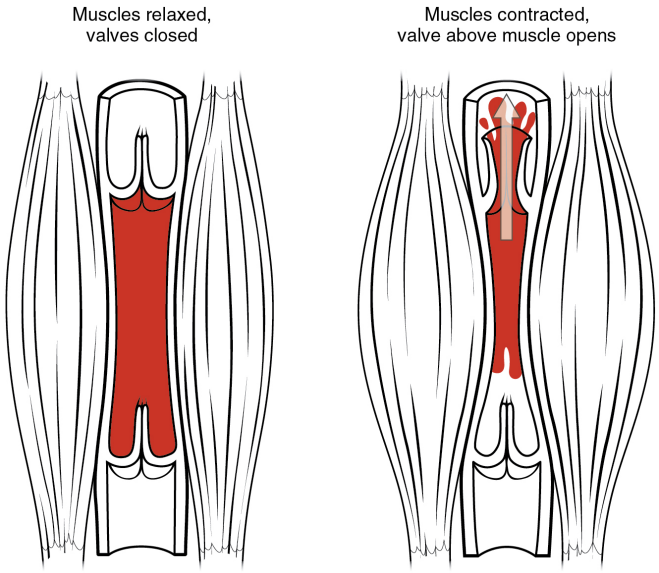

Figure 18.2.8: Skeletal Muscle Pump. The contraction of skeletal muscles surrounding a vein compresses the blood and increases the pressure in that area. This action forces blood closer to the heart where venous pressure is lower. Note the importance of the one-way valves to assure that blood flows only in the proper direction. (Image credit: "Skeletal Muscle Vein Pump" by OpenStax is licensed under CC BY 3.0)

Respiratory Pump

The **respiratory pump** aids blood flow through the veins of the thorax and abdomen. During inhalation, the volume of the thorax increases, largely through the contraction of the diaphragm, which moves downward and compresses the abdominal cavity. The elevation of the chest caused by the contraction of the external intercostal muscles also contributes to the increased volume of the thorax. The volume increase causes air pressure within the thorax to decrease, allowing us to inhale. Additionally, as air pressure within the thorax drops, blood pressure in the thoracic veins also decreases, falling below the pressure in the abdominal veins. This causes blood to flow along its pressure gradient from veins outside the thorax, where pressure is higher, into the

thoracic region, where pressure is now lower. This in turn promotes the return of blood from the thoracic veins to the atria. During exhalation, when air pressure increases within the thoracic cavity, pressure in the thoracic veins increases, speeding blood flow into the heart while valves in the veins prevent blood from flowing backward from the thoracic and abdominal veins.

DISORDERS OF THE...

Cardiovascular System: Edema and Varicose Veins

Despite the presence of valves and the contributions of other anatomical and physiological adaptations we will cover shortly, over the course of a day, some blood will inevitably pool, especially in the lower limbs, due to the pull of gravity. Any blood that accumulates in a vein will increase the pressure within it, which can then be reflected back into the smaller veins, venules, and eventually even the capillaries. Increased pressure will promote the flow of fluids out of the capillaries and into the interstitial fluid. The presence of excess tissue fluid around the cells leads to a condition called edema.

Most people experience a daily accumulation of tissue fluid, especially if they spend much of their work life on their feet (like most health professionals). However, clinical edema goes beyond normal swelling and requires medical treatment. Edema has many potential causes, including hypertension and heart failure, severe protein deficiency, renal failure, and many others. In order to treat edema, which is a sign rather than a discrete disorder, the underlying cause must be diagnosed and alleviated.

Figure 18.2.9: Varicose Veins. Varicose veins are commonly found in the superficial veins of the lower limbs. Defective valves cause localized pooling of blood in the veins that can lead to distention and deformity of the vessel appearing as lumps under the surface of the skin. (Image credit: "Left Calf and Varicose Veins" by Thomas Kriese is licensed under CC BY 2.0)

Edema may be accompanied by varicose veins, especially in the superficial veins of the legs (Figure 18.2.9). This disorder arises when defective valves allow blood to accumulate within the veins, causing them to distend, twist, and become visible on the surface of the integument. Varicose veins may occur in both sexes, but are more common in women and are often related to pregnancy. More than simple cosmetic blemishes, varicose veins are often painful and sometimes itchy or throbbing. Without treatment, they tend to grow worse over time. The use of support hose, as well as elevating the feet and legs whenever possible, may be helpful in alleviating this condition. Laser surgery and interventional radiologic procedures can reduce the size and severity of varicose veins. Severe cases may require conventional surgery to remove the damaged vessels. As there are typically redundant circulation patterns, that is, anastomoses, for the smaller and more superficial veins, removal does not typically impair the circulation. There is evidence that patients with varicose veins suffer a greater risk of developing a thrombus or clot.

Veins as Blood Reservoirs

In addition to their primary function of returning blood to the heart, veins may be considered blood reservoirs, since systemic

veins contain approximately 64 percent of the blood volume at any given time (Figure 18.2.10, Table 18.2.3). Their ability to hold this much blood is due to their high **capacitance**, that is, their capacity to distend (expand) readily to store a high volume of blood, even at a low pressure. The large lumens and relatively thin walls of veins make them far more distensible than arteries; thus, they are said to be **capacitance vessels**.

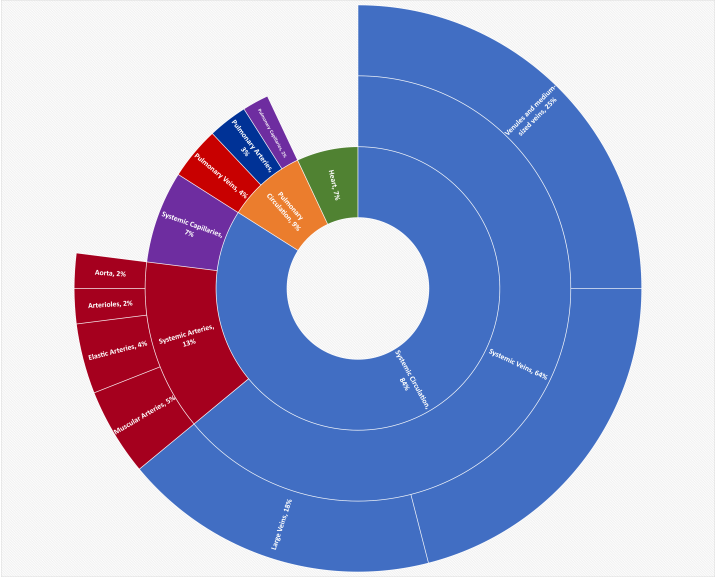

Figure 18.2.10: Graphical View of Distribution of Blood Flow. Blood spends a higher proportion of time in systemic veins than in any other part of the cardiovascular system. This chart shows the hierarchical percentages of blood flow found within each circuit of blood flow (inner ring), within the arteries, capillaries, and veins of each circuit (middle ring), and within each specific type of systemic vessel (outer ring). The same data used to create this graphic are given in Table 18.2.3. (Image credit: "Distribution of Blood Flow" by Julie Jenks is licensed under CC BY 4.0)

Table 18.2.3: Distribution of Blood Flow

Circuit of Blood Flow	Vessel Category	Specific Vessel Type	Percentage of Blood Flow
Systemic Circulation, 84%	Systemic Arteries, 13%	Aorta	2%
		Elastic Arteries	4%
		Muscular Arteries	5%
		Arterioles	2%
	Systemic Capillaries		7%
	Systemic Veins, 64%	Large Veins	18%
		Large venous network (liver, bone marrow, integument)	21%
		Venules and medium-sized veins	25%
Pulmonary Circulation, 9%		Pulmonary Arteries	3%
		Pulmonary Capillaries	2%
		Pulmonary Veins	4%
Heart			7%

Concept Review

Blood pumped by the heart flows through a series of vessels known as arteries, arterioles, capillaries, venules, and veins before

returning to the heart. Arteries transport blood away from the heart and branch into smaller vessels, forming arterioles. Arterioles distribute blood to capillary beds, the sites of exchange with the body tissues. Capillaries lead back to small vessels known as venules that flow into the larger veins and eventually back to the heart.

Arteries, arterioles, venules, and veins are composed of three tunics known as the tunica intima, tunica media, and tunica externa. The tunica intima is a thin layer composed of a simple squamous epithelium known as endothelium and a small amount of connective tissue. The tunica media is a thicker area composed of variable amounts of smooth muscle and connective tissue. It is the thickest layer in all but the largest arteries. The tunica externa is primarily a layer of connective tissue, although in veins, it also contains some smooth muscle. Blood flow through vessels can be dramatically increased or decreased by vasoconstriction and vasodilation. The arterial system is a relatively high-pressure system, so arteries have thick walls that appear round in cross section. The venous system is a lower-pressure system, containing veins that have larger lumens and thinner walls. They often appear flattened. Capillaries have only a tunica intima layer.

Review Questions

Q. The endothelium is found in the _____.

A. tunica intima

B. tunica media

C. tunica externa

D. lumen

Answer

Answer: A

Q. Nervi vasorum control _____.

A. vasoconstriction

B. vasodilation

C. capillary permeability

D. both vasoconstriction and vasodilation

Answer

Answer: D

Q. Closer to the heart, arteries would be expected to have a higher percentage of _____.

A. endothelium

B. smooth muscle fibers

C. elastic fibers

D. collagen fibers

Answer

Answer: C

Q. Which of the following best describes veins?

A. thick walled, small lumens, low pressure, lack valves

B. thin walled, large lumens, low pressure, have valves

C. thin walled, small lumens, high pressure, have valves

D. thick walled, large lumens, high pressure, lack valves

Answer

Answer: B

Q. An especially permeable type of capillary found in the liver and certain other tissues is called a _____.

A. capillary bed

B. fenestrated capillary

C. sinusoid capillary

D. metarteriole

Answer

Answer: C

Critical Thinking Questions

Q. Arterioles are often referred to as resistance vessels. Why?

Answer

A: Arterioles receive blood from arteries, which are vessels with a much larger lumen. As their own lumen averages just 30 micrometers or less, arterioles are critical in slowing down—or resisting—blood flow. The arterioles can also constrict or dilate, which varies their resistance, to help distribute blood flow to the tissues.

Q. A blood vessel with a few smooth muscle fibers and connective tissue, and only a very thin tunica externa conducts blood toward the heart. What type of vessel is this?

Answer

A: This is a venule.

Q. An obese patient comes to the clinic complaining of swollen feet and ankles, fatigue, shortness of breath, and often feeling "spaced out." She is a cashier in a grocery store, a job that requires her to stand all day. Outside of work, she engages in no physical activity. She confesses that, because of her weight, she finds even walking uncomfortable. Explain how the skeletal muscle pump might play a role in this patient's signs and symptoms.

Answer

A. People who stand upright all day and are inactive overall have very little skeletal muscle activity in the legs. Pooling of blood in the legs and feet is common. Venous return to the heart is reduced, a condition that in turn reduces cardiac output and therefore oxygenation of tissues throughout the body. This could at least partially account for the patient's fatigue and shortness of breath, as well as her "spaced out" feeling, which commonly reflects reduced oxygen to the brain.

Glossary

arteriole

(also, resistance vessel) very small artery that leads to a capillary

arteriovenous anastomosis
short vessel connecting an arteriole directly to a venule and bypassing the capillary beds

artery
blood vessel that conducts blood away from the heart; may be a conducting or distributing vessel

blood flow
movement of blood through a blood vessel or the heart

blood pressure
the pressure exerted by the blood on the walls of a blood vessel or the heart

capacitance
ability of a vein to distend and store blood

capacitance vessels
veins

capillary
smallest of blood vessels where physical exchange occurs between the blood and tissue cells surrounded by interstitial fluid

capillary bed
network of 10–100 capillaries connecting arterioles to venules

continuous capillary
most common type of capillary, found in virtually all tissues except epithelia and cartilage; contains very small gaps in the endothelial lining that permit exchange

elastic artery
(also, conducting artery) artery with abundant elastic fibers located closer to the heart, which maintains the pressure gradient and conducts blood to smaller branches

external elastic membrane
membrane composed of elastic fibers that separates the tunica media from the tunica externa; seen in larger arteries

fenestrated capillary
type of capillary with pores or fenestrations in the endothelium that allow for rapid passage of certain small materials

internal elastic membrane
membrane composed of elastic fibers that separates the tunica intima from the tunica media; seen in larger arteries

lumen
interior of a tubular structure such as a blood vessel or a portion of the alimentary canal through which blood, chyme, or other substances travel

metarteriole
short vessel arising from a terminal arteriole that branches to supply a capillary bed

microcirculation
blood flow through the capillaries

muscular artery
(also, distributing artery) artery with abundant smooth muscle in the tunica media that branches to distribute blood to the arteriole network

nervi vasorum
small nerve fibers found in arteries and veins that trigger contraction of the smooth muscle in their walls

perfusion
distribution of blood into the capillaries so the tissues can be supplied

permeable
allowing some substances to pass through

precapillary sphincters
circular rings of smooth muscle that surround the entrance to a capillary and regulate blood flow into that capillary

respiratory pump
increase in the volume of the thorax during inhalation that decreases air pressure, enabling venous blood to flow into the thoracic region, then exhalation increases pressure, moving blood into the atria

sinusoid capillary
rarest type of capillary, which has extremely large intercellular gaps in the basement membrane in addition to clefts and fenestrations; found in areas such as the bone marrow and liver where passage of large molecules occurs

skeletal muscle pump
effect on increasing blood pressure within veins by compression of the vessel caused by the contraction of nearby skeletal muscle

thoroughfare channel
continuation of the metarteriole that enables blood to bypass a capillary bed and flow directly into a venule, creating a vascular shunt

tunica externa
(also, tunica adventitia) outermost layer or tunic of a vessel (except capillaries)

tunica intima
(also, tunica interna) innermost lining or tunic of a vessel

tunica media
middle layer or tunic of a vessel (except capillaries)

vasa vasorum
small blood vessels located within the walls or tunics of larger vessels that supply nourishment to and remove wastes from the cells of the vessels

vascular shunt
continuation of the metarteriole and thoroughfare channel that allows blood to bypass the capillary beds to flow directly from the arterial to the venous circulation

vasoconstriction
constriction of the smooth muscle of a blood vessel, resulting in a decreased vascular diameter

vasodilation
relaxation of the smooth muscle in the wall of a blood vessel, resulting in an increased vascular diameter

vasomotion
irregular, pulsating flow of blood through capillaries and related structures

vein
blood vessel that conducts blood toward the heart

venous reserve
volume of blood contained within systemic veins in the integument, bone marrow, and liver that can be returned to the heart for circulation, if needed

venule
small vessel leading from the capillaries to veins

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18.3: Circulatory Pathways

By the end of this section, you will be able to:

- Identify the vessels through which blood travels within the pulmonary circuit, beginning from the right atrium of the heart and ending at the pulmonary vein
- Create a flow chart showing the major systemic arteries through which blood travels from the aorta and its major branches, to the most significant arteries feeding into the right and left upper and lower limbs
- Create a flow chart showing the major systemic veins through which blood travels from the feet to the right atrium of the heart

Virtually every cell, tissue, organ, and system in the body is impacted by the circulatory system. This includes the generalized and more specialized functions of transport of materials, capillary exchange, maintaining health by transporting white blood cells and various immunoglobulins (antibodies), hemostasis, regulation of body temperature, and helping to maintain acid-base balance. In addition to these shared functions, many systems enjoy a unique relationship with the circulatory system. Table 18.3.1 summarizes these relationships.

Table 18.3.1. *Summary of Interaction of the Circulatory System with Other Body Systems*

System	Role of Circulatory System
Digestive System	Delivers hormones: atrial natriuretic hormone (peptide) secreted by the heart atrial cells to help regulate blood volumes and pressures; epinephrine, ANH, angiotensin II, ADH, and thyroxine to help regulate blood pressure; estrogen to promote vascular health in women and men
Integumentary System	Carries clotting factors, platelets, and white blood cells for hemostasis, fighting infection, and repairing damage; regulates temperature by controlling blood flow to the surface, where heat can be dissipated; provides some coloration of integument; acts as a blood reservoir
Lymphatic System	Transports various white blood cells, including those produced by lymphatic tissue, and immunoglobulins (antibodies) throughout the body to maintain health; carries excess tissue fluid not able to be reabsorbed by the vascular capillaries back to the lymphatic system for processing
Muscular System	Provides nutrients and oxygen for contraction; removes lactic acid and distributes heat generated by contraction; muscular pumps aid in venous return; exercise contributes to cardiovascular health and helps to prevent atherosclerosis
Nervous System	Produces cerebrospinal fluid (CSF) within choroid plexuses; contributes to blood-brain barrier; cardiac and vasomotor centers regulate cardiac output and blood flow through vessels via autonomic system
Reproductive System	Aids in erection of genitalia in both sexes during sexual arousal; transports gonadotropic hormones that regulate reproductive functions

System	Role of Circulatory System
Respiratory System	Provides blood for critical exchange of gases to carry oxygen needed for metabolic reactions and carbon dioxide generated as byproducts of these processes
Skeletal System	Provides calcium, phosphate, and other minerals critical for bone matrix; transports hormones regulating buildup and absorption of matrix including growth hormone (somatotropin), thyroid hormone, calcitonin, and parathyroid hormone; erythropoietin stimulates myeloid cell hematopoiesis; some level of protection for select vessels by bony structures
Urinary System	Delivers 20% of resting circulation to kidneys for filtering, reabsorption of useful products, and secretion of excesses; regulates blood volume and pressure by regulating fluid loss in the form of urine and by releasing the enzyme renin that is essential in the renin-angiotensin-aldosterone mechanism

As you learn about the vessels of the systemic and pulmonary circuits, notice that many arteries and veins share the same names, parallel one another throughout the body, and are very similar on the right and left sides of the body. These pairs of vessels will be traced through only one side of the body. Where differences occur in branching patterns or when vessels are singular, this will be indicated. For example, you will find a pair of femoral arteries and a pair of femoral veins, with one vessel on each side of the body. In contrast, some vessels closer to the midline of the body, such as the aorta, are unique. Moreover, some superficial veins, such as the great saphenous vein in the femoral region, have no arterial counterpart. Another phenomenon that can make the study of vessels challenging is that names of vessels can change with location. Like a street that changes name as it passes through an intersection, an artery or vein can change names as it passes an anatomical landmark. For example, the left subclavian artery becomes the axillary artery as it passes through the body wall and into the axillary region, and then becomes the brachial artery as it flows from the axillary region into the upper arm (or brachium). You will also find examples of anastomoses where two blood vessels that previously branched reconnect. Anastomoses are especially common in veins, where they help maintain blood flow even when one vessel is blocked or narrowed, although there are some important ones in the arteries supplying the brain.

As you read about circular pathways, notice that there is an occasional, very large artery referred to as a **trunk**, a term indicating that the vessel gives rise to several smaller arteries. For example, the celiac trunk gives rise to the left gastric, common hepatic, and splenic arteries.

As you study this section, imagine you are on a “Voyage of Discovery” similar to Lewis and Clark’s expedition in 1804–1806, which followed rivers and streams through unfamiliar territory, seeking a water route from the Atlantic to the Pacific Ocean. You might envision being inside a miniature boat, exploring the various branches of the circulatory system. This simple approach has proven effective for many students in mastering these major circulatory patterns. Another approach that works well for many students is to create simple line drawings similar to the ones provided, labeling each of the major vessels. It is beyond the scope of this text to name every vessel in the body. However, we will attempt to discuss the major pathways for blood and acquaint you with the major named arteries and veins in the body. Also, please keep in mind that individual variations in circulation patterns are not uncommon.

Pulmonary Circulation

Recall that blood returning from the systemic circuit enters the right atrium (Figure 18.3.1) via the superior and inferior venae cavae and the coronary sinus, which drains the blood supply of the heart muscle. These vessels will be described more fully later in this section. This blood is relatively low in oxygen and relatively high in carbon dioxide, since much of the oxygen has been extracted for use by the tissues and the waste gas carbon dioxide was picked up to be transported to the lungs for elimination. From the right atrium, blood moves into the right ventricle, which pumps it to the lungs for gas exchange. This system of vessels is referred to as the **pulmonary circuit**.

The single vessel exiting the right ventricle is the **pulmonary trunk**. At the base of the pulmonary trunk is the pulmonary semilunar

valve, which prevents backflow of blood into the right ventricle during ventricular diastole. As the pulmonary trunk reaches the superior surface of the heart, it curves posteriorly and rapidly bifurcates (divides) into two branches, a left and a right **pulmonary artery**. To prevent confusion between these vessels, it is important to refer to the vessel exiting the heart as the pulmonary trunk, rather than also calling it a pulmonary artery. The pulmonary arteries in turn branch many times within the lung, forming a series of smaller arteries and arterioles that eventually lead to the pulmonary capillaries. The pulmonary capillaries surround lung structures known as alveoli that are the sites of oxygen and carbon dioxide exchange.

Once gas exchange is completed, oxygenated blood flows from the pulmonary capillaries into a series of pulmonary venules that eventually lead to a series of larger **pulmonary veins**. Four pulmonary veins, two on the left and two on the right, return blood to the left atrium. At this point, the pulmonary circuit is complete. Table 18.3.2 defines the major arteries and veins of the pulmonary circuit discussed in the text.

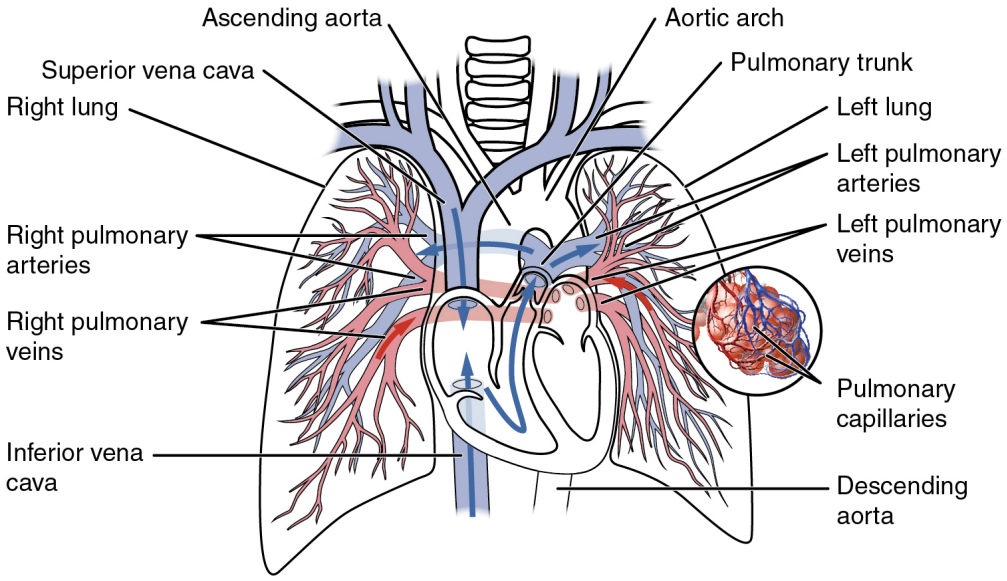

Figure 18.3.1: Pulmonary Circuit. Blood exiting from the right ventricle flows into the pulmonary trunk, which bifurcates into the two pulmonary arteries. These vessels branch to supply blood to the pulmonary capillaries, where gas exchange occurs within the lung alveoli. Blood returns via the pulmonary veins to the left atrium. (Image credit: "Pulmonary Circuit" by OpenStax is licensed under CC BY 3.0)

Table 18.3.2: Pulmonary Arteries and Veins

Vessel	Description
Pulmonary trunk	Single large vessel exiting the right ventricle that divides to form the right and left pulmonary arteries
Pulmonary arteries	Left and right vessels that form from the pulmonary trunk and lead to smaller arterioles and eventually to the pulmonary capillaries
Pulmonary veins	Two sets of paired vessels—one pair on each side—that are formed from the small venules, leading away from the pulmonary capillaries to flow into the left atrium

Overview of Systemic Arteries

Blood relatively high in oxygen concentration is returned from the pulmonary circuit to the left atrium via the four pulmonary veins. From the left atrium, blood moves into the left ventricle, which pumps blood into the aorta. The aorta and its branches—the systemic arteries—send blood to virtually every organ of the body (Figure 18.3.2).

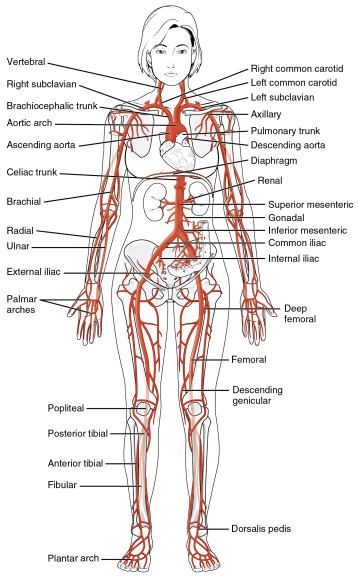

Figure 18.3.2: Systemic Arteries. The major systemic arteries shown here deliver oxygenated blood throughout the body. (Image credit: "Major Systemic Artery" by OpenStax is licensed under CC BY 3.0)

The Aorta

The **aorta** is the largest artery in the body (Figure 18.3.3). It arises from the left ventricle and eventually descends to the abdominal region, where it bifurcates at the level of the fourth lumbar vertebra into the two common iliac arteries. The aorta consists of the ascending aorta, the aortic arch, and the descending aorta, which passes through the diaphragm and a landmark that divides into the superior thoracic and inferior abdominal components. Arteries originating from the aorta ultimately distribute blood to virtually all tissues of the body. At the base of the aorta is the aortic semilunar valve that prevents backflow of blood into the left ventricle while the heart is relaxing. After exiting the heart, the **ascending aorta** moves in a superior direction for approximately 5 cm and ends at the sternal angle. Following this ascent, it reverses direction, forming a graceful arc to the left, called the **aortic arch**. The aortic arch descends toward the inferior portions of the body and ends at the level of the intervertebral disk between the fourth and fifth thoracic vertebrae. Beyond this point, the **descending aorta** continues close to the bodies of the vertebrae and passes through an opening in the diaphragm known as the **aortic hiatus**. Superior to the diaphragm, the aorta is called the **thoracic aorta**, and inferior to the diaphragm, it is called the **abdominal aorta**. The abdominal aorta terminates when it bifurcates into the two common iliac arteries at the level of the fourth lumbar vertebra. See Figure 18.3.3 for an illustration of the ascending aorta, the aortic arch, and the initial segment of the descending aorta plus major branches; Table 18.3.3 summarizes the structures of the aorta.

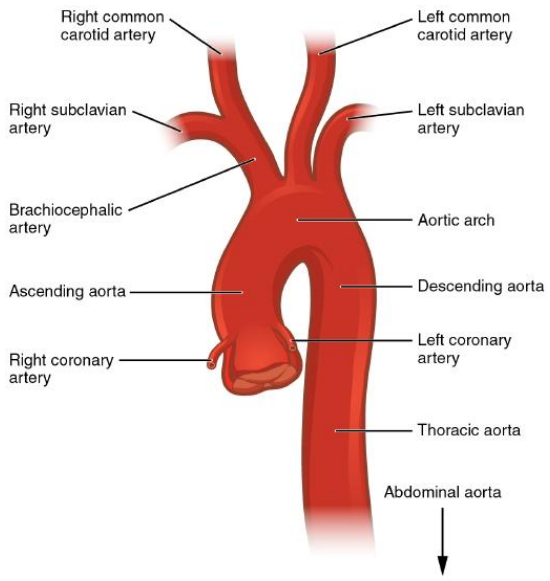

Figure 18.3.3: Aorta. The aorta has distinct regions, including the ascending aorta, aortic arch, and the descending aorta, which includes the thoracic and abdominal regions. (Image credit: "Aorta" by OpenStax is licensed under CC BY 3.0)

Table 18.3.3: Components of the Aorta

Vessel	Description
Aorta	Largest artery in the body, originating from the left ventricle and descending to the abdominal region, where it bifurcates into the common iliac arteries at the level of the fourth lumbar vertebra; arteries originating from the aorta distribute blood to virtually all tissues of the body
Ascending aorta	Initial portion of the aorta, rising superiorly from the left ventricle for a distance of approximately 5 cm
Aortic arch	Graceful arc to the left that connects the ascending aorta to the descending aorta; ends at the intervertebral disk between the fourth and fifth thoracic vertebrae
Descending aorta	Portion of the aorta that continues inferiorly past the end of the aortic arch; subdivided into the thoracic aorta and the abdominal aorta
Thoracic aorta	Portion of the descending aorta superior to the aortic hiatus
Abdominal aorta	Portion of the aorta inferior to the aortic hiatus and superior to the common iliac arteries

Coronary Circulation

The first vessels that branch from the ascending aorta are the paired coronary arteries (see Figure 18.3.3), which arise from two of the three sinuses in the ascending aorta just superior to the aortic semilunar valve. These sinuses contain the aortic baroreceptors and chemoreceptors critical to maintain cardiac function. The left coronary artery arises from the left posterior aortic sinus. The right coronary artery arises from the anterior aortic sinus. Normally, the right posterior aortic sinus does not give rise to a vessel.

The coronary arteries encircle the heart, forming a ring-like structure that divides into the next level of branches that supplies blood to the heart tissues. The chapter on the Heart covers coronary circulation in more detail.

Aortic Arch Branches

There are three major branches of the aortic arch: the brachiocephalic artery, the left common carotid artery, and the left subclavian (literally “under the clavicle”) artery. As you would expect based upon proximity to the heart, each of these vessels is classified as an elastic artery.

The brachiocephalic artery is located only on the right side of the body; there is no corresponding artery on the left. The brachiocephalic artery branches into the right subclavian artery and the right common carotid artery. The left subclavian and left common carotid arteries arise independently from the aortic arch but otherwise follow a similar pattern and distribution to the corresponding arteries on the right side (see Figure 18.3.2).

Each **subclavian artery** supplies blood to the arms, chest, shoulders, back, and central nervous system. It then gives rise to three major branches: the internal thoracic artery, the vertebral artery, and the thyrocervical artery. The **internal thoracic artery**, or mammary artery, supplies blood to the thymus, the pericardium of the heart, and the anterior chest wall. The **vertebral artery** passes through the vertebral foramen in the cervical vertebrae and then through the foramen magnum into the cranial cavity to supply blood to the brain and spinal cord. The paired vertebral arteries join together to form the large basilar artery at the base of the medulla oblongata. This is an example of an anastomosis. The subclavian artery also gives rise to the **thyrocervical artery** that provides blood to the thyroid, the cervical region of the neck, and the upper back and shoulder.

The **common carotid artery** divides into internal and external carotid arteries. The right common carotid artery arises from the brachiocephalic artery and the left common carotid artery arises directly from the aortic arch. The **external carotid artery** supplies blood to numerous structures within the face, lower jaw, neck, esophagus, and larynx. These branches include the lingual, facial, occipital, maxillary, and superficial temporal arteries. The **internal carotid artery** initially forms an expansion known as the carotid sinus, containing the carotid baroreceptors and chemoreceptors. Like their counterparts in the aortic sinuses, the information provided by these receptors is critical to maintaining cardiovascular homeostasis (Figure 18.3.4).

The internal carotid arteries along with the vertebral arteries are the two primary suppliers of blood to the human brain. Given the central role and vital importance of the brain to life, it is critical that blood supply to this organ remains uninterrupted. Recall that blood flow to the brain is remarkably constant, with approximately 20 percent of blood flow directed to this organ at any given time. When blood flow is interrupted, even for just a few seconds, a **transient ischemic attack (TIA)**, or mini-stroke, may occur, resulting in loss of consciousness or temporary loss of neurological function. In some cases, the damage may be permanent. Loss of blood flow for longer periods, typically between 3 and 4 minutes, will likely produce irreversible brain damage or a stroke, also called a **cerebrovascular accident (CVA)**. The locations of the arteries in the brain not only provide blood flow to the brain tissue but also prevent interruption in the flow of blood. Both the carotid and vertebral arteries branch once they enter the cranial cavity, and some of these branches form a structure known as the **arterial circle** (or **circle of Willis**), an anastomosis that is remarkably like a traffic circle that sends off branches (in this case, arterial branches to the brain). As a rule, branches to the anterior portion of the cerebrum are normally fed by the internal carotid arteries; the remainder of the brain receives blood flow from branches associated with the vertebral arteries.

The internal carotid artery continues through the carotid canal of the temporal bone and enters the base of the brain through the carotid foramen where it gives rise to several branches (Figure 18.3.4 and Figure 18.3.5). One of these branches is the **anterior cerebral artery** that supplies blood to the frontal lobe of the cerebrum. Another branch, the **middle cerebral artery**, supplies blood to the temporal and parietal lobes, which are the most common sites of CVAs. The **ophthalmic artery**, the third major branch, provides blood to the eyes.

The right and left anterior cerebral arteries join together to form an anastomosis called the **anterior communicating artery**. The initial segments of the anterior cerebral arteries and the anterior communicating artery form the anterior portion of the arterial circle. The posterior portion of the arterial circle is formed by a left and a right **posterior communicating artery** that branches from the **posterior cerebral artery**, which arises from the basilar artery. It provides blood to the posterior portion of the cerebrum and brain stem. The **basilar artery** is an anastomosis that begins at the junction of the two vertebral arteries and sends branches to the cerebellum and brain stem. It flows into the posterior cerebral arteries. Table 18.3.4 summarizes the aortic arch branches, including the major branches supplying the brain.

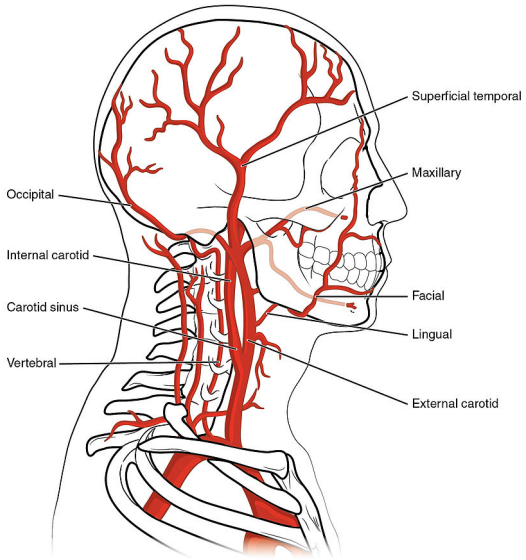

Figure 18.3.4: Arteries Supplying the Head and Neck. The common carotid artery gives rise to the external and internal carotid arteries. The external carotid artery remains superficial and gives rise to many arteries of the head. The internal carotid artery first forms the carotid sinus and then reaches the brain via the carotid canal and carotid foramen, emerging into the cranium via the foramen lacerum. The vertebral artery branches from the subclavian artery and passes through the transverse foramen in the cervical vertebrae, entering the base of the skull at the vertebral foramen. The subclavian artery continues toward the arm as the axillary artery. (Image credit: "Common Carotid Artery" by OpenStax is licensed under CC BY 3.0)

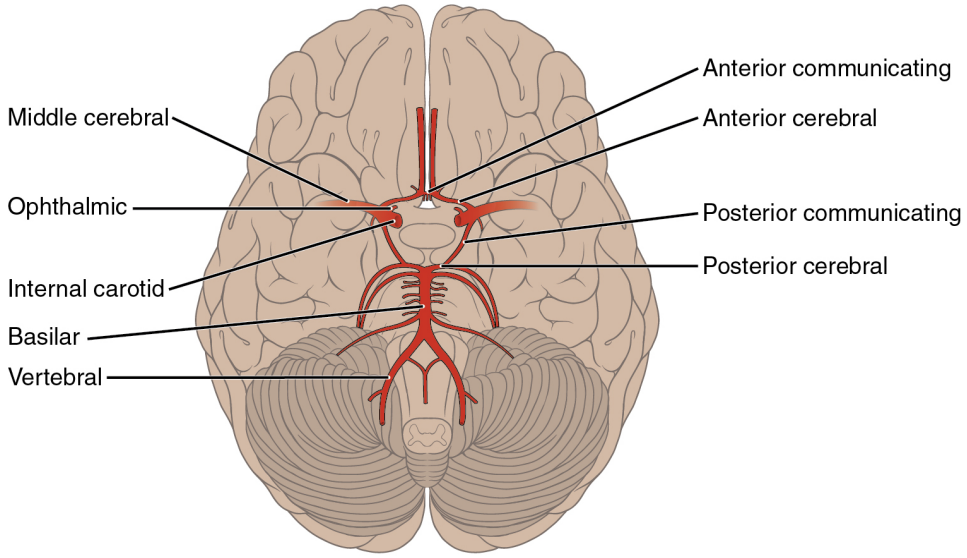

Figure 18.3.5: Arteries Serving the Brain. This inferior view shows the network of arteries serving the brain. The structure is referred to as the arterial circle or circle of Willis. (Image credit: "Arteries of the Brain" by OpenStax is licensed under CC BY 3.0)

Table 18.3.4: Aortic Arch Branches and Brain Circulation

Vessel	Description
Brachiocephalic artery	Single vessel located on the right side of the body; the first vessel branching from the aortic arch; gives rise to the right subclavian artery and the right common carotid artery; supplies blood to the head, neck, upper limb, and wall of the thoracic region
Subclavian artery	The right subclavian artery arises from the brachiocephalic artery while the left subclavian artery arises from the aortic arch; gives rise to the internal thoracic, vertebral, and thyrocervical arteries; supplies blood to the arms, chest, shoulders, back, and central nervous system
Internal thoracic artery	Also called the mammary artery; arises from the subclavian artery; supplies blood to the thymus, pericardium of the heart, and anterior chest wall

Vessel	Description
Vertebral artery	Arises from the subclavian artery and passes through the vertebral foramen through the foramen magnum to the brain; joins with the internal carotid artery to form the arterial circle; supplies blood to the brain and spinal cord
Thyrocervical artery	Arises from the subclavian artery; supplies blood to the thyroid, the cervical region, the upper back, and shoulder
Common carotid artery	The right common carotid artery arises from the brachiocephalic artery and the left common carotid artery arises from the aortic arch; each gives rise to the external and internal carotid arteries; supplies the respective sides of the head and neck
External carotid artery	Arises from the common carotid artery; supplies blood to numerous structures within the face, lower jaw, neck, esophagus, and larynx
Internal carotid artery	Arises from the common carotid artery and begins with the carotid sinus; goes through the carotid canal of the temporal bone to the base of the brain; combines with the branches of the vertebral artery, forming the arterial circle; supplies blood to the brain
Arterial circle or circle of Willis	An anastomosis located at the base of the brain that ensures continual blood supply; formed from the branches of the internal carotid and vertebral arteries; supplies blood to the brain
Anterior cerebral artery	Arises from the internal carotid artery; supplies blood to the frontal lobe of the cerebrum
Middle cerebral artery	Another branch of the internal carotid artery; supplies blood to the temporal and parietal lobes of the cerebrum
Ophthalmic artery	Branch of the internal carotid artery; supplies blood to the eyes
Anterior communicating artery	An anastomosis of the right and left internal carotid arteries; supplies blood to the brain
Posterior communicating artery	Branches of the posterior cerebral artery that form part of the posterior portion of the arterial circle; supplies blood to the brain
Posterior cerebral artery	Branch of the basilar artery that forms a portion of the posterior segment of the arterial circle of Willis; supplies blood to the posterior portion of the cerebrum and brain stem
Basilar artery	Formed from the fusion of the two vertebral arteries; sends branches to the cerebellum, brain stem, and the posterior cerebral arteries; the main blood supply to the brain stem

Thoracic Aorta and Major Branches

The thoracic aorta begins at the level of vertebra T5 and continues through to the diaphragm at the level of T12, initially traveling within the mediastinum to the left of the vertebral column. As it passes through the thoracic region, the thoracic aorta gives rise to several branches, which are collectively referred to as visceral branches and parietal branches (Figure 18.3.6). Those branches that supply blood primarily to visceral organs are known as the **visceral branches** and include the bronchial arteries, pericardial arteries, esophageal arteries, and the mediastinal arteries, each named after the tissues it supplies. Each **bronchial artery** (typically two on the left and one on the right) supplies systemic blood to the lungs and visceral pleura, in addition to the blood pumped to the lungs for oxygenation via the pulmonary circuit. The bronchial arteries follow the same path as the respiratory branches, beginning with the bronchi and ending with the bronchioles. There is considerable, but not total, intermingling of the systemic and pulmonary blood at anastomoses in the smaller branches of the lungs. This may sound incongruous—that is, the mixing of systemic arterial blood high in oxygen with the pulmonary arterial blood lower in oxygen—but the systemic vessels also deliver nutrients to the lung tissue just as they do elsewhere in the body. The mixed blood drains into typical pulmonary veins, whereas the bronchial artery branches remain separate and drain into bronchial veins described later. Each **pericardial artery** supplies blood to the pericardium, the **esophageal artery** provides blood to the esophagus, and the **mediastinal artery** provides blood to the mediastinum. The remaining thoracic aorta branches are collectively referred to as **parietal branches** or somatic branches, and include the intercostal and superior phrenic arteries. Each **intercostal artery** provides blood to the muscles of the

thoracic cavity and vertebral column. The **superior phrenic artery** provides blood to the superior surface of the diaphragm. Table 18.3.5 lists the arteries of the thoracic region.

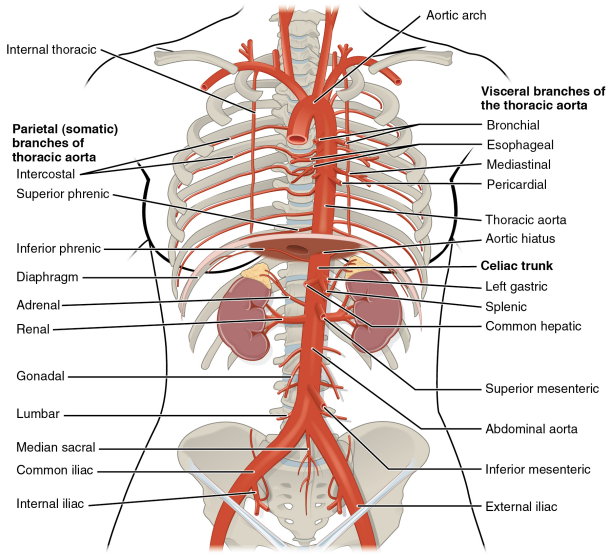

Figure 18.3.6: Arteries of the Thoracic and Abdominal Regions. The thoracic aorta gives rise to the arteries of the visceral and parietal branches. (Image credit: "Thoracic Abdominal Arteries" by OpenStax is licensed under CC BY 3.0)

Table 18.3.5. Arteries of the Thoracic Region

Vessel	Description
Visceral branches	A group of arterial branches of the thoracic aorta; supplies blood to the viscera (i.e., organs) of the thorax
Bronchial artery	Systemic branch from the aorta that provides oxygenated blood to the lungs; this blood supply is in addition to the pulmonary circuit that brings blood for oxygenation
Pericardial artery	Branch of the thoracic aorta; supplies blood to the pericardium
Esophageal artery	Branch of the thoracic aorta; supplies blood to the esophagus
Mediastinal artery	Branch of the thoracic aorta; supplies blood to the mediastinum
Parietal branches	Also called somatic branches, a group of arterial branches of the thoracic aorta; include those that supply blood to the thoracic wall, vertebral column, and the superior surface of the diaphragm
Intercostal artery	Branch of the thoracic aorta; supplies blood to the muscles of the thoracic cavity and vertebral column
Superior phrenic artery	Branch of the thoracic aorta; supplies blood to the superior surface of the diaphragm

Abdominal Aorta and Major Branches

After crossing through the diaphragm at the aortic hiatus, the thoracic aorta is called the abdominal aorta (see Figure 18.3.6). This vessel remains to the left of the vertebral column and is embedded in adipose tissue behind the peritoneal cavity. It formally ends at approximately the level of vertebra L4, where it bifurcates to form the common iliac arteries. Before this division, the abdominal aorta gives rise to several important branches. A single **celiac trunk** (artery) emerges and divides into the **left gastric artery** to supply blood to the stomach and esophagus, the **splenic artery** to supply blood to the spleen, and the **common hepatic artery**, which in turn gives rise to the hepatic artery proper to supply blood to the liver, the **right gastric artery** to supply blood to the

stomach, the **cystic artery** to supply blood to the gall bladder, and several branches, one to supply blood to the duodenum and another to supply blood to the pancreas. Two additional single vessels arise from the abdominal aorta. These are the superior and inferior mesenteric arteries. The **superior mesenteric artery** arises approximately 2.5 cm after the celiac trunk and branches into several major vessels that supply blood to the small intestine (duodenum, jejunum, and ileum), the pancreas, and a majority of the large intestine. The **inferior mesenteric artery** supplies blood to the distal segment of the large intestine, including the rectum. It arises approximately 5 cm superior to the common iliac arteries.

In addition to these single branches, the abdominal aorta gives rise to several significant paired arteries along the way. These include the inferior phrenic arteries, the adrenal arteries, the renal arteries, the gonadal arteries, and the lumbar arteries. Each **inferior phrenic artery** is a counterpart of a superior phrenic artery and supplies blood to the inferior surface of the diaphragm. The **adrenal artery** supplies blood to the adrenal (suprarenal) glands and arises near the superior mesenteric artery. Each **renal artery** branches approximately 2.5 cm inferior to the superior mesenteric arteries and supplies a kidney. The right renal artery is longer than the left since the aorta lies to the left of the vertebral column and the vessel must travel a greater distance to reach its target. Renal arteries branch repeatedly to supply blood to the kidneys. Each **gonadal artery** supplies blood to the gonads, or reproductive organs, and is also described as either an ovarian artery or a testicular artery (internal spermatic), depending upon the sex of the individual. An **ovarian artery** supplies blood to an ovary, uterine (Fallopian) tube, and the uterus, and is located within the suspensory ligament of the uterus. It is considerably shorter than a **testicular artery**, which ultimately travels outside the body cavity to the testes, forming one component of the spermatic cord. The gonadal arteries arise inferior to the renal arteries and are generally retroperitoneal. The ovarian artery continues to the uterus where it forms an anastomosis with the uterine artery that supplies blood to the uterus. Both the uterine arteries and vaginal arteries, which distribute blood to the vagina, are branches of the internal iliac artery. The four paired **lumbar arteries** are the counterparts of the intercostal arteries and supply blood to the lumbar region, the abdominal wall, and the spinal cord. In some instances, a fifth pair of lumbar arteries emerges from the median sacral artery.

The aorta divides at approximately the level of vertebra L4 into a left and a right **common iliac artery** but continues as a small vessel, the **median sacral artery**, into the sacrum. The common iliac arteries provide blood to the pelvic region and ultimately to the lower limbs. They split into external and internal iliac arteries approximately at the level of the lumbar-sacral articulation. Each **internal iliac artery** sends branches to the urinary bladder, the walls of the pelvis, the external genitalia, and the medial portion of the femoral region. In females, they also provide blood to the uterus and vagina. The much larger **external iliac artery** supplies blood to each of the lower limbs. Figure 18.3.7 shows the distribution of the major branches of the aorta into the thoracic and abdominal regions. Figure 18.3.8 shows the distribution of the major branches of the common iliac arteries. Table 18.3.6 summarizes the major branches of the abdominal aorta.

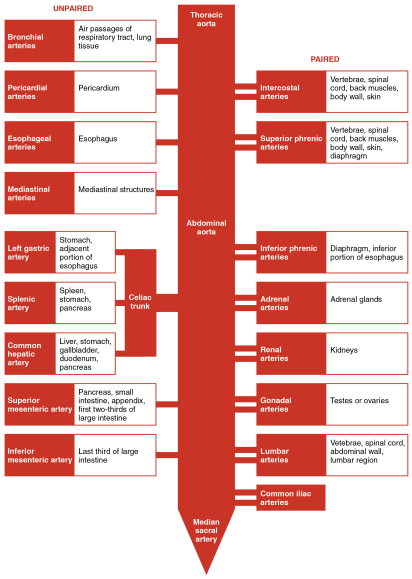

Figure 18.3.7: Major Branches of the Descending Aorta. The flow chart summarizes the distribution of the major branches of the aorta into the thoracic and abdominal regions. (Image credit: "Thoracic Abdominal Arteries" by OpenStax is licensed under CC BY 3.0)

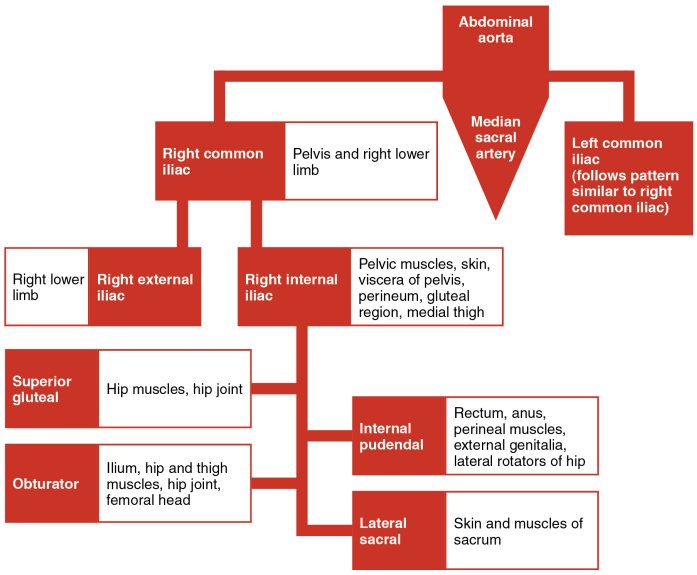

Figure 18.3.8: Major Branches of the Iliac Arteries. The flow chart summarizes the distribution of the major branches of the common iliac arteries into the pelvis and lower limbs. The left side follows a similar pattern to the right. (Image credit: "Iliac Artery Branches Chart" by OpenStax is licensed under CC BY 3.0)

Table 18.3.6: Arteries Branching from the Abdominal Aorta

Vessel	Description
Celiac trunk	Also called the celiac artery; a major branch of the abdominal aorta; gives rise to the left gastric artery, the splenic artery, and the common hepatic artery that forms the hepatic artery to the liver, the right gastric artery to the stomach, and the cystic artery to the gall bladder
Left gastric artery	Branch of the celiac trunk; supplies blood to the stomach
Splenic artery	Branch of the celiac trunk; supplies blood to the spleen
Common hepatic artery	Branch of the celiac trunk that forms the hepatic artery, the right gastric artery, and the cystic artery
Hepatic artery proper	Branch of the common hepatic artery; supplies systemic blood to the liver
Right gastric artery	Branch of the common hepatic artery; supplies blood to the stomach
Cystic artery	Branch of the common hepatic artery; supplies blood to the gall bladder
Superior mesenteric artery	Branch of the abdominal aorta; supplies blood to the small intestine (duodenum, jejunum, and ileum), the pancreas, and a majority of the large intestine
Inferior mesenteric artery	Branch of the abdominal aorta; supplies blood to the distal segment of the large intestine and rectum
Inferior phrenic arteries	Branches of the abdominal aorta; supply blood to the inferior surface of the diaphragm

Vessel	Description
Adrenal artery	Branch of the abdominal aorta; supplies blood to the adrenal (suprarenal) glands
Renal artery	Branch of the abdominal aorta; supplies each kidney
Gonadal artery	Branch of the abdominal aorta; supplies blood to the gonads or reproductive organs; also described as ovarian arteries or testicular arteries, depending upon the sex of the individual
Ovarian artery	Branch of the abdominal aorta; supplies blood to ovary, uterine (Fallopian) tube, and uterus
Testicular artery	Branch of the abdominal aorta; ultimately travels outside the body cavity to the testes and forms one component of the spermatic cord
Lumbar arteries	Branches of the abdominal aorta; supply blood to the lumbar region, the abdominal wall, and spinal cord
Common iliac artery	Branch of the aorta that leads to the internal and external iliac arteries
Median sacral artery	Continuation of the aorta into the sacrum
Internal iliac artery	Branch from the common iliac arteries; supplies blood to the urinary bladder, walls of the pelvis, external genitalia, and the medial portion of the femoral region; in females, also provides blood to the uterus and vagina
External iliac artery	Branch of the common iliac artery that leaves the body cavity and becomes a femoral artery; supplies blood to the lower limbs

Arteries Serving the Upper Limbs

As the subclavian artery exits the thorax into the axillary region, it is renamed the **axillary artery**. Although it does branch and supply blood to the region near the head of the humerus (via the humeral circumflex arteries), the majority of the vessel continues into the upper arm, or brachium, and becomes the brachial artery (Figure 18.3.9). The **brachial artery** supplies blood to much of the brachial region and divides at the elbow into several smaller branches, including the deep brachial arteries, which provide blood to the posterior surface of the arm, and the ulnar collateral arteries, which supply blood to the region of the elbow. As the brachial artery approaches the coronoid fossa, it bifurcates into the radial and ulnar arteries, which continue into the forearm, or antebrachium. The **radial artery** and **ulnar artery** parallel their namesake bones, giving off smaller branches until they reach the wrist, or carpal region. At this level, they fuse to form the superficial and deep **palmar arches** that supply blood to the hand, as well as the **digital arteries** that supply blood to the digits. Figure 18.3.10 shows the distribution of systemic arteries from the heart into the upper limb. Table 18.3.7 summarizes the arteries serving the upper limbs.

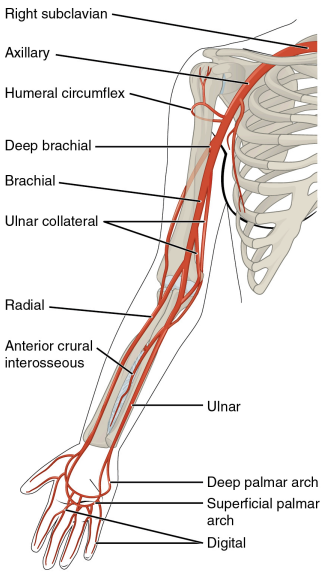

Figure 18.3.9: Major Arteries Serving the Upper Limb. The arteries that supply blood to the arms and hands are extensions of the subclavian arteries. (Image credit: "Thoracic Upper Limb Arteries" by OpenStax is licensed under CC BY 3.0)

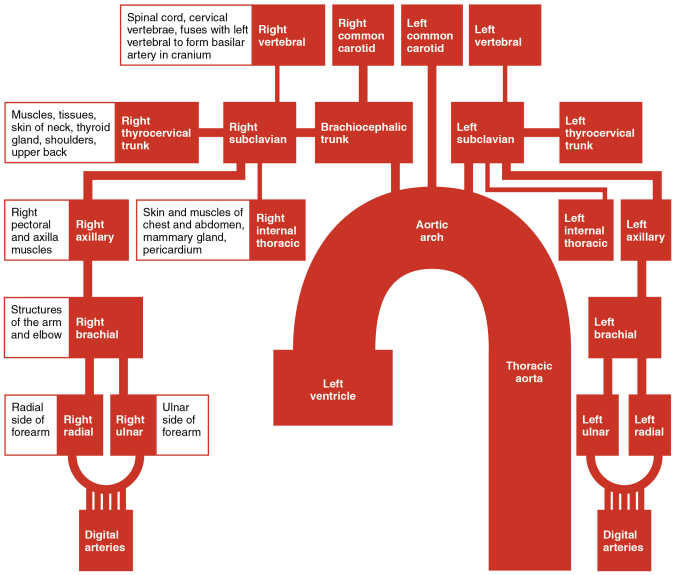

Figure 18.3.10: Major Arteries of the Neck and Upper Limb. The flow chart summarizes the distribution of the major arteries from the heart into the neck and upper limb. (Image credit: "Thoracic Upper Limb Arteries Chart" by OpenStax is licensed under CC BY 3.0)

Table 18.3.7: Arteries Serving the Upper Limbs

Vessel	Description
Axillary artery	Continuation of the subclavian artery as it penetrates the body wall and enters the axillary region; supplies blood to the region near the head of the humerus (humeral circumflex arteries); the majority of the vessel continues into the brachium and becomes the brachial artery
Brachial artery	Continuation of the axillary artery in the brachium; supplies blood to much of the brachial region; gives off several smaller branches that provide blood to the posterior surface of the arm in the region of the elbow; bifurcates into the radial and ulnar arteries at the coronoid fossa
Radial artery	Formed at the bifurcation of the brachial artery; parallels the radius; gives off smaller branches until it reaches the carpal region where it fuses with the ulnar artery to form the superficial and deep palmar arches; supplies blood to the lower arm and carpal region

Vessel	Description
Ulnar artery	Formed at the bifurcation of the brachial artery; parallels the ulna; gives off smaller branches until it reaches the carpal region where it fuses with the radial artery to form the superficial and deep palmar arches; supplies blood to the lower arm and carpal region
Palmar arches (superficial and deep)	Formed from anastomosis of the radial and ulnar arteries; supply blood to the hand and digital arteries
Digital arteries	Formed from the superficial and deep palmar arches; supply blood to the digits

Arteries Serving the Lower Limbs

The external iliac artery exits the body cavity and enters the femoral region of the lower leg (Figure 18.3.11). As it passes through the body wall, it is renamed the **femoral artery**. It gives off several smaller branches as well as the lateral **deep femoral artery** that in turn gives rise to a **lateral circumflex artery**. These arteries supply blood to the deep muscles of the thigh as well as ventral and lateral regions of the integument. The femoral artery also gives rise to the **genicular artery**, which provides blood to the region of the knee. As the femoral artery passes posterior to the knee near the popliteal fossa, it is called the popliteal artery. The **popliteal artery** branches into the anterior and posterior tibial arteries.

The **anterior tibial artery** is located between the tibia and fibula, and supplies blood to the muscles and integument of the anterior tibial region. Upon reaching the tarsal region, it becomes the **dorsalis pedis artery**, which branches repeatedly and provides blood to the tarsal and dorsal regions of the foot. The **posterior tibial artery** provides blood to the muscles and integument on the posterior surface of the tibial region. The fibular or peroneal artery branches from the posterior tibial artery. It bifurcates and becomes the **medial plantar artery** and **lateral plantar artery**, providing blood to the plantar surfaces. There is an anastomosis with the dorsalis pedis artery, and the medial and lateral plantar arteries form two arches called the **dorsal arch** (also called the arcuate arch) and the **plantar arch**, which provide blood to the remainder of the foot and toes. Figure 18.3.12 shows the distribution of the major systemic arteries in the lower limb. Table 18.3.8 summarizes the major systemic arteries discussed in the text.

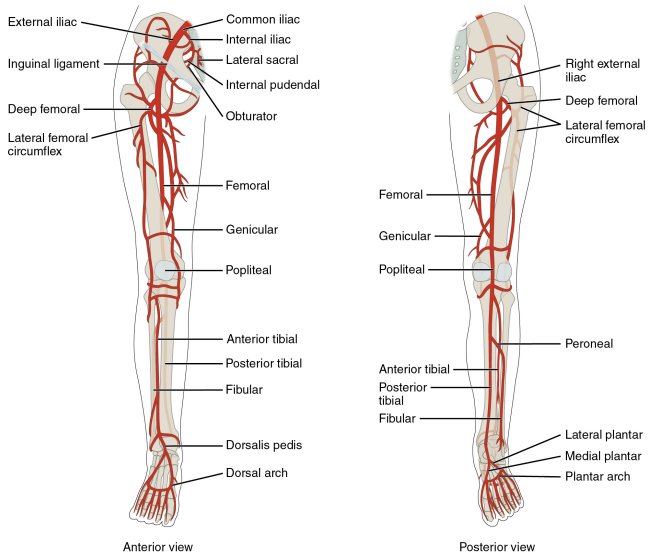

Figure 18.3.11: Major Arteries Serving the Lower Limb. Major arteries serving the lower limb are shown in anterior and posterior views. (Image credit: "Lower Limb Arteries" by OpenStax is licensed under CC BY 3.0)

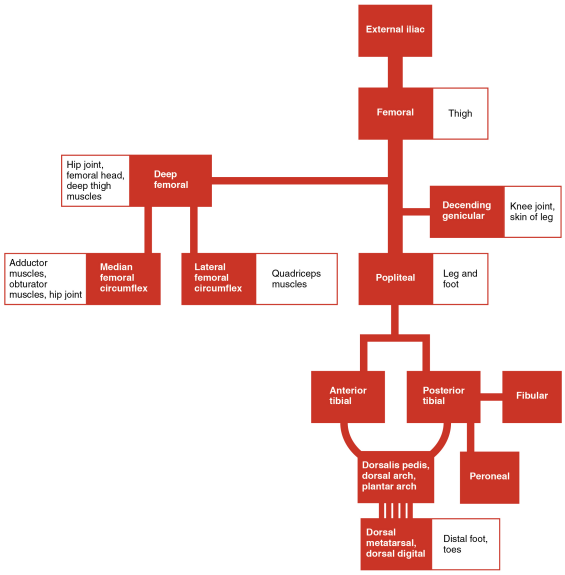

Figure 18.3.12: Systemic Arteries of the Lower Limb. The flow chart summarizes the distribution of the systemic arteries from the external iliac artery into the lower limb. (Image credit: "Lower Limb Arteries Chart" by OpenStax is licensed under CC BY 3.0)

Table 18.3.8: Arteries Serving the Lower Limbs

Vessel	Description
Femoral artery	Continuation of the external iliac artery after it passes through the body cavity; divides into several smaller branches, the lateral deep femoral artery, and the genicular artery; becomes the popliteal artery as it passes posterior to the knee
Deep femoral artery	Branch of the femoral artery; gives rise to the lateral circumflex arteries
Lateral circumflex artery	Branch of the deep femoral artery; supplies blood to the deep muscles of the thigh and the ventral and lateral regions of the integument
Genicular artery	Branch of the femoral artery; supplies blood to the region of the knee
Popliteal artery	Continuation of the femoral artery posterior to the knee; branches into the anterior and posterior tibial arteries
Anterior tibial artery	Branches from the popliteal artery; supplies blood to the anterior tibial region; becomes the dorsalis pedis artery
Dorsalis pedis artery	Forms from the anterior tibial artery; branches repeatedly to supply blood to the tarsal and dorsal regions of the foot
Posterior tibial artery	Branches from the popliteal artery and gives rise to the fibular or peroneal artery; supplies blood to the posterior tibial region
Medial plantar artery	Arises from the bifurcation of the posterior tibial arteries; supplies blood to the medial plantar surfaces of the foot
Lateral plantar artery	Arises from the bifurcation of the posterior tibial arteries; supplies blood to the lateral plantar surfaces of the foot

Vessel	Description
Dorsal or arcuate arch	Formed from the anastomosis of the dorsalis pedis artery and the medial and plantar arteries; branches supply the distal portions of the foot and digits
Plantar arch	Formed from the anastomosis of the dorsalis pedis artery and the medial and plantar arteries; branches supply the distal portions of the foot and digits

Overview of Systemic Veins

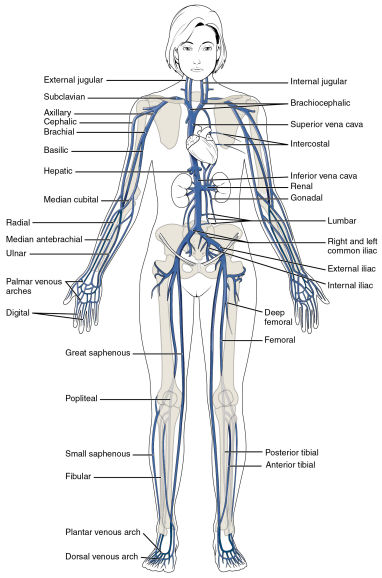

Figure 18.3.13: Major Systemic Veins of the Body. The major systemic veins of the body are shown here in an anterior view. (Image credit: "Major Systemic Veins" by OpenStax is licensed under CC BY 3.0)

The right atrium receives all of the systemic venous return. Most of the blood flows into either the superior vena cava or inferior vena cava. If you draw an imaginary line at the level of the diaphragm, systemic venous circulation from above that line will generally flow into the superior vena cava; this includes blood from the head, neck, chest, shoulders, and upper limbs. The exception to this is that most venous blood flow from the coronary veins flows directly into the coronary sinus and from there directly into the right atrium. Beneath the diaphragm, systemic venous flow enters the inferior vena cava, that is, blood from the abdominal and pelvic regions and the lower limbs.

The Superior Vena Cava

The **superior vena cava** drains most of the body superior to the diaphragm (Figure 18.3.14). On both the left and right sides, the **subclavian vein** forms when the axillary vein passes through the body wall from the axillary region. It fuses with the external and internal jugular veins from the head and neck to form the **brachiocephalic vein**. Each **vertebral vein** also flows into the brachiocephalic vein close to this fusion. These veins arise from the base of the brain and the cervical region of the spinal cord, and flow largely through the intervertebral foramina in the cervical vertebrae. They are the counterparts of the vertebral arteries. Each **internal thoracic vein**, also known as an internal mammary vein, drains the anterior surface of the chest wall and flows into the brachiocephalic vein.

The remainder of the blood supply from the thorax drains into the azygos vein. Each **intercostal vein** drains muscles of the thoracic wall, each **esophageal vein** delivers blood from the inferior portions of the esophagus, each **bronchial vein** drains the systemic circulation from the lungs, and several smaller veins drain the mediastinal region. Bronchial veins carry approximately 13 percent of the blood that flows into the bronchial arteries; the remainder intermingles with the pulmonary circulation and returns to the heart via the pulmonary veins. These veins flow into the **azygos vein**, and with the smaller **hemiazygos vein** (hemi- = “half”) on the left of the vertebral column, drain blood from the thoracic region. The hemiazygos vein does not drain directly into the superior vena cava but enters the brachiocephalic vein via the superior intercostal vein.

The azygos vein passes through the diaphragm from the thoracic cavity on the right side of the vertebral column and begins in the lumbar region of the thoracic cavity. It flows into the superior vena cava at approximately the level of T2, making a significant contribution to the flow of blood. It combines with the two large left and right brachiocephalic veins to form the superior vena cava.

Table 18.3.9 summarizes the veins of the thoracic region that flow into the superior vena cava.

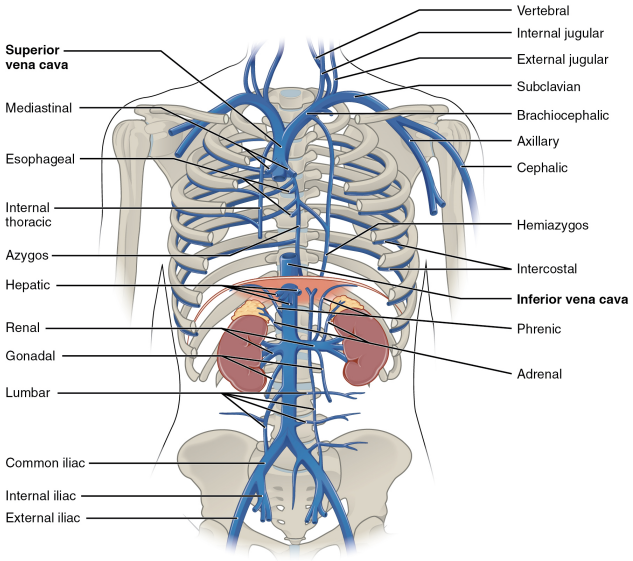

Figure 18.3.14: Veins of the Thoracic and Abdominal Regions. Veins of the thoracic and abdominal regions drain blood from the area above the diaphragm, returning it to the right atrium via the superior vena cava. (Image credit: "Thoracic Abdominal Veins" by OpenStax is licensed under CC BY 3.0)

Table 18.3.9: Veins of the Thoracic Region

Vessel	Description
Superior vena cava	Large systemic vein; drains blood from most areas superior to the diaphragm; empties into the right atrium
Subclavian vein	Located deep in the thoracic cavity; formed by the axillary vein as it enters the thoracic cavity from the axillary region; drains the axillary and smaller local veins near the scapular region and leads to the brachiocephalic vein
Brachiocephalic veins	Pair of veins that form from a fusion of the external and internal jugular veins and the subclavian vein; subclavian, external and internal jugulars, vertebral, and internal thoracic veins flow into it; drain the upper thoracic region and lead to the superior vena cava
Vertebral vein	Arises from the base of the brain and the cervical region of the spinal cord; passes through the intervertebral foramina in the cervical vertebrae; drains smaller veins from the cranium, spinal cord, and vertebrae, and leads to the brachiocephalic vein; counterpart of the vertebral artery
Internal thoracic veins	Also called internal mammary veins; drain the anterior surface of the chest wall and lead to the brachiocephalic vein
Intercostal vein	Drains the muscles of the thoracic wall and leads to the azygos vein
Esophageal vein	Drains the inferior portions of the esophagus and leads to the azygos vein
Bronchial vein	Drains the systemic circulation from the lungs and leads to the azygos vein
Azygos vein	Originates in the lumbar region and passes through the diaphragm into the thoracic cavity on the right side of the vertebral column; drains blood from the intercostal veins, esophageal veins, bronchial veins, and other veins draining the mediastinal region, and leads to the superior vena cava
Hemiazygos vein	Smaller vein complementary to the azygos vein; drains the esophageal veins from the esophagus and the left intercostal veins, and leads to the brachiocephalic vein via the superior intercostal vein

Veins of the Head and Neck

Blood from the brain and the superficial facial vein flow into each **internal jugular vein** (Figure 18.3.15). Blood from the more superficial portions of the head, scalp, and cranial regions, including the **temporal vein** and **maxillary vein**, flow into each **external jugular vein**. Although the external and internal jugular veins are separate vessels, there are anastomoses between them close to the thoracic region. Blood from the external jugular vein empties into the subclavian vein. Table 18.3.10 summarizes the major veins of the head and neck.

Table 18.3.10. Major Veins of the Head and Neck

Vessel	Description
Internal jugular vein	Parallel to the common carotid artery, which is more or less its counterpart, and passes through the jugular foramen and canal; primarily drains blood from the brain, receives the superficial facial vein, and empties into the subclavian vein
Temporal vein	Drains blood from the temporal region and flows into the external jugular vein
Maxillary vein	Drains blood from the maxillary region and flows into the external jugular vein
External jugular vein	Drains blood from the more superficial portions of the head, scalp, and cranial regions, and leads to the subclavian vein

Venous Drainage of the Brain

Circulation to the brain is both critical and complex (see Figure 18.3.15). Many smaller veins of the brain stem and the superficial veins of the cerebrum lead to larger vessels referred to as intracranial sinuses. These include the superior and inferior sagittal sinuses, straight sinus, cavernous sinuses, left and right sinuses, the petrosal sinuses, and the occipital sinuses. Ultimately, sinuses will lead back to either the inferior jugular vein or vertebral vein.

Most of the veins on the superior surface of the cerebrum flow into the largest of the sinuses, the **superior sagittal sinus**. It is located midsagittally between the meningeal and periosteal layers of the dura mater within the falx cerebri and, at first glance in images or models, can be mistaken for the subarachnoid space. Most reabsorption of cerebrospinal fluid occurs via the chorionic villi (arachnoid granulations) into the superior sagittal sinus. Blood from most of the smaller vessels originating from the inferior cerebral veins flows into the **great cerebral vein** and into the **straight sinus**. Other cerebral veins and those from the eye socket flow into the **cavernous sinus**, which flows into the **petrosal sinus** and then into the internal jugular vein. The **occipital sinus**, sagittal sinus, and straight sinuses all flow into the left and right **transverse sinuses** near the lambdoid suture. The transverse sinuses in turn flow into the **sigmoid sinuses** that pass through the jugular foramen and into the internal jugular vein. The internal jugular vein flows parallel to the common carotid artery and is more or less its counterpart. It empties into the brachiocephalic vein. The veins draining the cervical vertebrae and the posterior surface of the skull, including some blood from the occipital sinus, flow into the vertebral veins. These parallel the vertebral arteries and travel through the transverse foramina of the cervical vertebrae. The vertebral veins also flow into the brachiocephalic veins. Table 18.3.11 summarizes the major veins of the brain.

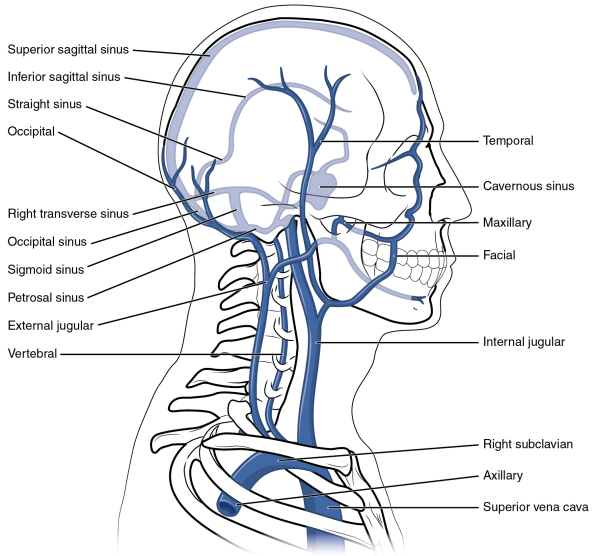

Figure 18.3.15: Veins of the Head and Neck. This left lateral view shows the veins of the head and neck, including the intercranial sinuses. (Image credit: "Head and Neck Veins" by OpenStax is licensed under CC BY 3.0)

Table 18.3.11. Major Veins of the Brain

Vessel	Description
Superior sagittal sinus	Enlarged vein located midsagittally between the meningeal and periosteal layers of the dura mater within the falx cerebri; receives most of the blood drained from the superior surface of the cerebrum and leads to the inferior jugular vein and the vertebral vein
Great cerebral vein	Receives most of the smaller vessels from the inferior cerebral veins and leads to the straight sinus
Straight sinus	Enlarged vein that drains blood from the brain; receives most of the blood from the great cerebral vein and leads to the left or right transverse sinus
Cavernous sinus	Enlarged vein that receives blood from most of the other cerebral veins and the eye socket, and leads to the petrosal sinus
Petrosal sinus	Enlarged vein that receives blood from the cavernous sinus and leads into the internal jugular veins
Occipital sinus	Enlarged vein that drains the occipital region near the falx cerebelli and leads to the left and right transverse sinuses, and also the vertebral veins
Transverse sinuses	Pair of enlarged veins near the lambdoid suture that drains the occipital, sagittal, and straight sinuses, and leads to the sigmoid sinuses
Sigmoid sinuses	Enlarged vein that receives blood from the transverse sinuses and leads through the jugular foramen to the internal jugular vein

Veins Draining the Upper Limbs

The **digital veins** in the fingers come together in the hand to form the **palmar venous arches** (Figure 18.3.16). From here, the veins come together to form the radial vein, the ulnar vein, and the median antebrachial vein. The **radial vein** and the **ulnar vein** parallel the bones of the forearm and join together at the antebrachium to form the **brachial vein**, a deep vein that flows into the axillary vein in the brachium.

The **median antebrachial vein** parallels the ulnar vein, is more medial in location, and joins the **basilic vein** in the forearm. As the basilic vein reaches the antecubital region, it gives off a branch called the **median cubital vein** that crosses at an angle to join the cephalic vein. The median cubital vein is the most common site for drawing venous blood in humans. The basilic vein

continues through the arm medially and superficially to the axillary vein.

The **cephalic vein** begins in the antebrachium and drains blood from the superficial surface of the arm into the axillary vein. It is extremely superficial and easily seen along the surface of the biceps brachii muscle in individuals with good muscle tone and in those without excessive subcutaneous adipose tissue in the arms.

The **subscapular vein** drains blood from the subscapular region and joins the cephalic vein to form the **axillary vein**. As it passes through the body wall and enters the thorax, the axillary vein becomes the subclavian vein.

Many of the larger veins of the thoracic and abdominal region and upper limb are further represented in the flow chart in Figure 18.3.17. Table 18.3.12 summarizes the veins of the upper limbs.

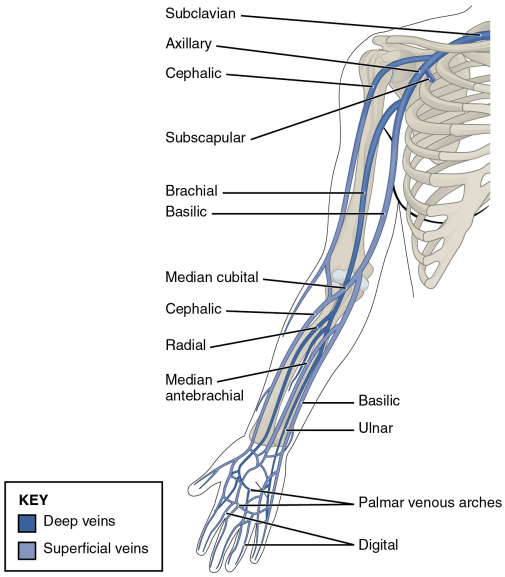

Figure 18.3.16: Veins of the Upper Limb. This anterior view shows the veins that drain the upper limb. (Image credit: "Thoracic Upper Limb Veins" by OpenStax is licensed under CC BY 3.0)

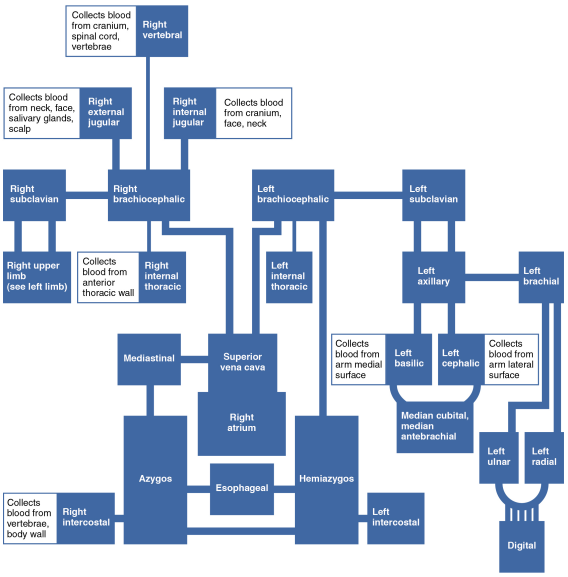

Figure 18.3.17: Veins Draining into the Superior Vena Cava. The flow chart summarizes the distribution of the veins flowing into the superior vena cava. (Image credit: "Veins Draining into Superior Vena Cava" by OpenStax is licensed under CC BY 3.0)

Table 18.3.12: Veins of the Upper Limbs

Vessel	Description
Digital veins	Drain the digits and lead to the palmar arches of the hand and dorsal venous arch of the foot
Palmar venous arches	Drain the hand and digits, and lead to the radial vein, ulnar veins, and the median antebrachial vein
Radial vein	Vein that parallels the radius and radial artery; arises from the palmar venous arches and leads to the brachial vein
Ulnar vein	Vein that parallels the ulna and ulnar artery; arises from the palmar venous arches and leads to the brachial vein
Brachial vein	Deeper vein of the arm that forms from the radial and ulnar veins in the lower arm; leads to the axillary vein
Median antebrachial vein	Vein that parallels the ulnar vein but is more medial in location; intertwines with the palmar venous arches; leads to the basilic vein
Basilic vein	Superficial vein of the arm that arises from the median antebrachial vein, intersects with the median cubital vein, parallels the ulnar vein, and continues into the upper arm; along with the brachial vein, it leads to the axillary vein
Median cubital vein	Superficial vessel located in the antecubital region that links the cephalic vein to the basilic vein in the form of a v; a frequent site from which to draw blood
Cephalic vein	Superficial vessel in the upper arm; leads to the axillary vein
Subscapular vein	Drains blood from the subscapular region and leads to the axillary vein
Axillary vein	The major vein in the axillary region; drains the upper limb and becomes the subclavian vein

The Inferior Vena Cava

Other than the small amount of blood drained by the azygos and hemiazygos veins, most of the blood inferior to the diaphragm drains into the inferior vena cava before it is returned to the heart (see Figure 18.3.14). Lying just beneath the parietal peritoneum in the abdominal cavity, the **inferior vena cava** parallels the abdominal aorta, where it can receive blood from abdominal veins. The lumbar portions of the abdominal wall and spinal cord are drained by a series of **lumbar veins**, usually four on each side. The ascending lumbar veins drain into either the azygos vein on the right or the hemiazygos vein on the left, and return to the superior vena cava. The remaining lumbar veins drain directly into the inferior vena cava.

Blood supply from the kidneys flows into each **renal vein**, normally the largest veins entering the inferior vena cava. A number of other, smaller veins empty into the left renal vein. Each **adrenal vein** drains the adrenal or suprarenal glands located immediately superior to the kidneys. The right adrenal vein enters the inferior vena cava directly, whereas the left adrenal vein enters the left renal vein.

From the male reproductive organs, each **testicular vein** flows from the scrotum, forming a portion of the spermatic cord. Each **ovarian vein** drains an ovary in females. Each of these veins is generically called a **gonadal vein**. The right gonadal vein empties directly into the inferior vena cava, and the left gonadal vein empties into the left renal vein.

Each side of the diaphragm drains into a **phrenic vein**; the right phrenic vein empties directly into the inferior vena cava, whereas the left phrenic vein empties into the left renal vein. Blood supply from the liver drains into each **hepatic vein** and directly into the inferior vena cava. Since the inferior vena cava lies primarily to the right of the vertebral column and aorta, the left renal vein is longer, as are the left phrenic, adrenal, and gonadal veins. The longer length of the left renal vein makes the left kidney the primary target of surgeons removing this organ for donation. Figure 18.3.18 provides a flow chart of the veins flowing into the inferior vena cava. Table 18.3.13 summarizes the major veins of the abdominal region.

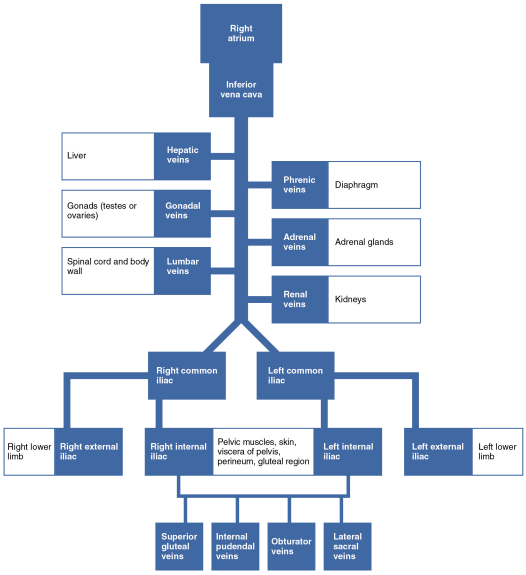

Figure 18.3.18: Venous Flow into Inferior Vena Cava. The flow chart summarizes veins that deliver blood to the inferior vena cava. (Image credit: "FlowChart Veins into VenaCava" by OpenStax is licensed under CC BY 3.0)

Table 18.3.13: Major Veins of the Abdominal Region

Vessel	Description
Inferior vena cava	Large systemic vein that drains blood from areas largely inferior to the diaphragm; empties into the right atrium
Lumbar veins	Series of veins that drain the lumbar portion of the abdominal wall and spinal cord; the ascending lumbar veins drain into the azygos vein on the right or the hemiazygos vein on the left; the remaining lumbar veins drain directly into the inferior vena cava
Renal vein	Largest vein entering the inferior vena cava; drains the kidneys and flows into the inferior vena cava
Adrenal vein	Drains the adrenal or suprarenal; the right adrenal vein enters the inferior vena cava directly and the left adrenal vein enters the left renal vein
Testicular vein	Drains the testes and forms part of the spermatic cord; the right testicular vein empties directly into the inferior vena cava and the left testicular vein empties into the left renal vein
Ovarian vein	Drains the ovary; the right ovarian vein empties directly into the inferior vena cava and the left ovarian vein empties into the left renal vein
Gonadal vein	Generic term for a vein draining a reproductive organ; may be either an ovarian vein or a testicular vein, depending on the sex of the individual
Phrenic vein	Drains the diaphragm; the right phrenic vein flows into the inferior vena cava and the left phrenic vein empties into the left renal vein
Hepatic vein	Drains systemic blood from the liver and flows into the inferior vena cava

Veins Draining the Lower Limbs

The superior surface of the foot drains into the digital veins, and the inferior surface drains into the **plantar veins**, which flow into a complex series of anastomoses in the feet and ankles, including the **dorsal venous arch** and the **plantar venous arch** (Figure 18.3.19). From the dorsal venous arch, blood supply drains into the anterior and posterior tibial veins. The **anterior tibial vein** drains the area near the tibialis anterior muscle and combines with the posterior tibial vein to form the popliteal vein. The **posterior tibial vein** drains the posterior surface of the tibia and joins the popliteal vein. The **fibular vein** drains the muscles and integument in proximity to the fibula and also joins the posterior tibial vein. The **small saphenous vein** located on the

lateral surface of the leg drains blood from the superficial regions of the lower leg and foot, and flows into the **popliteal vein**. As the popliteal vein passes behind the knee in the popliteal region, it becomes the femoral vein. It is palpable in patients without excessive adipose tissue.

Close to the body wall, the great saphenous vein, the deep femoral vein, and the femoral circumflex vein drain into the femoral vein. The **great saphenous vein** is a prominent surface vessel located on the medial surface of the leg and thigh that collects blood from the superficial portions of these areas. The **deep femoral vein**, as the name suggests, drains blood from the deeper portions of the thigh. The **femoral circumflex vein** forms a loop around the femur just inferior to the trochanters and drains blood from the areas in proximity to the head and neck of the femur.

As the **femoral vein** penetrates the body wall from the femoral portion of the lower limb, it becomes the **external iliac vein**, a large vein that drains blood from the leg to the common iliac vein. The pelvic organs and integument drain into the **internal iliac vein**, which forms from several smaller veins in the region, including the umbilical veins that run on either side of the bladder. The external and internal iliac veins combine near the inferior portion of the sacroiliac joint to form the common iliac vein. In addition to blood supply from the external and internal iliac veins, the **middle sacral vein** drains the sacral region into the **common iliac vein**. Similar to the common iliac arteries, the common iliac veins come together at the level of L5 to form the inferior vena cava.

Figure 18.3.20 is a flow chart of veins flowing into the lower limb. Table 18.3.14 summarizes the major veins of the lower limbs.

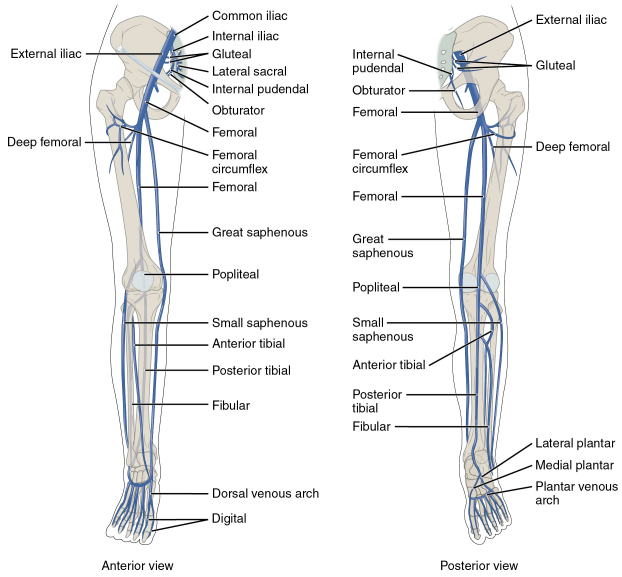

Figure 18.3.19: Major Veins Serving the Lower Limbs. Anterior and posterior views show the major veins that drain the lower limb into the inferior vena cava. (Image credit: "Lower Limb Veins Anterior Posterior" by OpenStax is licensed under CC BY 3.0)

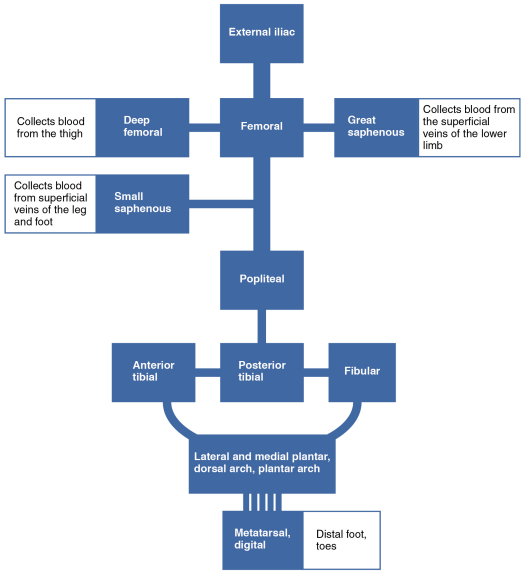

Figure 18.3.20: Major Veins of the Lower Limb. The flow chart summarizes venous flow from the lower limb. (Image credit: "Lower Limb Veins Chart" by OpenStax is licensed under CC BY 3.0)

Table 18.3.14: Veins of the Lower Limbs

Vessel	Description
Plantar veins	Drain the foot and flow into the plantar venous arch
Dorsal venous arch	Drains blood from digital veins and vessels on the superior surface of the foot
Plantar venous arch	Formed from the plantar veins; flows into the anterior and posterior tibial veins through anastomoses
Anterior tibial vein	Formed from the dorsal venous arch; drains the area near the tibialis anterior muscle and flows into the popliteal vein
Posterior tibial vein	Formed from the dorsal venous arch; drains the area near the posterior surface of the tibia and flows into the popliteal vein
Fibular vein	Drains the muscles and integument near the fibula and flows into the posterior tibial vein
Small saphenous vein	Located on the lateral surface of the leg; drains blood from the superficial regions of the lower leg and foot, and flows into the popliteal vein
Popliteal vein	Drains the region behind the knee and forms from the fusion of the fibular, anterior, and posterior tibial veins; flows into the femoral vein
Great saphenous vein	Prominent surface vessel located on the medial surface of the leg and thigh; drains the superficial portions of these areas and flows into the femoral vein
Deep femoral vein	Drains blood from the deeper portions of the thigh and flows into the femoral vein
Femoral circumflex vein	Forms a loop around the femur just inferior to the trochanters; drains blood from the areas around the head and neck of the femur; flows into the femoral vein
Femoral vein	Drains the upper leg; receives blood from the great saphenous vein, the deep femoral vein, and the femoral circumflex vein; becomes the external iliac vein when it crosses the body wall

Vessel	Description
External iliac vein	Formed when the femoral vein passes into the body cavity; drains the legs and flows into the common iliac vein
Internal iliac vein	Drains the pelvic organs and integument; formed from several smaller veins in the region; flows into the common iliac vein
Middle sacral vein	Drains the sacral region and flows into the left common iliac vein
Common iliac vein	Flows into the inferior vena cava at the level of L5; the left common iliac vein drains the sacral region; formed from the union of the external and internal iliac veins near the inferior portion of the sacroiliac joint

Hepatic Portal System

The liver is a complex biochemical processing plant. It packages nutrients absorbed by the digestive system; produces plasma proteins, clotting factors, and bile; and disposes of worn-out cell components and waste products. Instead of entering the circulation directly, absorbed nutrients and certain wastes (for example, materials produced by the spleen) travel to the liver for processing. They do so via the **hepatic portal system** (Figure 18.3.21). Portal systems begin and end in capillaries (two capillary beds are found in series between the arterial and venous sides of the circuit). In this case, the initial capillaries from the stomach, small intestine, large intestine, and spleen lead to the hepatic portal vein and end in specialized capillaries within the liver, the hepatic sinusoids. The hypothalamic-hypophyseal portal system is covered in the endocrine chapter.

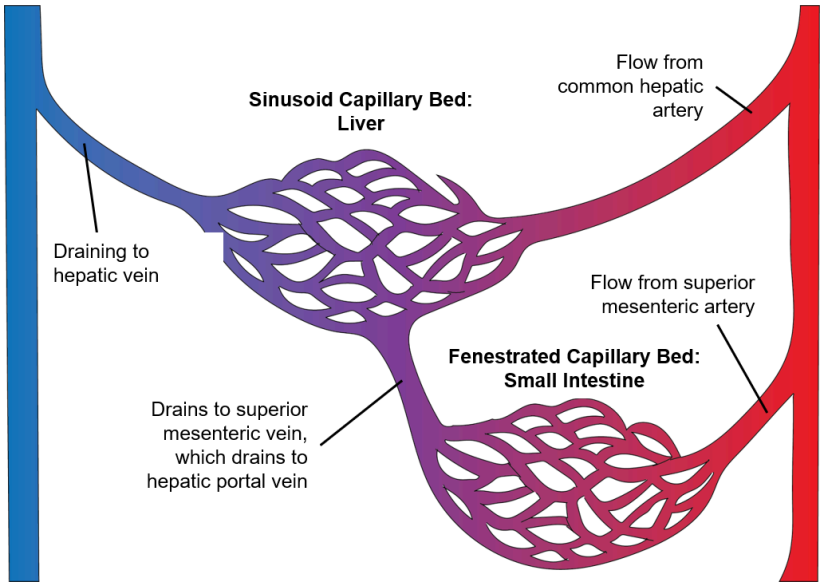

Figure 18.3.21: Hepatic Portal System. The liver receives blood from normal systemic circulation via the hepatic artery. It also receives and processes blood from other organs, delivered via the veins of the hepatic portal system. All blood exits the liver via the hepatic vein, which delivers the blood to the inferior vena cava. ("Hepatic Portal System" by Julie Jenks is a derivative of the original work by Daniel Donnelly and is licensed under CC BY 4.0)

The hepatic portal system consists of the hepatic portal vein and the veins that drain into it (Figure 18.3.22, Table 18.3.15). The hepatic portal vein itself is relatively short, beginning at the level of L2 with the confluence of the superior mesenteric and splenic veins. It also receives branches from the inferior mesenteric vein, plus the splenic veins and all their tributaries. The superior mesenteric vein receives blood from the small intestine, two-thirds of the large intestine, and the stomach. The inferior mesenteric vein drains the distal third of the large intestine, including the descending colon, the sigmoid colon, and the rectum. The splenic vein is formed from branches from the spleen, pancreas, and portions of the stomach, and the inferior mesenteric vein. After its formation, the hepatic portal vein also receives branches from the gastric veins of the stomach and cystic veins from the gall bladder. The hepatic portal vein delivers materials from these digestive and circulatory organs directly to the liver for processing.

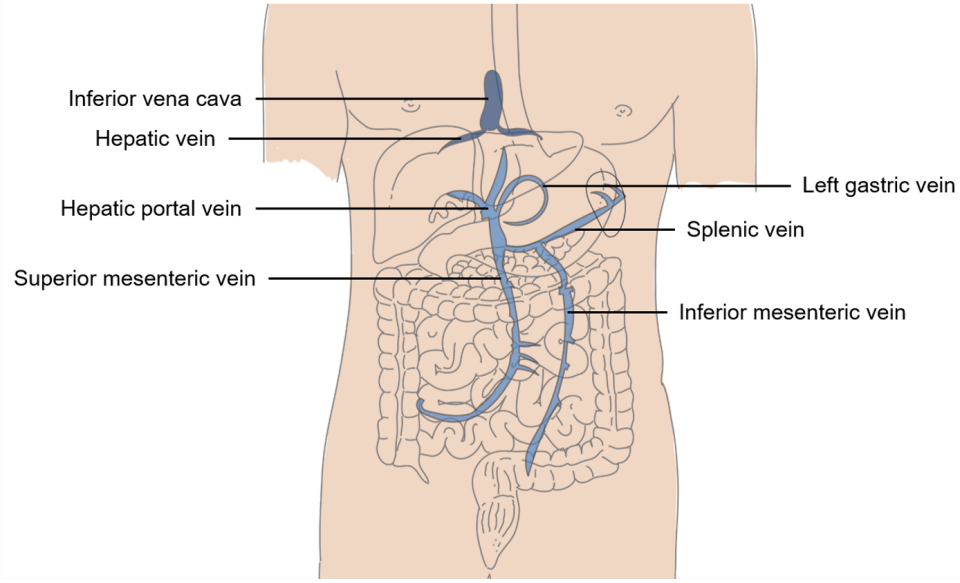

Figure 18.3.22: Veins Draining to and from Hepatic Portal System. The liver receives venous blood from many major veins draining from organs of the digestive system and the spleen. The superior mesenteric and left gastric veins drain into the hepatic portal vein. The inferior mesenteric vein drains into the splenic vein which drains into the hepatic portal vein. Venous blood drains from the liver via the hepatic veins into the inferior vena cava. ("Veins Draining to and from Hepatic Portal System" by Julie Jenks is a derivative of the original work by Daniel Donnelly and is licensed under CC BY 4.0)

Table 18.3.15 Veins of the Hepatic Portal System

Vessel	Description
Splenic vein	Drains blood from the spleen, stomach, and pancreas into the hepatic portal vein
Left gastric vein	Drains blood from the stomach into the hepatic portal vein
Inferior mesenteric vein	Drains blood from the distal part of large intestine into splenic vein
Superior mesenteric vein	Drains blood from the small intestine and proximal part of the large intestine into the hepatic portal vein
Hepatic portal vein	Drains blood from splenic vein, left gastric vein, and superior mesenteric vein into the sinusoid capillaries in the lobules of the liver

Because of the hepatic portal system, the liver receives its blood supply from two different sources: from normal systemic circulation via the hepatic artery and from the hepatic portal vein. The liver processes the blood from the portal system to remove certain wastes and excess nutrients, which are stored for later use. This processed blood, as well as the systemic blood that came from the hepatic artery, exits the liver via the right, left, and middle hepatic veins, and flows into the inferior vena cava. Overall systemic blood composition remains relatively stable, since the liver is able to metabolize the absorbed digestive components.

Concept Review

The right ventricle pumps oxygen-depleted blood into the pulmonary trunk and right and left pulmonary arteries, which carry it to the right and left lungs for gas exchange. Oxygen-rich blood is transported by pulmonary veins to the left atrium. The left ventricle pumps this blood into the aorta. The main regions of the aorta are the ascending aorta, aortic arch, and descending aorta, which is further divided into the thoracic and abdominal aorta. The coronary arteries branch from the ascending aorta. After oxygenating tissues in the capillaries, systemic blood is returned to the right atrium from the venous system via the superior vena cava, which drains most of the veins superior to the diaphragm, the inferior vena cava, which drains most of the veins inferior to the diaphragm, and the coronary veins via the coronary sinus. The hepatic portal system carries blood to the liver for processing before it enters circulation. Review the figures provided in this section for circulation of blood through the blood vessels.

Review Questions

Q. The coronary arteries branch off of the _____.

A. aortic valve

B. ascending aorta

C. aortic arch

D. thoracic aorta

Answer

Answer: B

Q. Which of the following statements is true?

A. The left and right common carotid arteries both branch off of the brachiocephalic trunk.

B. The brachial artery is the distal branch of the axillary artery.

C. The radial and ulnar arteries join to form the palmar arch.

D. All of the above are true.

Answer

Answer: C

Q. Arteries serving the stomach, pancreas, and liver all branch from the _____.

A. superior mesenteric artery

B. inferior mesenteric artery

C. celiac trunk

D. splenic artery

Answer

Answer: C

Q. The right and left brachiocephalic veins _____.

A. drain blood from the right and left internal jugular veins

B. drain blood from the right and left subclavian veins

C. drain into the superior vena cava

D. all of the above are true

Answer

Answer: D

Q. The hepatic portal system delivers blood from the digestive organs to the _____.

A. liver

B. hypothalamus

C. spleen

D. left atrium

Answer

Answer: A

Critical Thinking Questions

Q. Identify the ventricle of the heart that pumps oxygen-depleted blood and the arteries of the body that carry oxygen-depleted blood.

Answer

A. The right ventricle of the heart pumps oxygen-depleted blood to the pulmonary arteries.

Q. What organs do the gonadal veins drain?

Answer

A. The gonadal veins drain the testes in males and the ovaries in females.

Q. What arteries play the leading roles in supplying blood to the brain?

Answer

A. The internal carotid arteries and the vertebral arteries provide most of the brain's blood supply.

Glossary

abdominal aorta
portion of the aorta inferior to the aortic hiatus and superior to the common iliac arteries

adrenal artery
branch of the abdominal aorta; supplies blood to the adrenal (suprarenal) glands

adrenal vein
drains the adrenal or suprarenal glands that are immediately superior to the kidneys; the right adrenal vein enters the inferior vena cava directly and the left adrenal vein enters the left renal vein

anterior cerebral artery
arises from the internal carotid artery; supplies the frontal lobe of the cerebrum

anterior communicating artery
anastomosis of the right and left internal carotid arteries; supplies blood to the brain

anterior tibial artery
branches from the popliteal artery; supplies blood to the anterior tibial region; becomes the dorsalis pedis artery

anterior tibial vein
forms from the dorsal venous arch; drains the area near the tibialis anterior muscle and leads to the popliteal vein

aorta
largest artery in the body, originating from the left ventricle and descending to the abdominal region where it bifurcates into the common iliac arteries at the level of the fourth lumbar vertebra; arteries originating from the

aorta distribute blood to virtually all tissues of the body

aortic arch
arc that connects the ascending aorta to the descending aorta; ends at the intervertebral disk between the fourth and fifth thoracic vertebrae

aortic hiatus
opening in the diaphragm that allows passage of the thoracic aorta into the abdominal region where it becomes the abdominal aorta

arterial circle
(also, circle of Willis) anastomosis located at the base of the brain that ensures continual blood supply; formed from branches of the internal carotid and vertebral arteries; supplies blood to the brain

ascending aorta
initial portion of the aorta, rising from the left ventricle for a distance of approximately 5 cm

axillary artery
continuation of the subclavian artery as it penetrates the body wall and enters the axillary region; supplies blood to the region near the head of the humerus (humeral circumflex arteries); the majority of the vessel continues into the brachium and becomes the brachial artery

axillary vein
major vein in the axillary region; drains the upper limb and becomes the subclavian vein

azygos vein
originates in the lumbar region and passes through the diaphragm into the thoracic cavity on the right side of the vertebral column; drains blood from the intercostal veins, esophageal veins, bronchial veins, and other veins draining the mediastinal region; leads to the superior vena cava

basilar artery
formed from the fusion of the two vertebral arteries; sends branches to the cerebellum, brain stem, and the posterior cerebral arteries; the main blood supply to the brain stem

basilic vein
superficial vein of the arm that arises from the palmar venous arches, intersects with the median cubital vein, parallels the ulnar vein, and continues into the upper arm; along with the brachial vein, it leads to the axillary vein

brachial artery
continuation of the axillary artery in the brachium; supplies blood to much of the brachial region; gives off several smaller branches that provide blood to the posterior surface of the arm in the region of the elbow; bifurcates into the radial and ulnar arteries at the coronoid fossa

brachial vein
deeper vein of the arm that forms from the radial and ulnar veins in the lower arm; leads to the axillary vein

brachiocephalic artery
single vessel located on the right side of the body; the first vessel branching from the aortic arch; gives rise to the right subclavian artery and the right common carotid artery; supplies blood to the head, neck, upper limb, and wall of the thoracic region

brachiocephalic vein
one of a pair of veins that form from a fusion of the external and internal jugular veins and the subclavian vein; subclavian, external and internal jugulars, vertebral, and internal thoracic veins lead to it; drains the upper thoracic region and flows into the superior vena cava

bronchial artery
systemic branch from the aorta that provides oxygenated blood to the lungs in addition to the pulmonary circuit

bronchial vein
drains the systemic circulation from the lungs and leads to the azygos vein

cavernous sinus
enlarged vein that receives blood from most of the other cerebral veins and the eye socket, and leads to the petrosal sinus

celiac trunk
(also, celiac artery) major branch of the abdominal aorta; gives rise to the left gastric artery, the splenic artery, and the common hepatic artery that forms the hepatic artery to the liver, the right gastric artery to the stomach, and the cystic artery to the gall bladder

cephalic vein
superficial vessel in the upper arm; leads to the axillary vein

cerebrovascular accident (CVA)
blockage of blood flow to the brain; also called a stroke

circle of Willis
(also, arterial circle) anastomosis located at the base of the brain that ensures continual blood supply; formed from branches of the internal carotid and vertebral arteries; supplies blood to the brain

common carotid artery
right common carotid artery arises from the brachiocephalic artery, and the left common carotid arises from the aortic arch; gives rise to the external and internal carotid arteries; supplies the respective sides of the head and neck

common hepatic artery
branch of the celiac trunk that forms the hepatic artery, the right gastric artery, and the cystic artery

common iliac artery
branch of the aorta that leads to the internal and external iliac arteries

common iliac vein
one of a pair of veins that flows into the inferior vena cava at the level of L5; the left common iliac vein drains the sacral region; divides into external and internal iliac veins near the inferior portion of the sacroiliac joint

cystic artery
branch of the common hepatic artery; supplies blood to the gall bladder

deep femoral artery
branch of the femoral artery; gives rise to the lateral circumflex arteries

deep femoral vein
drains blood from the deeper portions of the thigh and leads to the femoral vein

descending aorta
portion of the aorta that continues downward past the end of the aortic arch; subdivided into the thoracic aorta and the abdominal aorta

digital arteries
formed from the superficial and deep palmar arches; supply blood to the digits

digital veins
drain the digits and feed into the palmar arches of the hand and dorsal venous arch of the foot

dorsal arch
(also, arcuate arch) formed from the anastomosis of the dorsalis pedis artery and medial and plantar arteries; branches supply the distal portions of the foot and digits

dorsal venous arch
drains blood from digital veins and vessels on the superior surface of the foot

dorsalis pedis artery
: forms from the anterior tibial artery; branches repeatedly to supply blood to the tarsal and dorsal regions of the foot

esophageal artery
: branch of the thoracic aorta; supplies blood to the esophagus

esophageal vein
: drains the inferior portions of the esophagus and leads to the azygos vein

external carotid artery
: arises from the common carotid artery; supplies blood to numerous structures within the face, lower jaw, neck, esophagus, and larynx

external iliac artery
: branch of the common iliac artery that leaves the body cavity and becomes a femoral artery; supplies blood to the lower limbs

external iliac vein
: formed when the femoral vein passes into the body cavity; drains the legs and leads to the common iliac vein

external jugular vein
: one of a pair of major veins located in the superficial neck region that drains blood from the more superficial portions of the head, scalp, and cranial regions, and leads to the subclavian vein

femoral artery
: continuation of the external iliac artery after it passes through the body cavity; divides into several smaller branches, the lateral deep femoral artery, and the genicular artery; becomes the popliteal artery as it passes posterior to the knee

femoral circumflex vein
: forms a loop around the femur just inferior to the trochanters; drains blood from the areas around the head and neck of the femur; leads to the femoral vein

femoral vein
: drains the upper leg; receives blood from the great saphenous vein, the deep femoral vein, and the femoral circumflex vein; becomes the external iliac vein when it crosses the body wall

fibular vein
: drains the muscles and integument near the fibula and leads to the posterior tibial vein

genicular artery
: branch of the femoral artery; supplies blood to the region of the knee

gonadal artery
: branch of the abdominal aorta; supplies blood to the gonads or reproductive organs; also described as ovarian arteries or testicular arteries, depending upon the sex of the individual

gonadal vein
: generic term for a vein draining a reproductive organ; may be either an ovarian vein or a testicular vein, depending on the sex of the individual

great cerebral vein
: receives most of the smaller vessels from the inferior cerebral veins and leads to the straight sinus

great saphenous vein
: prominent surface vessel located on the medial surface of the leg and thigh; drains the superficial portions of these areas and leads to the femoral vein

hemiazygos vein
: smaller vein complementary to the azygos vein; drains the esophageal veins from the esophagus and the left

intercostal veins, and leads to the brachiocephalic vein via the superior intercostal vein

hepatic artery proper
branch of the common hepatic artery; supplies systemic blood to the liver

hepatic portal system
specialized circulatory pathway that carries blood from digestive organs to the liver for processing before being sent to the systemic circulation

hepatic vein
drains systemic blood from the liver and flows into the inferior vena cava

inferior mesenteric artery
branch of the abdominal aorta; supplies blood to the distal segment of the large intestine and rectum

inferior phrenic artery
branch of the abdominal aorta; supplies blood to the inferior surface of the diaphragm

inferior vena cava
large systemic vein that drains blood from areas largely inferior to the diaphragm; empties into the right atrium

intercostal artery
branch of the thoracic aorta; supplies blood to the muscles of the thoracic cavity and vertebral column

intercostal vein
drains the muscles of the thoracic wall and leads to the azygos vein

internal carotid artery
arises from the common carotid artery and begins with the carotid sinus; goes through the carotid canal of the temporal bone to the base of the brain; combines with branches of the vertebral artery forming the arterial circle; supplies blood to the brain

internal iliac artery
branch from the common iliac arteries; supplies blood to the urinary bladder, walls of the pelvis, external genitalia, and the medial portion of the femoral region; in females, also provide blood to the uterus and vagina

internal iliac vein
drains the pelvic organs and integument; formed from several smaller veins in the region; leads to the common iliac vein

internal jugular vein
one of a pair of major veins located in the neck region that passes through the jugular foramen and canal, flows parallel to the common carotid artery that is more or less its counterpart; primarily drains blood from the brain, receives the superficial facial vein, and empties into the subclavian vein

internal thoracic artery
(also, mammary artery) arises from the subclavian artery; supplies blood to the thymus, pericardium of the heart, and the anterior chest wall

internal thoracic vein
(also, internal mammary vein) drains the anterior surface of the chest wall and leads to the brachiocephalic vein

lateral circumflex artery
branch of the deep femoral artery; supplies blood to the deep muscles of the thigh and the ventral and lateral regions of the integument

lateral plantar artery
arises from the bifurcation of the posterior tibial arteries; supplies blood to the lateral plantar surfaces of the foot

left gastric artery
branch of the celiac trunk; supplies blood to the stomach

lumbar arteries
branches of the abdominal aorta; supply blood to the lumbar region, the abdominal wall, and spinal cord

lumbar veins
drain the lumbar portion of the abdominal wall and spinal cord; the superior lumbar veins drain into the azygos vein on the right or the hemiazygos vein on the left; blood from these vessels is returned to the superior vena cava rather than the inferior vena cava

maxillary vein
drains blood from the maxillary region and leads to the external jugular vein

medial plantar artery
arises from the bifurcation of the posterior tibial arteries; supplies blood to the medial plantar surfaces of the foot

median antebrachial vein
vein that parallels the ulnar vein but is more medial in location; intertwines with the palmar venous arches

median cubital vein
superficial vessel located in the antecubital region that links the cephalic vein to the basilic vein in the form of a v; a frequent site for a blood draw

median sacral artery
continuation of the aorta into the sacrum

mediastinal artery
branch of the thoracic aorta; supplies blood to the mediastinum

middle cerebral artery
another branch of the internal carotid artery; supplies blood to the temporal and parietal lobes of the cerebrum

middle sacral vein
drains the sacral region and leads to the left common iliac vein

occipital sinus
enlarged vein that drains the occipital region near the falx cerebelli and flows into the left and right transverse sinuses, and also into the vertebral veins

ophthalmic artery
branch of the internal carotid artery; supplies blood to the eyes

ovarian artery
branch of the abdominal aorta; supplies blood to the ovary, uterine (Fallopian) tube, and uterus

ovarian vein
drains the ovary; the right ovarian vein leads to the inferior vena cava and the left ovarian vein leads to the left renal vein

palmar arches
superficial and deep arches formed from anastomoses of the radial and ulnar arteries; supply blood to the hand and digital arteries

palmar venous arches
drain the hand and digits, and feed into the radial and ulnar veins

parietal branches
(also, somatic branches) group of arterial branches of the thoracic aorta; includes those that supply blood to the thoracic cavity, vertebral column, and the superior surface of the diaphragm

pericardial artery
branch of the thoracic aorta; supplies blood to the pericardium

petrosal sinus
enlarged vein that receives blood from the cavernous sinus and flows into the internal jugular vein

phrenic vein
drains the diaphragm; the right phrenic vein flows into the inferior vena cava and the left phrenic vein leads to the left renal vein

plantar arch
formed from the anastomosis of the dorsalis pedis artery and medial and plantar arteries; branches supply the distal portions of the foot and digits

plantar veins
drain the foot and lead to the plantar venous arch

plantar venous arch
formed from the plantar veins; leads to the anterior and posterior tibial veins through anastomoses

popliteal artery
continuation of the femoral artery posterior to the knee; branches into the anterior and posterior tibial arteries

popliteal vein
continuation of the femoral vein behind the knee; drains the region behind the knee and forms from the fusion of the anterior and posterior tibial veins

posterior cerebral artery
branch of the basilar artery that forms a portion of the posterior segment of the arterial circle; supplies blood to the posterior portion of the cerebrum and brain stem

posterior communicating artery
branch of the posterior cerebral artery that forms part of the posterior portion of the arterial circle; supplies blood to the brain

posterior tibial artery
branch from the popliteal artery that gives rise to the fibular or peroneal artery; supplies blood to the posterior tibial region

posterior tibial vein
forms from the dorsal venous arch; drains the area near the posterior surface of the tibia and leads to the popliteal vein

pulmonary artery
one of two branches, left and right, that divides off from the pulmonary trunk and leads to smaller arterioles and eventually to the pulmonary capillaries

pulmonary circuit
system of blood vessels that provide gas exchange via a network of arteries, veins, and capillaries that run from the heart, through the body, and back to the lungs

pulmonary trunk
single large vessel exiting the right ventricle that divides to form the right and left pulmonary arteries

pulmonary veins
two sets of paired vessels, one pair on each side, that are formed from the small venules leading away from the pulmonary capillaries that flow into the left atrium

radial artery
formed at the bifurcation of the brachial artery; parallels the radius; gives off smaller branches until it reaches the carpal region where it fuses with the ulnar artery to form the superficial and deep palmar arches; supplies blood to the lower arm and carpal region

radial vein
parallels the radius and radial artery; arises from the palmar venous arches and leads to the brachial vein

renal artery
branch of the abdominal aorta; supplies each kidney

renal vein
largest vein entering the inferior vena cava; drains the kidneys and leads to the inferior vena cava

right gastric artery
branch of the common hepatic artery; supplies blood to the stomach

sigmoid sinuses
enlarged veins that receive blood from the transverse sinuses; flow through the jugular foramen and into the internal jugular vein

small saphenous vein
located on the lateral surface of the leg; drains blood from the superficial regions of the lower leg and foot, and leads to the popliteal vein

splenic artery
branch of the celiac trunk; supplies blood to the spleen

straight sinus
enlarged vein that drains blood from the brain; receives most of the blood from the great cerebral vein and flows into the left or right transverse sinus

subclavian artery
right subclavian arises from the brachiocephalic artery, whereas the left subclavian artery arises from the aortic arch; gives rise to the internal thoracic, vertebral, and thyrocervical arteries; supplies blood to the arms, chest, shoulders, back, and central nervous system

subclavian vein
located deep in the thoracic cavity; becomes the axillary vein as it enters the axillary region; drains the axillary and smaller local veins near the scapular region; leads to the brachiocephalic vein

subscapular vein
drains blood from the subscapular region and leads to the axillary vein

superior mesenteric artery
branch of the abdominal aorta; supplies blood to the small intestine (duodenum, jejunum, and ileum), the pancreas, and a majority of the large intestine

superior phrenic artery
branch of the thoracic aorta; supplies blood to the superior surface of the diaphragm

superior sagittal sinus
enlarged vein located midsagittally between the meningeal and periosteal layers of the dura mater within the falx cerebri; receives most of the blood drained from the superior surface of the cerebrum and leads to the inferior jugular vein and the vertebral vein

superior vena cava
large systemic vein; drains blood from most areas superior to the diaphragm; empties into the right atrium

temporal vein
drains blood from the temporal region and leads to the external jugular vein

testicular artery
branch of the abdominal aorta; will ultimately travel outside the body cavity to the testes and form one component of the spermatic cord

testicular vein
drains the testes and forms part of the spermatic cord; the right testicular vein empties directly into the inferior vena cava and the left testicular vein empties into the left renal vein

thoracic aorta
portion of the descending aorta superior to the aortic hiatus

thyrocervical artery
arises from the subclavian artery; supplies blood to the thyroid, the cervical region, the upper back, and shoulder

transient ischemic attack (TIA)
temporary loss of neurological function caused by a brief interruption in blood flow; also known as a mini-stroke

transverse sinuses
pair of enlarged veins near the lambdoid suture that drain the occipital, sagittal, and straight sinuses, and leads to the sigmoid sinuses

trunk
large vessel that gives rise to smaller vessels

ulnar artery
formed at the bifurcation of the brachial artery; parallels the ulna; gives off smaller branches until it reaches the carpal region where it fuses with the radial artery to form the superficial and deep palmar arches; supplies blood to the lower arm and carpal region

ulnar vein
parallels the ulna and ulnar artery; arises from the palmar venous arches and leads to the brachial vein

vertebral artery
arises from the subclavian artery and passes through the vertebral foramen through the foramen magnum to the brain; joins with the internal carotid artery to form the arterial circle; supplies blood to the brain and spinal cord

vertebral vein
arises from the base of the brain and the cervical region of the spinal cord; passes through the intervertebral foramina in the cervical vertebrae; drains smaller veins from the cranium, spinal cord, and vertebrae, and leads to the brachiocephalic vein; counterpart of the vertebral artery

visceral branches
branches of the descending aorta that supply blood to the viscera

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18.4: Development of Blood Vessels and Fetal Circulation

By the end of this section, you will be able to:

- Describe the development of blood vessels
- Distinguish fetal circulation from newborn circulation

In a developing embryo, the heart has developed enough by day 21 post-fertilization to begin beating. Circulation patterns are clearly established by the fourth week of embryonic life. It is critical to the survival of the developing human that the circulatory system forms early to supply the growing tissue with nutrients and gases, and to remove waste products. Blood cells and vessel production in structures outside the embryo proper called the yolk sac, chorion, and connecting stalk begin about 15 to 16 days following fertilization. Development of these circulatory elements within the embryo itself begins approximately 2 days later. During those first few weeks, blood vessels begin to form from the embryonic mesoderm. The precursor cells are known as **hemangioblasts**. These in turn differentiate into **angioblasts**, which give rise to the blood vessels and pluripotent stem cells, which differentiate into the formed elements of blood. Together, these cells form masses known as **blood islands** scattered throughout the embryonic disc. Spaces appear on the blood islands that develop into vessel lumens. The endothelial lining of the vessels arise from the angioblasts within these islands. Surrounding mesenchymal cells give rise to the smooth muscle and connective tissue layers of the vessels. While the vessels are developing, the pluripotent stem cells begin to form the blood.

Vascular tubes also develop on the blood islands, and they eventually connect to one another as well as to the developing, tubular heart. Thus, the developmental pattern, rather than beginning from the formation of one central vessel and spreading outward, occurs in many regions simultaneously with vessels later joining together. This **angiogenesis**—the creation of new blood vessels from existing ones—continues as needed throughout life as we grow and develop.

Blood vessel development often follows the same pattern as nerve development. This occurs because the many factors directing growth of nerves also stimulate blood vessels to grow near the nerves in the same area. Whether a given vessel develops into an artery or a vein is dependent upon local concentrations of signaling proteins.

As the embryo grows within the mother's uterus, its requirements for nutrients and gas exchange also grow. The placenta—a circulatory organ unique to pregnancy—develops jointly from the embryo and uterine wall structures to fill this need. Emerging from the placenta is the **umbilical vein**, which carries oxygen-rich blood from the mother to the fetal inferior vena cava via the ductus venosus to the heart that pumps it into fetal circulation. Two **umbilical arteries** carry oxygen-depleted fetal blood, including wastes and carbon dioxide, to the placenta. Remnants of the umbilical arteries remain in the adult as the medial umbilical ligaments.

There are three major shunts—alternate paths for blood flow—found in the circulatory system of the fetus. Two of these shunts divert blood from the pulmonary to the systemic circuit, whereas the third connects the umbilical vein to the inferior vena cava. The first two shunts are critical during fetal life, when the lungs are compressed, filled with amniotic fluid, and nonfunctional, and gas exchange is provided by the placenta. These shunts close shortly after birth, however, when the newborn begins to breathe. The third shunt persists a bit longer but becomes nonfunctional once the umbilical cord is severed. The three shunts are as follows (Figure 18.4.1):

- The **foramen ovale** is an opening in the interatrial septum that allows blood to flow from the right atrium to the left atrium. A valve associated with this opening prevents backflow of blood during the fetal period. As the newborn begins to breathe and blood pressure in the atria increases, this shunt closes. The fossa ovalis remains in the interatrial septum after birth, marking the location of the former foramen ovale.
- The **ductus arteriosus** is a short, muscular vessel that connects the pulmonary trunk to the aorta. Most of the blood pumped from the right ventricle into the pulmonary trunk is thereby diverted into the aorta. Only enough blood reaches the fetal lungs to maintain the developing lung tissue. When the newborn takes the first breath, pressure within the lungs drops dramatically, and both the lungs and the pulmonary vessels expand. As the amount of oxygen increases, the smooth muscles in the wall of the ductus arteriosus constrict, sealing off the passage. Eventually, the muscular and endothelial components of the ductus arteriosus degenerate, leaving only the connective tissue component of the ligamentum arteriosum.
- The **ductus venosus** is a temporary blood vessel that branches from the umbilical vein, allowing much of the freshly oxygenated blood from the placenta—the organ of gas exchange between the mother and fetus—to bypass the fetal liver and go directly to the fetal heart. The ductus venosus closes slowly during the first weeks of infancy and degenerates to become

the ligamentum venosum.

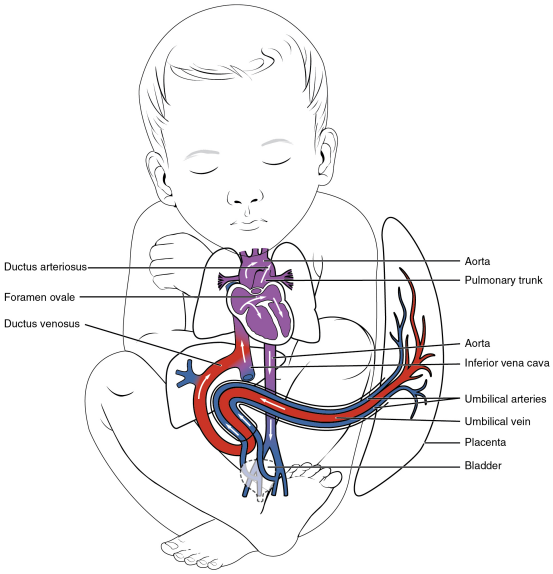

Figure 18.4.1: Fetal Shunts. The foramen ovale in the interatrial septum allows blood to flow from the right atrium to the left atrium. The ductus arteriosus is a temporary vessel, connecting the aorta to the pulmonary trunk. The ductus venosus links the umbilical vein to the inferior vena cava largely through the liver. (Image credit: "Fetal Circulation" by OpenStax is licensed under CC BY 3.0)

Concept Review

Blood vessels begin to form from the embryonic mesoderm. The precursor hemangioblasts differentiate into angioblasts, which give rise to the blood vessels and pluripotent stem cells that differentiate into the formed elements of the blood. Together, these cells form blood islands scattered throughout the embryo. Extensions known as vascular tubes eventually connect the vascular network. As the embryo grows within the mother's womb, the placenta develops to supply blood rich in oxygen and nutrients via the umbilical vein and to remove wastes in oxygen-depleted blood via the umbilical arteries. Three major shunts found in the fetus are the foramen ovale and ductus arteriosus, which divert blood from the pulmonary to the systemic circuit, and the ductus venosus, which carries freshly oxygenated blood high in nutrients from the placenta to the fetal heart.

Review Questions

Q. Blood islands are _____.

A. clusters of blood-filtering cells in the placenta

B. masses of pluripotent stem cells scattered throughout the fetal bone marrow

C. vascular tubes that give rise to the embryonic tubular heart

D. masses of developing blood vessels and formed elements scattered throughout the embryonic disc

Answer

Answer: D

Q. Which of the following statements is true?

A. Two umbilical veins carry oxygen-depleted blood from the fetal circulation to the placenta.

B. One umbilical vein carries oxygen-rich blood from the placenta to the fetal heart.

C. Two umbilical arteries carry oxygen-depleted blood to the fetal lungs.

D. None of the above are true.

Answer

Answer: B

Q. The ductus venosus is a shunt that allows _____.

A. fetal blood to flow from the right atrium to the left atrium

B. fetal blood to flow from the right ventricle to the left ventricle

C. most freshly oxygenated blood to flow into the fetal heart

D. most oxygen-depleted fetal blood to flow directly into the fetal pulmonary trunk

Answer

Answer: C

Critical Thinking Questions

Q. All tissues, including malignant tumors, need a blood supply. Explain why drugs called angiogenesis inhibitors would be used in cancer treatment.

Answer

A. Angiogenesis inhibitors are drugs that inhibit the growth of new blood vessels. They can impede the growth of tumors by limiting their blood supply and therefore their access to gas and nutrient exchange.

Q. Explain why the umbilical vein, which carries oxygenated blood, referred to as a vein.

Answer

A. The categorization of arteries and veins has only to do with the direction the blood flows in relation to the heart, not oxygen content of the blood within the vessel. The umbilical vein brings oxygenated blood from the placenta toward the baby's heart. Vessels that are routed toward the heart are categorized as veins while vessels that are routed away from the heart are categorized as arteries.

Q. Explain the location and importance of the ductus arteriosus in fetal circulation.

Answer

A. The ductus arteriosus is a blood vessel that provides a passageway between the pulmonary trunk and the aorta during fetal life. Most blood ejected from the fetus' right ventricle and entering the pulmonary trunk is diverted through this structure into the fetal aorta, thus bypassing the fetal lungs.

Glossary

angioblasts
stem cells that give rise to blood vessels

angiogenesis
development of new blood vessels from existing vessels

blood islands
masses of developing blood vessels and formed elements from mesodermal cells scattered throughout the embryonic disc

ductus arteriosus
shunt in the fetal pulmonary trunk that diverts oxygenated blood back to the aorta

ductus venosus
shunt that causes oxygenated blood to bypass the fetal liver on its way to the inferior vena cava

foramen ovale
shunt that directly connects the right and left atria and helps to divert oxygenated blood from the fetal pulmonary circuit

hemangioblasts
embryonic stem cells that appear in the mesoderm and give rise to both angioblasts and pluripotent stem cells

umbilical arteries
pair of vessels that runs within the umbilical cord and carries fetal blood low in oxygen and high in waste to the placenta for exchange with maternal blood

umbilical vein
single vessel that originates in the placenta and runs within the umbilical cord, carrying oxygen- and nutrient-rich blood to the fetal heart

vascular tubes
rudimentary blood vessels in a developing fetus

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19: LYMPHATIC AND IMMUNE SYSTEM

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19.1: Introduction to the Lymphatic and Immune Systems

19.2: Functions of the Lymphatic and Immune Systems

19.3: Anatomy of Lymphatic Vessels

19.4: Anatomy of Lymphatic Organs and Tissues

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19.1: Introduction to the Lymphatic and Immune Systems

Chapter Learning Objectives:

After studying this chapter, you will be able to:

- Explain the location, structure, and function of the components of the lymphatic system
- Discuss the integration of the lymphatic system with other body systems
- Explain how the structure and organization of lymphatic vessels and lymph nodes are suited to their functions
- Describe the temporal organization of the immune system
- Distinguish primary and secondary adaptive immune responses

Rather than being made up of a distinct set of organs like most body systems, the immune system is integrated within each of the body's systems to prevent or slow infection, fight sickness, and rid the body of debris and abnormal cells. The immune system is made up of a combination of anatomical and physiological barriers and specialized cells, including the white blood cells and their derivatives, as well as proteins and other molecules. The lymphatic system is comprised of a distinct set of organs and tissues whose primary functions support the immune system.

DISORDERS OF THE...

Immune System: HIV and AIDS

In June 1981, the Centers for Disease Control and Prevention (CDC), in Atlanta, Georgia, published a report of an unusual cluster of five patients in Los Angeles, California. All five were diagnosed with a rare pneumonia caused by a fungus called Pneumocystis jirovecii (formerly known as Pneumocystis carinii). Why was this unusual? Although commonly found in the lungs of healthy individuals, this fungus is an opportunistic pathogen that causes disease in individuals with suppressed or underdeveloped immune systems. The very young, whose immune systems have yet to mature, and the elderly, whose immune systems have declined with age, are particularly susceptible. The five patients from LA, though, were between 29 and 36 years of age and should have been in the prime of their lives, immunologically speaking. What could be going on?

A few days later, a cluster of eight cases was reported in New York City, also involving young patients, this time exhibiting a rare form of skin cancer known as Kaposi's sarcoma. This cancer of the cells that line the blood and lymphatic vessels was previously observed as a relatively innocuous disease of the elderly. The disease that doctors saw in 1981 was frighteningly more severe, with multiple, fast-growing lesions that spread to all parts of the body, including the trunk and face. Could the immune systems of these young patients have been compromised in some way? Indeed, when they were tested, they exhibited extremely low numbers of a specific type of white blood cell in their bloodstreams, indicating that they had somehow lost a major part of the immune system. Acquired immune deficiency syndrome, or AIDS, turned out to be a new disease caused by the previously unknown human immunodeficiency virus (HIV), a virus that is transmitted sexually or by contact with infected blood.

HIV infection had a grim prognosis in the early years. The first treatment was approved in 1987, but had limited efficacy in the long term. Additional anti-retroviral drugs (ARDs, targeting HIV as an RNA virus) were developed over the next ten years and eventually treatment with a combination of anti-HIV drugs termed "highly active antiretrovirals" (HAART) was approved in 1996, reportedly reducing HIV deaths by 60 to 80% in those with access to the treatment. HIV infection is now a chronic, manageable disease for those with adequate access to healthcare. As of the 30th anniversary of World AIDS Day in 2018, treatment can suppress HIV virus levels to below detectable limits with minimal risk of transmitting the virus to a partner. ARDs are now approved for pre-exposure prophylactic (PrEP) use to prevent infection in those that are HIV-negative but at elevated risk of contracting the virus.

Along with all this progress, the epidemic has highlighted global inequities in access to healthcare. Worldwide, as of 2018, it was estimated that 25% of those living with HIV do not know they are infected with HIV. Learn more about why the HIV epidemic is not over.

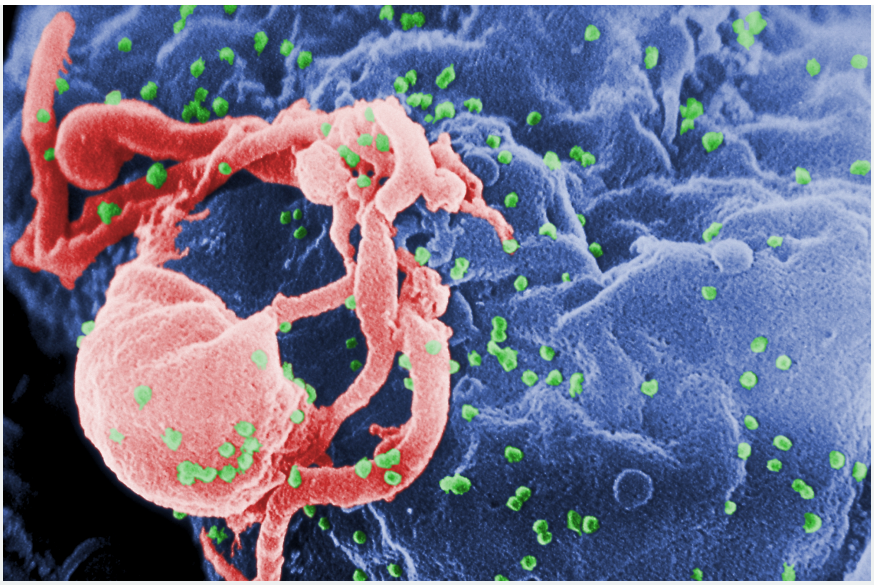

Figure 19.1.1: HIV Virus. In this scanning electron micrograph, HIV virions (green particles) are budding off the surface of a cultured lymphocyte (pink structure). (Image credit: "HIV Budding Color" by C. Goldsmith is in the Public Domain)

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"Why the HIV Epidemic Is Not Over." *World Health Organization*, World Health Organization. 28 Nov 2018. [Accessed 15 Dec 2020]

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19.2: Functions of the Lymphatic and Immune Systems

By the end of this section, you will be able to:

- Explain the overall functions of the lymphatic system
- Describe the temporal organization of the immune system
- Distinguish primary and secondary adaptive immune responses

Functions of the Lymphatic System

The functions of the lymphatic system are integral to the immune system because structures of the lymphatic system function to produce, develop, house and distribute leukocytes, but the lymphatic system also supports other body systems in a couple of ways. A network of lymphatic vessels provide a one-way route to return excess fluid from tissues back to the bloodstream to maintain blood volume and also distribute leukocytes throughout the body. Along the way, the fluid is filtered for pathogens and debris as it passes through lymph nodes. Lymphatic capillaries serving the small intestine also collect lipid products of digestion that are too large to enter blood capillaries. These lipids are transported to the bloodstream via the lymphatic vessels. Lymph is the watery fluid connective tissue found in lymphatic vessels whose cellular components include primarily lymphocytes along with phagocytic macrophages and other specialized leukocytes. The watery matrix of lymph is similar to the plasma of blood; it contains dissolved nutrients, waste products, and plasma proteins.

Lymphoid tissues and organs are so-called because they contain fluid that resembles lymph, and they support lymphocyte production, development, storage, and functions in a variety of locations in the body. Dense collections of leukocytes suspended in reticular connective tissue that remove debris and fight infection within organs of other body systems constitute lymphoid tissues such as the tonsils and mucosa-associated lymphoid tissues (MALT). The lymphatic system also includes distinct organs that support the immune system including the thymus, spleen, and red bone marrow. The vessels, tissues, and organs of the lymphatic system are summarized in Figure 19.2.1 and Table 19.2.1 and will be covered in more detail in subsequent sections of this chapter.

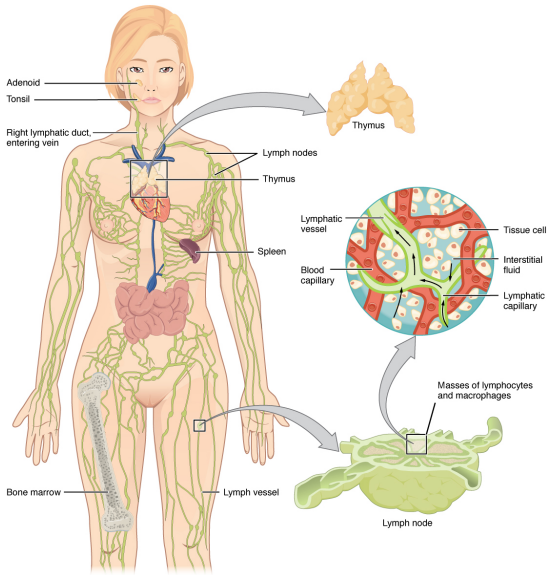

Figure 19.2.1: Anatomy of the Lymphatic System. Lymphatic vessels, with lymph nodes along their length, as well as the tonsils, thymus, spleen, and red bone marrow are all organs of the lymphatic system. (Image credit: "Anatomy of the Lymphatic System" by OpenStax is licensed under CC BY 3.0)

Table 19.2.1. Structures of the Lymphatic System

Structure	Examples	Functions
Lymphatic Vessels	Lymphatic capillaries, vessels, trunks, and ducts containing lymph	• Return excess fluid from tissues to the bloodstream • Distribute lymphocytes and other leukocytes throughout the body • Transport lipid products of digestion to the bloodstream
Lymphoid Tissues	Tonsils, Mucosa-Associated Lymphoid Tissue (MALT)	• Support lymphocyte production, storage, and distribution
Lymphoid Organs	Lymph Nodes, Thymus, Red Bone Marrow, Spleen	• Support lymphocyte production, storage, and distribution • Filter blood and lymph of debris, abnormal cells, and pathogens

The Organization of Immune Function

The structures of the lymphatic system play integral roles in supporting the immune system, which is responsible for ridding the body of cellular debris and abnormal cells as well as preventing and fighting infection.

The immune system is a collection of barriers, cells, and soluble proteins that interact and communicate with each other in extraordinarily complex ways. The modern model of immune function is organized into three phases based on the timing of their effects. The three temporal phases or lines of defense are summarized in Table 19.2.2.

Table 19.2.2. Organization of the Immune System's Lines of Defense

Line of Defense	Temporal Response	Type of Immunity	Description	Function(s)
First Line of Defense	Instantaneous	Innate	Barrier defenses such as skin and mucus membranes	*Prevent* pathogenic invasion into the body tissues

Line of Defense	Temporal Response	Type of Immunity	Description	Function(s)
Second Line of Defense	Rapid	Innate	Non-specific internal defenses including cells, soluble factor, inflammatory response	• Discover and slow the progression of pathogenic infection, • Rid the body of debris, including dead and abnormal cells, • Promote healing after tissue damage
Third Line of Defense	Slow	Adaptive	Specific responses mediated by lymphocytes	• Eradicate pathogenic infection • Retain memory for secondary response

The functions of the immune system are woven into the anatomy of every body system. Innate immunity refers to defenses that are present from birth, including both the infection-preventing **barrier defenses** and the cellular and physiological internal defenses that respond if the barrier defenses are breached. The **innate internal immune responses** are non-specific and designed to discover and slow the progression of an infection-causing pathogen (Figure 19.2.2). A **pathogen** is any agent capable of causing infection, such as a virus, bacterium, or fungal organism. **Adaptive immune responses** are designed to recognize, destroy, and retain a memory of a specific pathogen by adapting to each specific pathogen after it is discovered in the body.

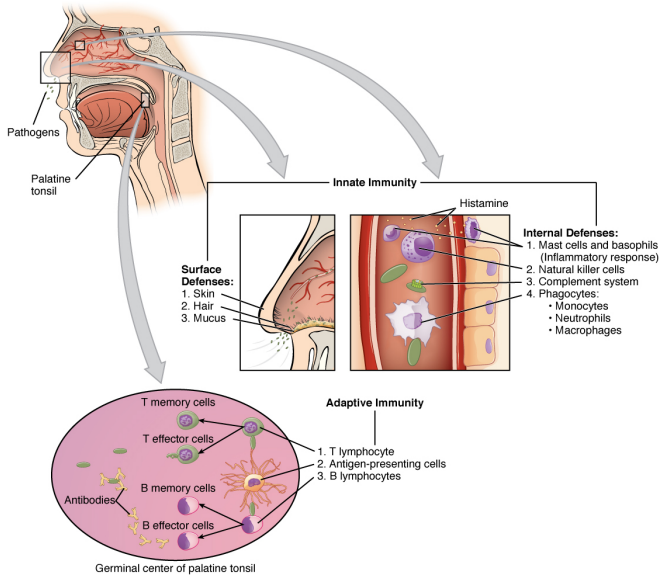

Figure 19.2.2: Cooperation between Elements of Innate and Adaptive Immunity. The innate immune system includes barrier defenses aimed at preventing infection and internal defenses aimed at slowing the spread of infection while activating adaptive immunity. Adaptive immune responses are slower but most effective in eradicating infection. (Image credit: "Cooperation Between Innate and Immune Responses" by OpenStax is licensed under CC BY 3.0)

Barrier Defenses

Epithelial barriers are consistently present and optimized for barrier defense as well as their other functions. Epithelial tissues near the outside of the body produce specialized secretions that physiologically enhance the physical barriers to further deter potential infection. For example, the inside of the nose has an epithelial barrier with hairs and a coating of mucus that function to trap pathogens. Further, in areas that are exposed to the environment, body fluids such as sweat, sebum, and urine have antimicrobial properties and also maintain conditions, such as lipid content or pH, that encourage the growth of beneficial microorganisms. The combination of these beneficial microorganisms living on or inside the body on the apical surface of epithelial tissues constitutes the **microbiome**, and its population size outnumbers human cells in the body. The microbiome is an important part of barrier defenses because one of its roles is to out-compete pathogenic microorganisms to prevent infection.

Cooperation between Innate and Adaptive Immunity

In the event a pathogen successfully penetrates the barrier defenses and enters the body, its detection by the immune system will solicit a dynamic response. The innate internal defenses include cells and physiological responses that function to slow the spread of infection. Physiological responses include inflammation, triggered by histamine secreted by basophils and/or mast cells, and the complement system, in which proteins and other molecules participate in fighting the infection to slow its progression. These physiological responses will not be covered in detail here.

Cells of the innate internal immune response do not recognize specific antigens like the lymphocytes of the adaptive immune response. Instead they have receptors that recognize patterns in the surface antigens that simply distinguish whether any immune response is warranted. If a cell or particle is recognized as "self", a normally functioning part the body, no immune response is warranted. However, if a cell or particle is recognized as "non-self" because the pattern of surface antigens signify it does not belong in the body, a dynamic immune response is triggered. Detection of pathogens or even your own cells that are abnormal because they may be pre-cancerous or infected by an intracellular pathogen such as a virus will solicit a response. The adaptive immune response requires cooperation with elements of innate immunity, but also specialized structures of the lymphatic system from which to coordinate adaptive responses.

Phagocytes: Macrophages, Dendritic Cells, and Neutrophils

A phagocyte is a cell that is able to surround and engulf a particle or cell, a process called **phagocytosis**. The phagocytes of the immune system engulf other particles or cells, either to clean an area of debris, old cells, or to kill pathogens. The phagocytes

are the body's fast-acting defense against microorganisms that have breached barrier defenses and have entered the vulnerable tissues of the body.

Many of the cells of the immune system have a phagocytic ability, at least at some point during their life cycles. Phagocytosis is an important and effective mechanism of destroying pathogens during innate immune responses. The phagocyte takes the organism inside itself as a phagosome, which subsequently fuses with a lysosome containing digestive enzymes that effectively kill most pathogens. On the other hand, some bacteria including *Mycobacteria tuberculosis*, the cause of tuberculosis, may be resistant to these enzymes and are therefore much more difficult to clear from the body. Macrophages, neutrophils, and dendritic cells are the major phagocytes of the immune system.

A **macrophage** is an irregularly shaped phagocyte that is the most versatile of the phagocytes in the body. Macrophages move through tissues and squeeze through capillary walls using foot-like extensions called pseudopodia. They not only participate in innate immune responses but have also evolved to cooperate with lymphocytes to facilitate the adaptive immune response. Macrophages exist in many tissues of the body, either freely roaming through connective tissues or fixed to reticular fibers within specific tissues such as lymph nodes. When pathogens breach the body's barrier defenses, macrophages are the first responders in lymphoid and connective tissues outside the bloodstream. **Dendritic cells** are similar to macrophages, but have slightly more branched shape to further increase their surface area (thus the name, dendr- refers to a tree branch). Dendritic cells are typically found in epithelial tissues. Both macrophages and dendritic cells are **antigen-presenting cells (APCs)**, meaning they present fragments of the antigens belonging to pathogens they have engulfed and destroyed to T lymphocytes to activate the adaptive immune response. A **monocyte** is a circulating precursor cell that differentiates into either a macrophage or dendritic cell, which can be rapidly attracted to areas of infection by signal molecules of inflammation.

Natural Killer Cells (NK Cells)

Natural killer cells (NK cells) are a type of lymphocyte that belongs to the innate internal immune response. NK cells have the ability to induce apoptosis, that is programmed cell death, in cells infected with intracellular pathogens such as bacteria and viruses. NK cells recognize these cells by mechanisms that are still not well understood, but that presumably involve their surface receptors. NK cells can induce apoptosis, in which a cascade of events inside the cell causes its self destruction. If apoptosis is induced before the virus has the ability to synthesize and assemble all its components, no infectious virus will be released from the cell, thus preventing further infection.

Innate internal immune responses (and early adaptive responses) are in many cases ineffective at completely controlling pathogen growth. However, they slow pathogen growth and allow time for the adaptive immune response to strengthen and either control or eliminate the pathogen. The innate immune system also sends signals to the cells of the adaptive immune system, guiding them in how to attack the pathogen. Thus, these are the two important arms of the immune response.

The Benefits of the Adaptive Immune Response

Three aspects of the adaptive immune response make it particularly effective: specificity, immunological memory, and self-recognition. All three of these benefits are made possible by the unique physiological mechanisms of lymphocyte development and proliferation. Lymphocytes are stored in many tissues and organs of the lymphatic system that are strategically located throughout the body ready to be activated and coordinate adaptive responses.

The specificity of the adaptive immune response—its ability to specifically recognize and make a response against a wide variety of pathogens—is its great strength. Antigens, the small chemical groups often associated with pathogens, are recognized by receptors on the surface of B and T lymphocytes. The adaptive immune response to these antigens is so versatile that it can respond to nearly any pathogen.

Upon first exposure to a new pathogen, a naïve T cell is activated and expresses a receptor that specifically corresponds to the antigen of the pathogen. The activated T cell then rapidly divides creating an army of lymphocytes expressing that same specific receptor to fight off the pathogen, as well as an army of memory cells to retain T cells that have adapted to the specific pathogen for some time (depending on the pathogen, these memory cells could last for months or for a lifetime). If exposed to the same pathogen again, the memory cells will re-activate a rapid secondary response that will overwhelm the pathogen before symptoms present. This is known as immunological memory.

A third important feature of the adaptive immune response is its ability to distinguish between self-antigens, those that are normally present in the body, and non-self antigens, those that might be on a potential pathogen. As T and B cells mature, there

are mechanisms in place that prevent them from recognizing self-antigen, preventing a damaging immune response against the body. These mechanisms are not 100 percent effective, however, and their breakdown leads to autoimmune diseases, which will be discussed later in this chapter.

T Cell-mediated Immune Responses

The immune system's first exposure to a pathogen is called a **primary adaptive immune response**. Symptoms of a first infection, called primary disease, are always relatively severe because it takes time for an initial adaptive immune response to a pathogen to become effective.

In the case primary adaptive immune response, naïve T cells (naïve because they have not yet developed specificity for a particular antigen), such as those stored in the tonsils, become activated to recognize a specific antigen and begin dividing rapidly by mitosis. Each T cell clone has a receptor specific for a particular antigen "hard-wired" into its DNA, and all of its progeny will have identical DNA and T cell receptors, forming clones of the original T cell that will recognize the antigen of a specific pathogen. This proliferation of T cells is called clonal expansion and is necessary to make the immune response strong enough to effectively control a pathogen.

During a primary adaptive immune response, both **memory T cells** and **effector T cells** are generated. Effector T cells act immediately to eradicate the pathogen. Memory T cells are longer-lived and, depending on the pathogen, can even persist for a lifetime. Memory cells are primed to act rapidly upon re-exposure to the same pathogen, generating a **secondary adaptive immune response** that is stronger and faster than the primary response. This rapid, secondary adaptive response generates large numbers of effector T cells so fast that the pathogen is often overwhelmed before it can cause any symptoms of disease. This is what is meant by immunity to a disease. The same pattern of primary and secondary immune responses occurs in B cells and the antibody response.

Types of T Cells

Helper T cells (Th, T4, or $CD4^+$ T cells) interact with the antigen-presenting cells like macrophages and dendritic cells. Helper T cells activate other types of T cells and B cells to mount a response to a specific antigen, but they activate innate immune cells as well by secreting cytokine signaling molecules.

Cytotoxic T cells (Tc, T8, or $CD8^+$ T cells) are T cells that kill target cells by inducing apoptosis (programmed cell death) using the same mechanism as NK cells. As was discussed earlier with NK cells, killing a virally infected cell before the virus can complete its replication cycle results in the production of no infectious particles. As more cytotoxic T cells are developed during an immune response, they overwhelm the ability of the virus to cause disease. In addition, each cytotoxic T cell can kill more than one target cell, making them especially effective. Cytotoxic T cells are so important in the antiviral immune response that some speculate that this was the main reason the adaptive immune response evolved in the first place.

Regulatory T cells, or suppressor T cells, are the most recently discovered of the types listed here, so less is understood about them. Exactly how they function is still under investigation, but it is known that they suppress other T cell immune responses. This is an important feature of the immune response, because if clonal expansion during immune responses were allowed to continue uncontrolled, these responses could lead to autoimmune diseases and other medical issues.

Not only do T cells directly destroy pathogens, but they regulate nearly all other types of the adaptive immune response as well.

B Lymphocytes and Antibodies

Antibodies were the first component of the adaptive immune response to be characterized by scientists working on the immune system. It was already known that individuals who survived a bacterial infection were immune to re-infection with the same pathogen. Early microbiologists took serum from an immune patient and mixed it with a fresh culture of the same type of bacteria, then observed the bacteria under a microscope. The bacteria became clumped in a process called agglutination. When a different bacterial species was used, the agglutination did not happen. Thus, there was something in the serum of immune individuals that could specifically bind to and agglutinate bacteria.

Scientists now know the cause of the agglutination is an **antibody** molecule, also called an **immunoglobulin**. What is an antibody? An antibody protein is essentially a secreted form of the antigen-specific receptor. Not surprisingly, the same genes

encode both the secreted antibodies and the surface receptors; just one minor difference in the way these proteins are synthesized distinguishes them.

Antibodies circulate in the blood plasma to alert the immune system to the presence of the matching antigen (and thereby the pathogen). Antibodies have several mechanisms by which they participate in physiological immune responses. For example, in the case of a virus, agglutination (binding of the antibodies to antigens) may prevent the pathogen from infecting a cell and reproducing by blocking the ability of the virus to bind its target cell.

B Cell Activation and Clonal Selection

After a naïve B cell is activated by binding to its corresponding antigen, it undergoes clonal expansion, producing both memory B cells and cells that differentiate into plasma cells.

- Memory B cells function in a way similar to memory T cells. They lead to a stronger and faster secondary response when compared to the primary response.
- Plasma cells produce and secrete antibodies specifically corresponding to the antigen that activated the naïve B cell. After secreting antibodies for a specific period, they die, as most of their energy is devoted to making antibodies and not to maintaining themselves.

Clonal selection and expansion of B cells, as well as the primary and secondary immune response phases, work similarly to those of T cells and are depicted in Figure 19.2.3). Eventually, the plasma cells secrete antibodies with antigenic specificity identical to those that were on the surfaces of the selected B cells. Many identical clones of both plasma cells and memory B cells are generated simultaneously. Upon a second exposure to the same pathogen, the corresponding memory B cell becomes activated to divide and create additional memory B cells and plasma cells that will produce and secrete antibodies.

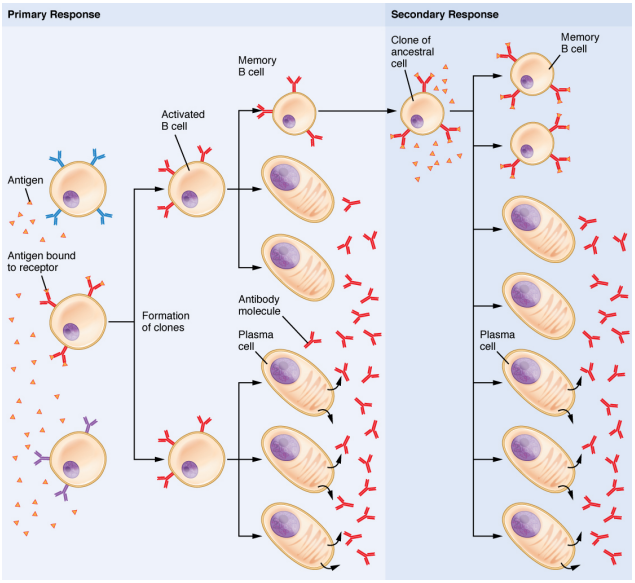

Figure 19.2.3: Comparison of Primary and Secondary B Lymphocyte Responses. During a primary B cell immune response, both antibody-secreting plasma cells and memory B cells are produced by mitotic cell division. Memory cells allow for the differentiation of more plasma cells and memory B cells during secondary responses upon subsequent exposure to the same antigen. (Image credit: "Clonal Selection of B Cells" by OpenStax is licensed under CC BY 3.0)

Concept Review

Structures of the lymphatic system support immune system function, but also carry out other specific functions. Lymphatic structures include vessels, tissues, and distinct organs. The immune system can be organized into temporal lines of defense that include the innate barrier defenses, non-specific innate internal immune responses, and the adaptive immune response. The adaptive immune response is mediated by T and B lymphocytes. Primary adaptive lymphocyte responses describe the slow but steady clonal expansion of lymphocytes programmed to respond to a specific antigen and eradicate it after primary infection. The primary adaptive lymphocyte response also yields long-lived memory T and B cells that can allow a more rapid adaptive immune response upon secondary infection with the same antigen-containing pathogen.

Review Questions

Q. Which enzymes in macrophages are important for clearing intracellular bacteria?

A. metabolic

B. mitochondrial

C. nuclear

D. lysosomal

Answer

Answer: D

Q. Which of the following cells is phagocytic?

A. plasma cell

B. macrophage

C. B cell

D. NK cell

Answer

Answer: B

Q. Which of the following cells is important in the innate immune response?

A. B cells

B. T cells

C. macrophages

D. plasma cells

Answer

Answer: C

Q. Which type of immune response works in concert with cytotoxic T cells against virally infected cells?

A. natural killer cells

B. complement

C. antibodies

D. memory

Answer

Answer: A

Critical Thinking Questions

Q. Distinguish primary and secondary adaptive immune responses to a viral infection.

Answer

A. A primary adaptive immune response occurs in response to the first exposure to a new viral infection. An antigen from the virus is presented to a helper T lymphocyte by an antigen-presenting cell (typically a macrophage or dendritic cell). T and B lymphocytes are cloned, forming effector and memory cells. Effector cells (cytotoxic T cells and plasma cells) that will work to eradicate the virus immediately. Cytotoxic T cells will induce apoptosis (programmed cell death) in cells infected with the virus. Plasma cells will produce and secrete antibodies to target the antigen of the virus. Memory cells are longer-lived cells that will activate a secondary immune response in case of a future exposure to the same antigen-containing virus.

Glossary

adaptive immune response
relatively slow but very specific and effective immune response controlled by lymphocytes

antibody
antigen-specific protein secreted by plasma cells; immunoglobulin

antigen
molecule recognized by the receptors of B and T lymphocytes

antigen-presenting cell (APC)
cell that presents a fragment of an antigen to T cells to induce an adaptive immune response

barrier defenses
antipathogen defenses deriving from a barrier that physically prevents pathogens from entering the body to establish an infection

B cells
lymphocytes that act by differentiating into an antibody-secreting plasma cell

cytotoxic T cells (Tc, T8, or $CD8^+$ T cells)
T lymphocytes with the ability to induce apoptosis in target cells

dendritic cell
phagocyte and antigen-presenting cell (APC) typically found in epithelial tissues such as the epidermis

effector T cells
immune cells with a direct, adverse effect on a pathogen

first line of defense
temporal classification for the barrier defenses of the immune system that serve to prevent infection

helper T cells (Th, T4, or $CD4^+$ T cells)
T cells that secrete cytokines to enhance other immune responses, involved in activation of both B and T cell lymphocytes

immune system
series of barriers, cells, and soluble mediators that combine to response to infections of the body with pathogenic organisms

innate internal immune response
rapid but relatively nonspecific immune response

macrophage
amoeboid phagocyte found in several tissues throughout the body; also an APC

memory T cells
long-lived immune cell reserved for future exposure to an pathogen

microbiome
the combination of beneficial microorganisms living on and inside the human body

monocyte
precursor to macrophages and dendritic cells seen in the blood

naïve lymphocyte
mature B or T cell that has not yet encountered antigen for the first time

neutrophil
phagocytic white blood cell recruited from the bloodstream to the site of infection via the bloodstream

pathogen
any microorganism or acellular particle that causes infection; examples include viruses (acellular), bacteria, fungi, protozoans, and parasitic worms

phagocytosis
movement of material from the outside to the inside of the cells via vesicles made from invaginations of the plasma membrane

plasma cell
differentiated B cell that is actively secreting antibody

natural killer cell (NK)
cytotoxic lymphocyte of innate immune response

second line of defense
temporal classification for the innate immune response that rapidly, but nonspecifically responds to pathogens to slow the spread of infection and also promotes healing after tissue damage

T cell
lymphocyte that acts by secreting molecules that regulate the immune system or by causing the destruction of foreign cells, viruses, and cancer cells

third line of defense
temporal classification for the adaptive immune response that responds more slowly, but also specifically and more effectively to eradicate infection

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19.3: Anatomy of Lymphatic Vessels

By the end of this section, you will be able to:

- Explain the structure and function of the lymphatic vessels
- Describe the asymmetrical pattern of lymphatic drainage into the bloodstream

A significant portion of the lymphatic system is comprised of a network of lymphatic vessels routed near the blood vessels of the cardiovascular system. The lymphatic vessels function to collect and transport fluid from the tissues of the body back to the bloodstream to help maintain a consistent blood volume. They also function to collect and transport dietary lipids and some lipid-soluble vitamins from the small intestine to the bloodstream and to distribute leukocytes throughout the body for housekeeping and immune defense.

Lymphatic Vessels

The **lymphatic vessels** begin as open-ended capillaries, which feed into larger and larger lymphatic vessels, and eventually empty into the bloodstream by a series of ducts. The fluid contained within lymphatic vessels is called **lymph** (lympha means "clear water"), a watery fluid that contains lymphocytes and other types of white blood cells, as well as proteins and lipids.

Blood pressure causes leakage of fluid from the blood capillaries, resulting in the accumulation of fluid in the interstitial space—that is, spaces between individual cells in the tissues. In humans, 20 liters of plasma is released into the interstitial space of the tissues each day due to capillary filtration. Once this filtrate is out of the bloodstream and in the tissue spaces, it is referred to as interstitial fluid. Of this, 17 liters is reabsorbed directly by the blood vessels. But what happens to the remaining three liters? Lymphatic capillaries drain the excess fluid away from the tissues and carry it back to the bloodstream via the network of lymphatic vessels. Lymph is the term used to describe interstitial fluid once it has entered the lymphatic system.

This cycle of fluids from blood plasma to interstitial fluid to lymph aids in oxygen and nutrient delivery to tissues as well as waste and pathogen removal away from tissues: it ensures that the body's cells are constantly exposed to fresh fluid.

Lymphatic Capillaries

Lymphatic capillaries, also called the terminal lymphatics, are vessels where interstitial fluid enters the lymphatic system to become lymph fluid. Located in almost every tissue in the body, these vessels are typically interlaced among the blood capillaries of the circulatory system in the soft connective tissues of the body (Figure 19.3.1). Exceptions are the red bone marrow, bones, teeth, and the cornea of the eye, which do not contain lymphatic vessels.

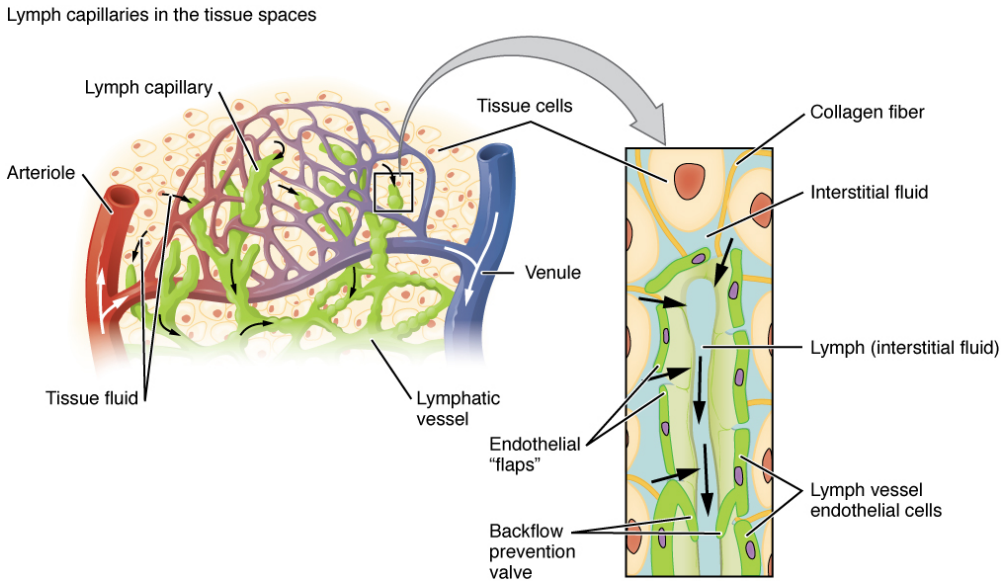

Figure 19.3.1: Lymphatic Capillaries. Lymphatic capillaries are interlaced with the arterioles, blood capillaries, and venules of the cardiovascular system. Collagen fibers anchor a lymphatic capillary in the tissue (inset). Interstitial fluid slips through spaces between the overlapping endothelial cells that compose the lymphatic capillary. (Image credit: "Lymphatic Capillaries" by OpenStax is licensed under CC BY 3.0)

Lymphatic capillaries are formed by one simple layer of endothelial cells and represent the open end of the system, allowing interstitial fluid to flow into them via overlapping endothelial cells that form "flaps" that function like valves (see Figure 19.3.1). When interstitial fluid pressure is low, the endothelial flaps close to prevent backflow of fluid from the capillary into the tissue. As interstitial pressure increases due to an increase in excess fluid, the spaces between the endothelial cells open up, allowing the fluid to enter the lymphatic capillary. Entry of fluid into lymphatic capillaries is also enabled by the collagen fibers that anchor the capillaries to surrounding structures. As interstitial pressure increases, the fibers pull on the endothelial cell flaps, opening them further to allow easy entry of fluid.

In the small intestine, lymphatic capillaries called **lacteals** are critical for the transport of dietary lipids and lipid-soluble vitamins to the bloodstream. In the small intestine, dietary triglycerides combine with other lipids and proteins, and enter the lacteals to form a milky fluid called **chyle**. The chyle then travels through the lymphatic vessels, and drains into the bloodstream.

Larger Lymphatic Vessels, Trunks, and Ducts

Larger lymphatic vessels are similar to veins in terms of their three-tunic structure and the presence of one-way valves to prevent backflow. These one-way valves are located fairly close to one another, and each one causes a bulge in the lymphatic vessel, giving the vessels a beaded appearance (see Figure 19.3.1). A major distinction between the lymphatic and cardiovascular systems in humans is that lymph is not actively pumped by the heart, but is pulled into the lymphatic capillaries by a pressure gradient (capillary action) and is forced through the vessels by similar mechanisms that help venous blood return to the heart: the contraction of skeletal muscles during body movements and the pressure gradients created by breathing. The one-way valves in lymphatic vessels keep the lymph from flowing backwards as it moves toward its destination.

Lymph is filtered for debris and pathogens in **lymph nodes** as it drains through lymphatic vessels. Humans have about 500–600 lymph nodes positioned at regular intervals along the length of lymphatic vessels throughout the body and clustered in some regions of the body. Examples of clustered lymph nodes include the axillary nodes near the armpit and the inguinal nodes near the groin (Figure 19.3.2). Lymph nodes are covered in more detail in the next section.

In general, lymphatic vessels of the subcutaneous tissues of the skin, that is, the superficial lymphatics, follow the same routes as veins, whereas the deep lymphatic vessels of the viscera generally follow the paths of arteries. The superficial and deep lymphatics eventually merge to form larger lymphatic vessels known as **lymphatic trunks**. There are four pairs of lymphatic trunks, each collecting lymph from a region of either the left or right side of the body, as well as a single **intestinal trunk**. Lymph from the head and neck drains into the **jugular trunks**. Lymph from the superficial thorax and the upper limb drains into the **subclavian trunks**. Lymph from the deep thorax drains into the **bronchomediastinal trunks**. Lymph from the lower limbs and pelvis drains into the **lumbar trunks**.

The largest lymphatic vessels that drain into the bloodstream are the **lymphatic ducts**. The overall drainage of fluid into the bloodstream via the lymphatic ducts is asymmetrical. The **right lymphatic duct** receives lymph from only the upper right portion of the body via the right jugular, subclavian, and bronchomediastinal trunks. The right lymphatic duct drains into the right subclavian vein lateral to its junction with the right internal jugular vein. The lymph from the rest of the body drains into the **thoracic duct** via all the remaining lymphatic trunks. The thoracic duct itself begins just beneath the diaphragm in the **cisterna chyli**, a sac-like chamber that receives lymph from the lower abdomen, pelvis, and lower limbs by way of the left and right lumbar trunks and the intestinal trunk. The left jugular, subclavian, and bronchomediastinal trunks drain into the thoracic duct near its entrance into the left subclavian vein, which is lateral to the junction of the left subclavian vein and left internal jugular vein.

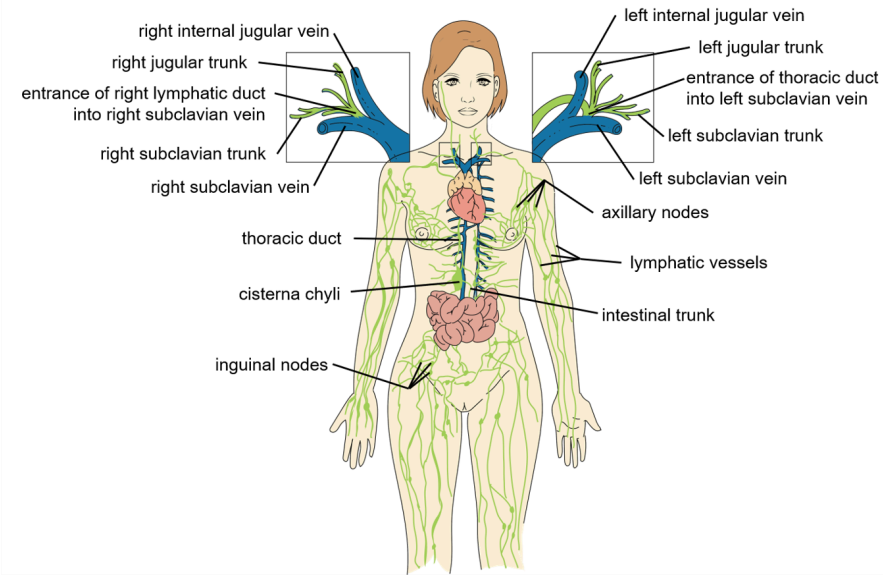

Figure 19.3.2: Overview of Lymphatic Vessels. Lymphatic vessels drain into lymphatic trunks. Lymphatic trunks drain into the right lymphatic duct from the upper portion of the right side of the body and into the larger thoracic duct from the upper portion of the left side of the body and both sides of the lower portion of the body. (Image Credit: “Lymphatic Vessels, Trunks, and Ducts" by Julie Jenks is a derivative of the original work by Daniel Donnelly and is licensed under CC BY 4.0)

DISORDERS OF THE....

Lymphatic System: Lymphedema

Edema is the term for localized swelling in the body, caused by fluid becoming trapped in the tissues. Lymphedema is caused by damage in the vasculature of the lymphatic system, such as by being blocked by cancer cells or destroyed by injury. When the fluid cannot flow properly to drain away from an area and be returned to the bloodstream, protein-rich interstitial fluid accumulates in the tissue spaces upstream of the damage. Figure 19.3.3 compares the degree of visible swelling in the left extremity impacted by each of 4 potential stages of lymphedema severity. Lymphedema may lead to serious medical consequences.

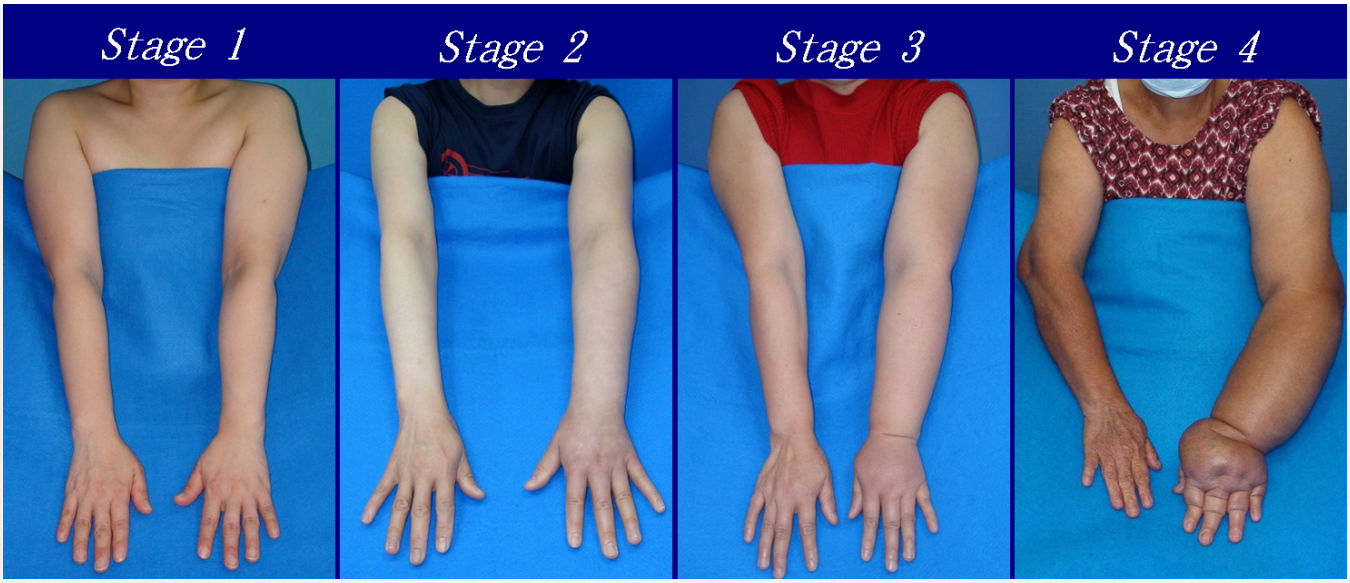

Figure 19.3.3: Lymphedema. When lymphatic vessels are unable to adequately return fluid to the bloodstream, the excess interstitial fluid can build up in a region of the body, typically one extremity. The resulting swelling is called lymphedema, which can be categorized into stages according to its severity. (Image credit: "Upper Limb Lymphedema" by DocHealer is licensed under CC BY-SA 4.0)

RECENT DISCOVERIES IN ANATOMY

Lymphatic Vessels near the Brain

Prior to the 2015 discovery of lymphatic vessels in the dura mater surrounding the brain, maps of lymphatic vessels would depict an unexpected absence of lymphatic vessels around the brain (Figure \({19{.}3{.}\eatSpaces{4} \endSpaces}\.a)). We now understand there are lymphatic vessels embedded alongside the venous sinuses in the dura mater meningeal layer surrounding the brain (Figure \({19{.}3{.}\eatSpaces{4} \endSpaces}\.b)).

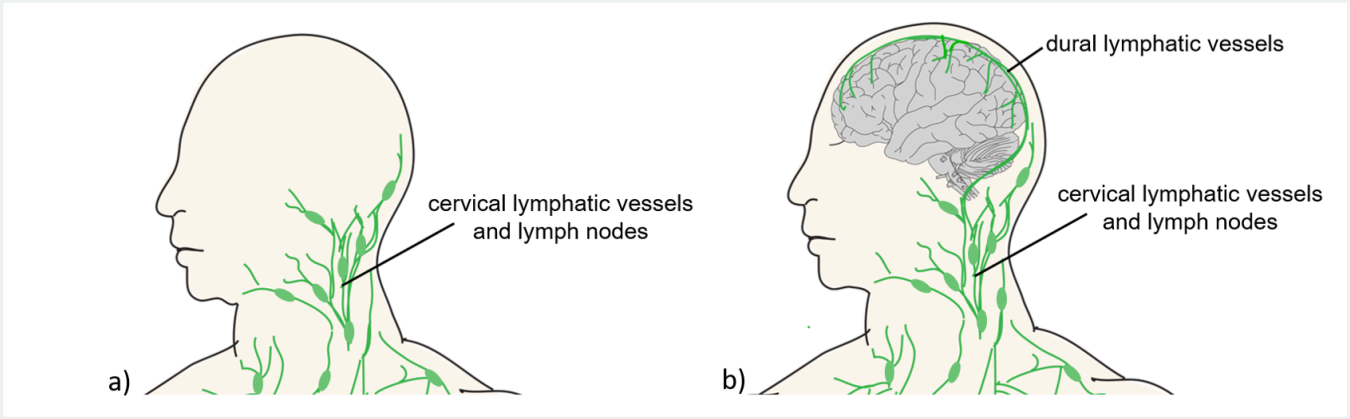

Figure 19.3.4: Dural Lymphatic Vessels. a) map of lymphatic vessels in the head and neck prior to 2015 showed only the cervical lymphatic vessels and lymph nodes. b) map of lymphatic vessels in the head and neck after the discovery of dural lymphatic vessels published in 2015 with the addition of the dural lymphatic vessels. (Image credit: “Dural Lymphatic Vessels" by Julie Jenks is a derivative of the original work by Daniel Donnelly and is licensed under CC BY 4.0)

The discovery of dural lymphatic vessels adds to the understanding of several mechanisms involved in draining cerebrospinal fluid (CSF) away from the subarachnoid space around the brain. Cerebrospinal fluid supplies nervous tissue with nutrients and also collects waste products from it, so CSF is constantly secreted into spaces within and surrounding the brain and spinal cord and it is also drained away at the same rate. It has long been understood that cerebrospinal fluid drains into the dural sinuses of the bloodstream. CSF fluid can also drain into dural lymphatic vessels. Yet another mechanism of draining

CSF away from the brain was described in 2012. The mechanism was dubbed the glymphatic system because while lymphatic vessels are not found deep to the dura mater around the brain, there is evidence that fluid flows along the surface of blood vessels in perivascular channels formed by astrocytes toward drainage sites (Figure 19.3.5).

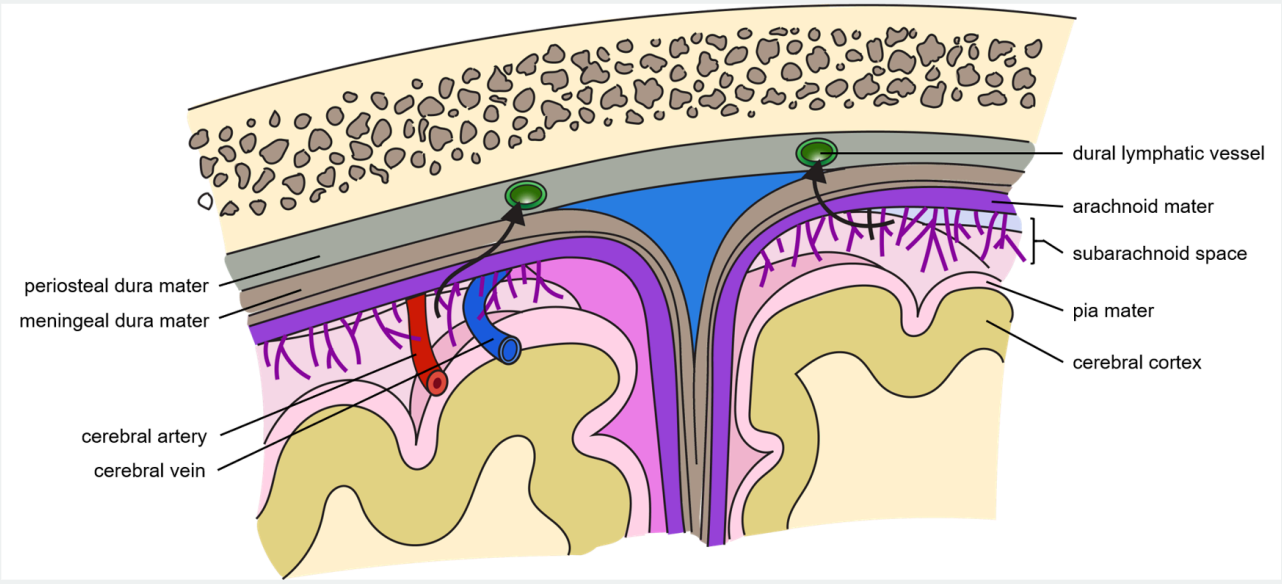

Figure 19.3.5: Glymphatics and Dural Lymphatic Vessels. The lymphatic system plays two key roles in the drainage of waste-containing cerebrospinal fluid from around the brain: glymphatic mechanisms (the perivascular countercurrent movement of fluid along the surface of veins and venules rather than within additional lymphatic vessels) and drainage directly into dural lymphatic vessels. (Image credit: "Glymphatics and Dural Lymphatic Vessels" by Julie Jenks is a derivative of the original work by Daniel Donnelly and is licensed under CC BY 4.0)

At the time the discovery of the glymphatic mechanism was published in 2012, it was thought that it worked to drain fluid away from the brain in the absence of nearby lymphatic vessels, but now a more dynamic picture illustrates multiple mechanisms for draining fluid away from the very metabolically active brain. The physiology of the glymphatic system mechanism of drainage is still not fully understood.

INTERACTIVE LINK

Watch this video on the role of sleep in the activity of the glymphatic system in draining fluid away from the brain. Keep in mind this video was published in 2014 prior to the discovery of the dural lymphatic vessels. What disease is associated with the accumulation of beta-amyloid proteins in the fluid around the brain caused by inadequate drainage of fluid?

Answer available at the end of this section.

Concept Review

The lymphatic vessels include a network of capillaries, vessels, trunks, and ducts that remove interstitial fluid from the tissues and return it the blood filtered of debris and pathogens by passage through lymph nodes. The lymphatics are also used to transport dietary lipids and distribute cells of the immune system.

Review Questions

Q. Which structure allows lymph from the lower right limb to enter the bloodstream?

A. thoracic duct

B. right lymphatic duct

C. right lymphatic trunk

D. left lymphatic trunk

Answer

Answer: A

Critical Thinking Questions

Q. Describe the flow of lymph from its origins in interstitial fluid somewhere in the left arm to its emptying into the venous bloodstream.

Answer

A. Fluid enters lymphatic capillaries when rising pressure caused by the build-up of interstitial fluid pushes open a flap where adjacent endothelial cells of a lymphatic capillary overlap. The interstitial fluid is then called lymph and it drains into larger lymphatic vessels. The lymph can only go in one direction due to one-way valves in the vessels, and it eventually drains into the left subclavian trunk. The left subclavian trunk merges with the thoracic duct that drains the lymph into the left subclavian vein near the internal jugular vein.

Glossary

bronchomediastinal trunks
pair of large lymphatics that collect lymph from smaller lymphatic vessels in the deep thorax

chyle
lipid-rich lymph inside the lymphatic capillaries of the small intestine

cisterna chyli
bag-like vessel that forms the beginning of the thoracic duct

intestinal trunk
large lymphatic that collects lymph from smaller lymphatic vessels in the abdomen

jugular trunks
pair of large lymphatics that collect lymph from smaller lymphatic vessels in the head and neck

lacteal
lymphatic capillary of the small intestine that collects milky lipid-rich chyle from the small intestine

lumbar trunks
pair of large lymphatics that collect lymph from smaller lymphatic vessels in the lower limbs and pelvis

lymph
watery fluid in a lymphatic vessel that contains leukocytes, plasma proteins, and lipids

lymph node
one of the bean-shaped organs found associated with the lymphatic vessels that function to filter lymph of debris and pathogens

lymphatic capillaries
smallest of the lymphatic vessels and the origin of lymph flow

lymphatic system
network of lymphatic vessels, lymph nodes, and ducts that carries lymph from the tissues and back to the bloodstream

lymphatic trunks
large lymphatics that collect lymph from smaller lymphatic vessels and empties into the blood via lymphatic ducts

lymphedema
swelling, typically in one extremity, caused by an accumulation of interstitial fluid in tissues upstream of damaged or blocked lymphatic vessels

lymphocytes
white blood cells characterized by a large nucleus and small rim of cytoplasm

right lymphatic duct
drains lymph fluid from the upper right side of body into the right subclavian vein

subclavian trunks
pair of large lymphatics that collect lymph from the upper limb and superficial thorax

thoracic duct
large duct that drains lymph from the lower limbs, left thorax, left upper limb, and the left side of the head

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Answers

INTERACTIVE LINK

Inadequate drainage of fluid has been implicated in the accumulation of beta-amyloid proteins that can lead to the development of Alzheimer's disease.

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19.4: Anatomy of Lymphatic Organs and Tissues

By the end of this section, you will be able to:

- Describe the structure and function of the primary and secondary lymphatic organs
- Describe the structure, function, and location of lymphoid tissues

Lymphoid organs are distinct structures consisting of multiple tissue types. The category can be further subdivided into primary lymphoid organs, which support lymphocyte production and development, and secondary lymphoid organs, which support lymphocyte storage and function. Lymphoid tissues are concentrations of lymphocytes and other immune cells within other organs of the body.

Primary Lymphoid Organs and Lymphocyte Development

The differentiation and development of B and T cells is critical to the adaptive immune response. When the body is exposed to a new pathogen, lymphocytes of the adaptive immune response must "learn" the new antigen associated with the pathogen, mount an effective response to eradicate the pathogen, and "remember" the antigen in case the body is exposed again in the future by forming memory cells. It is also through this process that the body (ideally) learns to destroy only pathogens and leaves the body's own cells relatively intact. The **primary lymphoid organs** are the bone marrow and thymus gland. The lymphoid organs are where lymphocytes proliferate and mature.

Bone Marrow

Yellow bone marrow consists of adipose tissue, consisting largely of fat cells for energy storage (Figure 19.4.1) and is primarily located in the medullary cavity of adult long bones. **Red bone marrow** is a loose collection of cells where hematopoiesis (blood cell formation) occurs surrounding a framework of reticular connective tissue. Red bone marrow is primarily located surrounding the trabeculae of spongy bone.

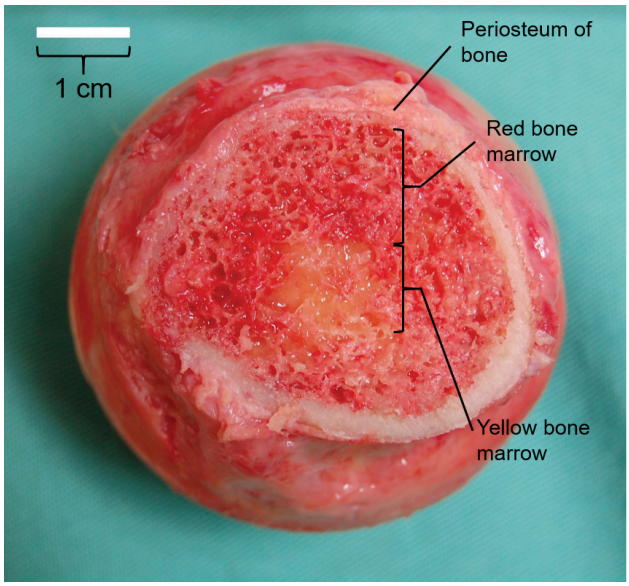

Figure 19.4.1: Bone Marrow. A layer of spongy bone over 1 cm thick with red bone marrow filling the spaces around its trabeculae forms the majority of the head of the femur, covered in periosteum and surrounding a spot of yellow bone marrow at the center slightly less than 1 cm in diameter. (Image credit: "Bone Marrow" by Julie Jenks is licensed under CC BY 4.0 / A derivative from the original work)

Hematopoiesis is summarized in Figure 19.4.2 and was covered in more detail in the blood chapter. In the embryo, blood cells are made in the yolk sac. As development proceeds, this function is taken over by the spleen, lymph nodes, and liver. Later, the

red bone marrow takes over most hematopoietic functions, although the final stages of the differentiation of some cells may take place in other organs. The B cell undergoes nearly all of its development in the red bone marrow, whereas the immature T cell, called a **thymocyte**, leaves the bone marrow and matures largely in the thymus gland.

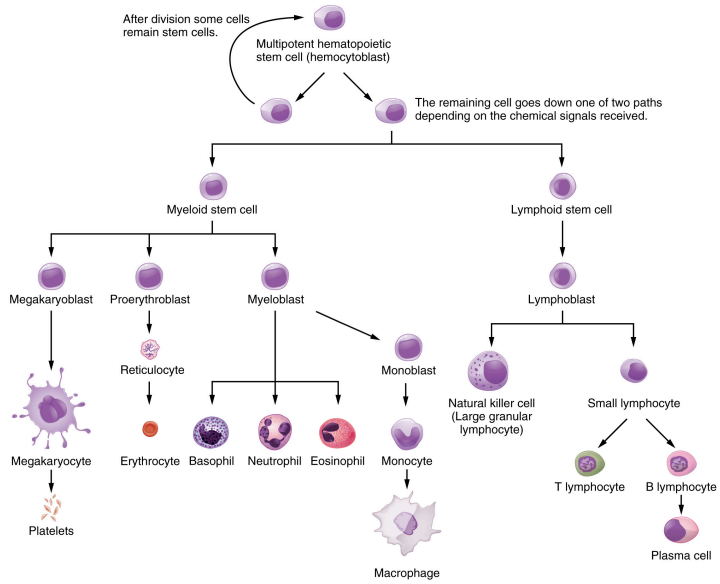

Figure 19.4.2: Hematopoietic System of Bone Marrow. Hematopoiesis is the proliferation and differentiation of the formed elements of blood. (Image credit: "Hematopoietic System of the Bone Marrow" by Julie Jenks is licensed under CC BY 4.0 / A derivative from the original work)

Thymus

The **thymus** gland is a bilobed organ found in the space between the sternum and the aorta of the heart (Figure 19.4.3) that serves as a specialized structure in which T lymphocytes mature. The thymus is most active early in life as you are exposed to and build immunity to many pathogens. After puberty, the thymus slowly but continuously decreases in activity and size as its tissue is replaced with a mix of fibrous and adipose connective tissues.

In the thymus, the maturation of T lymphocytes begins with thymocytes. Thymocytes travel through the bloodstream from the red bone marrow to the thymus. Thymocytes are precursors to T lymphocytes that lack the surface proteins mature T lymphocytes use to recognize an antigen and coordinate an adaptive immune response. There is a multi-step physiological process by which T lymphocytes mature into naïve T lymphocytes ready to be activated for an adaptive immune response.

Dense irregular connective tissue holds the lobes of the thymus closely together but also separates them and forms a fibrous capsule. The fibrous capsule further divides the thymus into lobules via extensions called trabeculae. Blood vessels and nerves are routed within the trabeculae. The outer region of each lobule is known as the cortex and here the structure of the thymus forms a **blood-thymus barrier** to prevent the thymocytes from being exposed to antigens from the bloodstream before they mature. The densely packed thymocytes in the cortex stain more intensely than the rest of the thymus (see Figure 19.4.3). The medulla contains a less dense collection of thymocytes, epithelial cells, macrophages, and dendritic cells, so it appears more lightly stained in the micrograph. Thymocytes move from the cortex to the medulla as they mature where the lack of the blood-thymus barrier allows them to enter the bloodstream and travel to other lymphatic structures to await activation for an adaptive immune response.

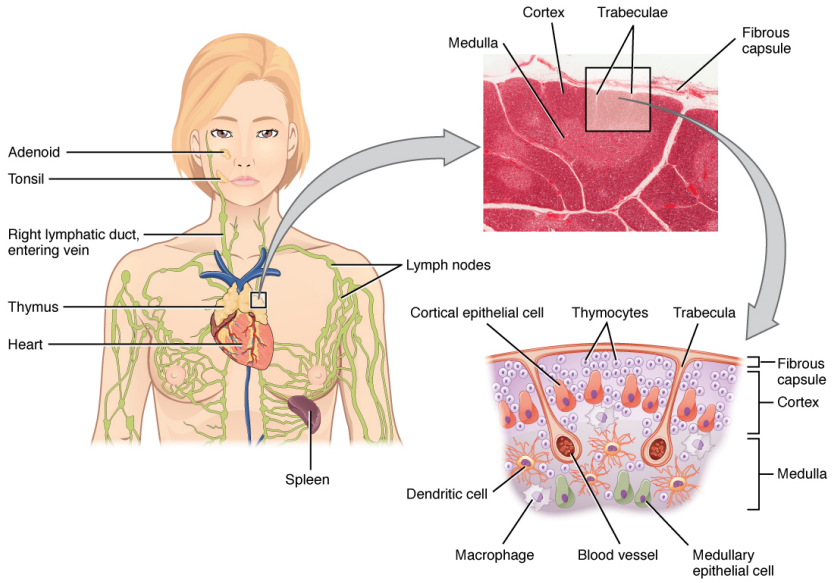

Figure 19.4.3: Location, Structure, and Histology of the Thymus. The thymus lies above the heart. The trabeculae and lobules, including the darkly staining cortex and the lighter staining medulla of each lobule, are clearly visible in the light micrograph of the thymus of a newborn. LM × 100. (Image credit: "The Location Structure and Histology of the Thymus" by OpenStax is licensed under CC BY 3.0 / Micrograph provided by the Regents of the University of Michigan Medical School © 2012)

AGING AND THE...

Immune System

By the year 2050, 25 percent of the population of the United States will be 60 years of age or older. The CDC estimates that 80 percent of those 60 years and older have one or more chronic diseases associated with deficiencies of the immune systems. This loss of immune function with age is called immunosenescence. To treat this growing population, medical professionals must better understand the aging process. One major cause of age-related immune deficiencies is thymic involution, the shrinking of the thymus gland that begins after puberty, at a rate of about three percent tissue loss per year, and continues until 35–45 years of age, when the rate declines to about one percent loss per year for the rest of one's life. At that pace, the total loss of thymic epithelial tissue and thymocytes would occur at about 120 years of age. Thus, this age is a theoretical limit to a healthy human lifespan.

Thymic involution has been observed in all vertebrate species that have a thymus gland. Animal studies have shown that transplanted thymic grafts between inbred strains of mice involuted according to the age of the donor and not of the recipient, implying the process is genetically programmed. There is evidence that the thymic microenvironment, so vital to the development of naïve T cells, loses thymic epithelial cells according to the decreasing expression of the FOXN1 gene with age.

It is also known that thymic involution can be altered by hormone levels. Sex hormones such as estrogen and testosterone enhance involution, and the hormonal changes in pregnant women cause a temporary thymic involution that reverses itself, when the size of the thymus and its hormone levels return to normal, usually after lactation ceases. What does all this tell us? Can we reverse immunosenescence, or at least slow it down? The potential is there for using thymic transplants from younger donors to keep thymic output of naïve T cells high. Gene therapies that target gene expression are also seen as future possibilities. The more we learn through immunosenescence research, the more opportunities there will be to develop therapies, even though these therapies will likely take decades to develop. The ultimate goal is for everyone to live and be healthy longer, but there may be limits to immortality imposed by our genes and hormones.

DISORDERS OF THE...

Immune System: Autoimmune Responses

The worst cases of the immune system over-reacting are autoimmune diseases. Somehow, tolerance breaks down and the immune systems in individuals with these diseases begin to attack their own bodies, causing significant damage. The trigger for these diseases is, more often than not, unknown and the treatments are usually based on resolving or minimizing the symptoms using immunosuppressive and anti-inflammatory drugs such as steroids. These diseases can be localized and crippling, as in rheumatoid arthritis, or diffuse in the body with multiple symptoms that differ in different individuals, as is the case with systemic lupus erythematosus (Figure 19.4.4).

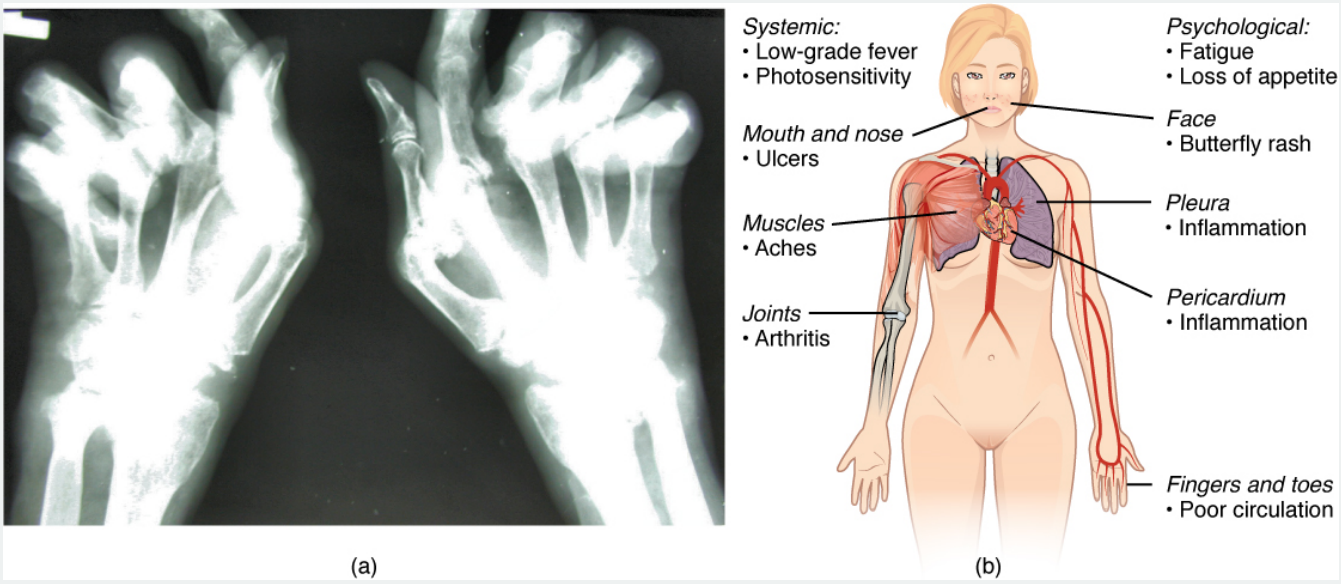

Figure 19.4.4: Autoimmune Disorders: Rheumatoid Arthritis and Lupus. (a) Extensive damage to the right hand of a rheumatoid arthritis sufferer introduces deformity in the fingers as shown in the x-ray. (b) A variety of possible symptoms of systemic lupus erythematosus include low-grade fever and photosensitivity, fatigue and loss of appetite, ulcers in the mouth and nose, a butterfly rash on the face, achy muscles, arthritis of the joints, inflammation in the pleura and pericardium, and poor circulation in the fingers and toes. (Image credit: "Autoimmune Disorders Rheumatoid Arthritis and Lupus" by OpenStax is licensed under CC BY 3.0)

Environmental triggers seem to play large roles in autoimmune responses. One explanation for the breakdown of tolerance is that, after certain bacterial infections, an immune response to a component of the bacterium cross-reacts with a self-antigen. This mechanism is seen in rheumatic fever, a result of infection with *Streptococcus* bacteria, which causes strep throat. The antibodies to this pathogen's M protein cross-react with an antigenic component of heart myosin, a major contractile protein of the heart that is critical to its normal function. The antibody binds to these molecules and activates complement proteins, causing damage to the heart, especially to the heart valves. On the other hand, some theories propose that having multiple common infectious diseases actually prevents autoimmune responses. The fact that autoimmune diseases are rare in countries that have a high incidence of infectious diseases supports this idea.

There are genetic factors in autoimmune diseases as well. Overall, there are more than 80 different autoimmune diseases, which are a significant health problem in the elderly. Table 19.4.1 lists several of the most common autoimmune diseases, along with the antigens that are targeted and symptoms of the disease.

Table 19.4.1: Autoimmune Diseases

Disease	Autoantigen	Symptoms
Celiac disease	Tissue transglutaminase	Damage to small intestine
Diabetes mellitus type I	Beta cells of pancreas	Low insulin production; inability to regulate serum glucose
Graves' disease	Thyroid-stimulating hormone receptor (antibody blocks receptor)	Hyperthyroidism
Hashimoto's thyroiditis	Thyroid-stimulating hormone receptor (antibody mimics hormone and stimulates receptor)	Hypothyroidism

Disease	Autoantigen	Symptoms
Lupus erythematosus	Nuclear DNA and proteins	Damage to many body systems
Myasthenia gravis	Acetylcholine receptor in neuromuscular junctions	Debilitating muscle weakness
Rheumatoid arthritis	Joint capsule antigens	Chronic inflammation of joints

Secondary Lymphoid Organs and their Roles in Immune Responses

Lymphocytes develop and mature in the primary lymphoid organs, but they mount immune responses from the **secondary lymphoid organs**. A **naïve lymphocyte** is one that has left the primary organ and entered a secondary lymphoid organ. Naïve lymphocytes are fully functional immunologically, sometimes referred to as immunocompetency, but have yet to encounter an antigen to which to respond. In addition to circulating in the blood and lymph, lymphocytes concentrate in secondary lymphoid organs, which include the lymph nodes, spleen, and lymphoid tissues associated with several organs in the body. All of these tissues have many features in common, including the following:

- An internal structure of reticular connective tissue with associated fixed macrophages
- The presence of **lymphoid follicles**, collections of lymphocytes, with specific B cell-rich and T cell-rich areas
- **Germinal centers**, which are the sites of activated (rapidly dividing) B lymphocytes and plasma cells, with the exception of the spleen
- Specialized post-capillary vessels known as **high endothelial venules**; the cells lining these venules are thicker and more columnar than normal endothelial cells, which allow cells from the blood to directly enter these tissues

Lymph Nodes

As described in the previous section, lymph nodes are positioned at regular intervals along the length of lymphatic vessels. Lymph nodes function to remove debris and pathogens from the lymph, and are thus sometimes referred to as the “filters of the lymph” (Figure 19.4.5). Any bacteria that infect the interstitial fluid are taken up by the lymphatic capillaries and transported to a regional lymph node. Dendritic cells and macrophages within this organ internalize and kill many of the pathogens and debris that pass through, thereby removing them from the body. The lymph node is the most common site of activation of adaptive immune responses mediated by T cells, B cells, and accessory cells of the adaptive immune system. This is why swollen lymph nodes can be a sign of infection.

Like the thymus, the bean-shaped lymph nodes are surrounded by a tough capsule of dense connective tissue and are separated into compartments by trabeculae, extensions of the capsule. In addition to the structure provided by the capsule and trabeculae, the structural support of the lymph node is provided by a series of reticular fibers laid down by fibroblasts of its reticular connective tissue framework. Several afferent lymphatic vessels deliver lymph into the convex side of a lymph node and a one-way valve in each vessel near where it connects with the lymph node prevents back-flow of lymph. One or two efferent lymphatic vessels allow lymph to flow out of the concave hilum of the lymph node. The tissue inside the lymph node consists of two generalized regions: the cortex and the medulla. The cortex is nearest the convex side of the node and contains lymphoid follicles where activated lymphocytes proliferate. The medulla, nearest the hilum of each node, is rich with lymphocytes (T cells, B cells, and plasma cells), as well as macrophages and dendritic cells.

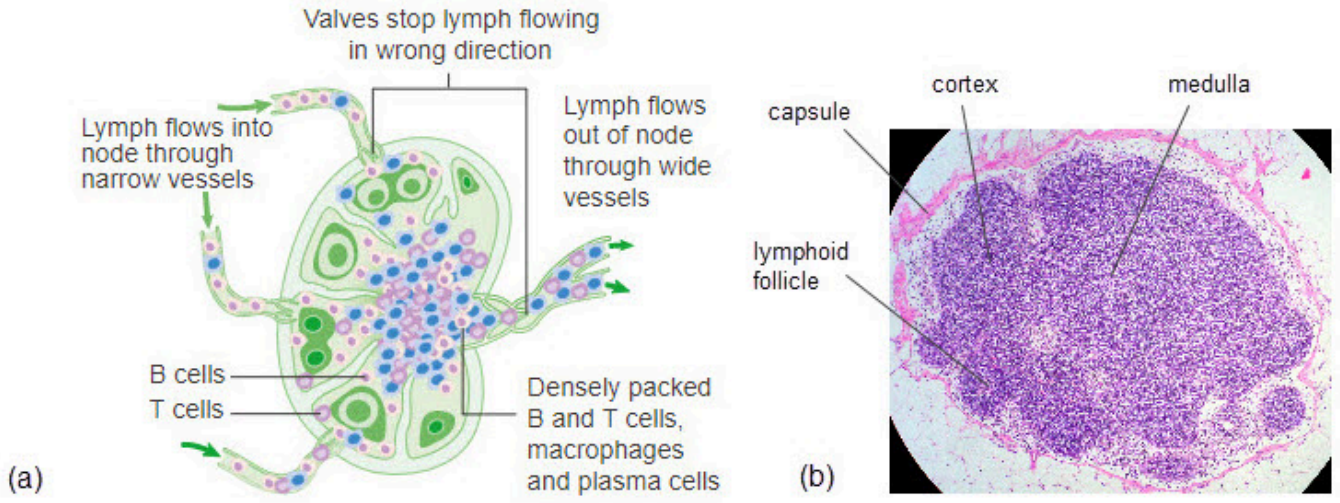

Figure 19.4.5: Lymph Node. (a) Lymph flows into a lymph node via afferent vessels through the open cusps of one-way valves that prevent lymph from flowing in the wrong direction. Within the lymph node, lymph flows past densely packed immune cells that remove debris and pathogens (including B and T cells, macrophages, and plasma cells), and then out of the node through more back-flow preventing one-way valves into efferent vessels. (b) Histological view of lymph node cross-section showing capsule surrounding several visible lymphoid follicles in the cortex surrounding the medulla that is densely packed with dark-staining cells. (Image credit: "Lymph Node" by Julie Jenks is licensed under CC BY 4.0 / a derivative from the original work in (a) and the original work in (b))

Spleen

The spleen is located inferior and medial to the curve of the diaphragm and lateral to the stomach in the upper left quadrant of the abdomen. It is built on a framework of reticular connective tissue and surrounded by a capsule of dense irregular connective tissue that invaginates into trabeculae to divide the spleen into nodules (Figure 19.4.6). Upon entering the spleen, the splenic artery splits into several arterioles and eventually into sinusoid capillaries. Blood from the capillaries subsequently collects in venules that drain into the splenic vein.

Within each splenic nodule is a large area of **red pulp** surrounding the sinusoid capillaries that is so-called because it consists mainly of erythrocytes. The red pulp consists of reticular fibers with fixed macrophages attached, free macrophages, and other formed elements of the blood, including some lymphocytes. The red pulp primarily functions in phagocytosis of worn-out erythrocytes and bloodbourne pathogens. Aside from the blood vessels, the remaining tissue of each nodule is called the **white pulp**, so-called because it lacks the erythrocytes found in the red pulp. The white pulp surrounds the arteriole and resembles the lymphoid follicles of the lymph nodes. It consists of germinal centers of dividing B cells surrounded by T cells and accessory cells, including macrophages and dendritic cells. Germinal centers function as a site of T cell and B cell activation. The marginal zone is the region where the white pulp transitions to the red pulp and their functions mix.

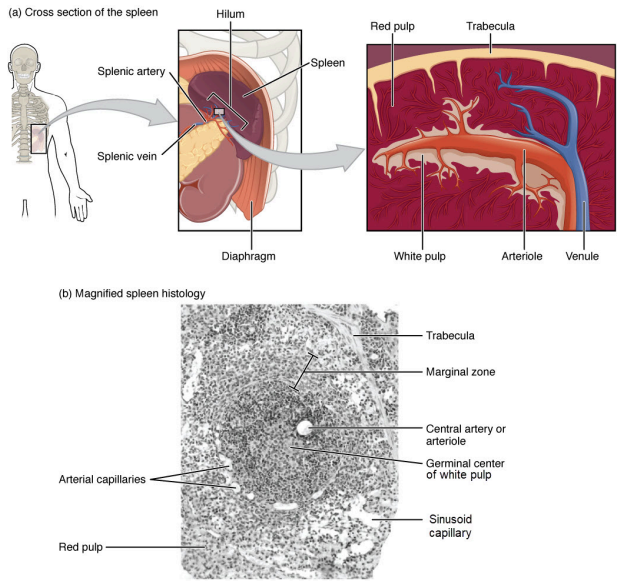

Figure 19.4.6: Location, Structure, and Histology of the Spleen. (a) The spleen is lateral to the stomach and pancreas. A cross-section reveals trabeculae that divide the spleen into nodules consisting of an arteriole surrounded by white pulp and feeding sinusoid capillaries surrounded by red pulp that drain to a venule (b) A micrograph of spleen tissue shows the red pulp and white pulp separated by a marginal zone. The white pulp contains germinal centers and is centrally located in the nodule surrounding the arteriole and arterial capillaries. EM × 660. (Image credit: "Spleen" by Julie Jenks is licensed under CC BY 4.0 / A derivative from the original work / Micrograph provided by the Regents of the University of Michigan Medical School © 2012)

Lymphoid Nodules

The other lymphoid tissues, **lymphoid nodules**, have a simpler architecture than the spleen and lymph nodes in that they consist of a dense cluster of lymphocytes on a framework of reticular connective tissue without a surrounding fibrous capsule. These nodules are associated with the mucus membranes of the respiratory and digestive tracts, areas routinely exposed to environmental pathogens.

Tonsils are lymphoid nodules located along the inner surface of the pharynx and are important in developing immunity to oral pathogens (Figure 19.4.7).

- The **pharyngeal tonsil**, sometimes referred to as the adenoid, is located in the superoposterior of the nasopharynx
- The **palatine tonsils** are in the lateral wall of the oropharynx
- The **lingual tonsil** faces the oropharynx in the wall at the posterior of the tongue

Swelling of the tonsils is an indication of an active immune response to infection. Histologically, tonsils do not contain a complete capsule, and the epithelial layer invaginates deeply into the interior of the tonsil to form tonsillar crypts. The crypts allow all sorts of materials taken into the body through eating and breathing to accumulate in the tonsils, actually “encouraging” pathogens to penetrate deep into the tonsillar tissues where T cells and B cells in the germinal centers can be activated for an adaptive immune response. This seems to be the major function of tonsils—to help children’s bodies recognize, destroy, and develop immunity to common environmental pathogens so that they will be protected in their later lives. Tonsils are often removed in those children who have recurring throat infections, especially those involving the palatine tonsils on either side of the throat, whose swelling may interfere with their breathing and/or swallowing.

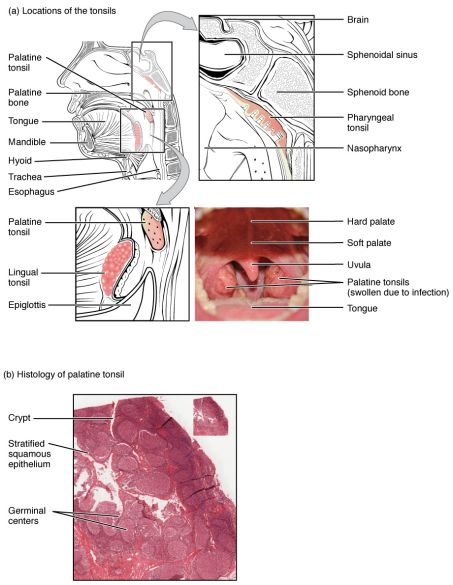

Figure 19.4.7: Locations and Histology of the Tonsils. (a) The pharyngeal tonsil is located in the superoposterior wall of the nasopharynx, the palatine tonsils are located in the lateral wall of the oropharynx, and the lingual tonsil is located in the anterior wall of the oropharynx at the posterior of the tongue. (b) A micrograph shows the crypts lined with stratified squamous epithelium superficial to the germinal centers of the palatine tonsil. LM × 40. (Image credit: "Location and Histology of Tonsils" by OpenStax is licensed under CC BY 3.0 / Micrograph provided by the Regents of the University of Michigan Medical School © 2012)

Mucosa-associated lymphoid tissue (MALT) consists of an aggregate of lymphoid follicles directly associated with the mucous membrane epithelia. MALT makes up dome-shaped structures found underlying the mucosa of the gastrointestinal tract, breast tissue, lungs, and eyes. Peyer's patches, a type of MALT in the small intestine, are especially important for immune responses against ingested substances (Figure 19.4.8). Peyer's patches contain specialized endothelial cells called M (or microfold) cells that sample material from the intestinal lumen and transport it to nearby follicles so that adaptive immune responses to potential pathogens can be mounted.

Figure 19.4.8: Mucosa-Associated Lymphoid Tissue (MALT) Nodule. The mucosa-associated lymphoid nodules in the small intestine are called Peyer's patches. LM × 40. (Image credit: "Mucosa Associated Lymphoid Tissue (MALT) Nodule" by OpenStax is licensed under CC BY 3.0 / Micrograph provided by the Regents of the University of Michigan Medical School © 2012)

Concept Review

Lymphoid organs are comprised of multiple tissues forming a distinct structure in the body. Primary lymphoid organs include

bone marrow and the thymus. Lymphocytes and other blood cells are produced in red bone marrow while lipids are stored for long-term energy in yellow bone marrow. B lymphocytes remain in red bone marrow to develop into naïve B lymphocytes. The thymus is the organ in which immature T lymphocytes are stored and develop into naïve T lymphocytes. Naïve T and B lymphocytes travel to secondary lymphoid organs, lymph nodes and the spleen, from where they can be activated for the adaptive immune response. Lymph nodes filter lymph for invaders, abnormal cells, and debris as it drains to the bloodstream through lymphatic vessels. The spleen, in the white pulp, filters the blood for invaders, abnormal cells, and debris as it circulates through the bloodstream. The red pulp of the spleen also filters the blood and serves to remove worn-out red blood cells from circulation. Concentrations of lymphocytes and other immune cells within mucus membranes of other organ systems are called lymphoid tissues or nodules. The tonsils surround the pharynx while mucosa-associated lymphoid tissue (MALT) are found in mucus membranes of the gastrointestinal tract, breast tissue, lungs, and eyes.

Review Questions

Q. Which of the lymphoid nodules is most likely to see food-bourne antigens first?

A. tonsils

B. Peyer's patches

C. bronchus-associated lymphoid tissue

D. mucosa-associated lymphoid tissue

Answer

Answer: A

Critical Thinking Questions

Q. Compare and contrast functions of the lymph nodes and the spleen.

Answer

A. Both lymph nodes and the spleen filter transport fluids in the body for pathogens, abnormal cells, and debris. Lymph nodes are positioned at intervals along lymphatic vessels to filter lymph as it travels through the lymphatic vessels. The spleen filters blood as it travels through the blood stream. Both lymph nodes and the spleen are secondary lymphoid organs meaning they contain concentrations of naïve lymphocytes and other immune cells from which an adaptive immune response can be mounted.

Glossary

afferent lymphatic vessels
lead into a lymph node

bone marrow
tissue found inside bones; the site of all blood cell differentiation and maturation of B lymphocytes

efferent lymphatic vessels
lead out of a lymph node

germinal centers
clusters of rapidly proliferating B cells found in secondary lymphoid tissues

high endothelial venules
vessels containing unique endothelial cells specialized to allow migration of lymphocytes from the blood to the lymph node

lingual tonsil
lymphoid nodule in the anterior wall of the oropharynx posterior to the tongue

lymph node
one of the bean-shaped organs found associated with the lymphatic vessels

lymphoid nodules
unencapsulated patches of lymphoid tissue found throughout the body

mucosa-associated lymphoid tissue (MALT)
lymphoid nodule associated with the mucosa

palatine tonsils
lymphoid nodules in the right and left lateral walls of the oropharynx

pharyngeal tonsil (adenoid)
lymphoid nodule in the superoposterior wall of the nasopharynx

primary lymphoid organ
site where lymphocytes mature and proliferate; red bone marrow and thymus gland

red pulp
region of a spleen nodule that is so-called because it is filled with many erythrocytes that surrounds the sinusoid capillaries and functions primarily to remove worn-out erythrocytes from circulation

secondary lymphoid organs
sites where lymphocytes mount adaptive immune responses; examples include lymph nodes and spleen

spleen
secondary lymphoid organ that filters pathogens from the blood (white pulp) and removes degenerating or damaged blood cells (red pulp)

thymocyte
immature T cell found in the thymus

thymus
primary lymphoid organ; where T lymphocytes proliferate and mature

tonsils
lymphoid nodules associated with the pharynx

white pulp
region of a spleen nodule that is filled with germinal centers surrounding the arteriole that functions to activate B cells and T cells

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20: RESPIRATORY SYSTEM

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20.1: Introduction to the Respiratory System

20.2: Organs and Structures of the Respiratory System

20.3: The Lungs

20.4: The Processes of the Respiratory System

20.5: Embryonic Development of the Respiratory System

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20.1: Introduction to the Respiratory System

Chapter Learning Objectives:

After studying this chapter, you will be able to:

- List the structures of the respiratory system
- List the major functions of the respiratory system
- Outline the forces that allow for air movement into and out of the lungs
- Describe the development of the respiratory system in the embryo

Hold your breath. Really! See how long you can hold your breath as you continue reading...How long can you do it? Chances are you are feeling uncomfortable already. A typical human cannot survive without breathing for more than 3 minutes, and even if you wanted to hold your breath longer, your autonomic nervous system would take control. This is because every cell in the body needs to run the oxidative stages of cellular respiration, the process by which energy is produced in the form of adenosine triphosphate (ATP). For oxidative phosphorylation to occur, oxygen is used as a reactant and carbon dioxide is released as a waste product.

Figure 20.1.1: Mountain Climbers. The thin air at high elevations can strain the human respiratory system. (Image credit: "Aiguille du Midi, Mont-Blanc" by Cristian Bortes is licensed under CC BY 2.0)

You may be surprised to learn that although oxygen is a critical need for cells, it is actually the accumulation of carbon dioxide that primarily drives your need to breathe. Carbon dioxide is exhaled and oxygen is inhaled through the respiratory system, which includes muscles to move air into and out of the lungs, passageways through which air moves, and microscopic gas exchange surfaces covered by capillaries. The circulatory system transports gases from the lungs to tissues throughout the body and vice versa. A variety of diseases can affect the respiratory system, such as asthma, emphysema, chronic obstruction pulmonary disorder (COPD), and lung cancer. All of these conditions affect the gas exchange process and result in labored breathing and other difficulties.

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20.2: Organs and Structures of the Respiratory System

By the end of this section, you will be able to:

- List the structures that make up the respiratory system
- Compare and contrast the histology and functions of the conducting zone and the respiratory zone

The major organs of the respiratory system function primarily to provide oxygen to body tissues for cellular respiration, remove the waste product carbon dioxide, and help to maintain acid-base balance. Portions of the respiratory system are also used for non-vital functions, such as sensing odors, speech production, and for straining, such as during childbirth or coughing (Figure 20.2.1).

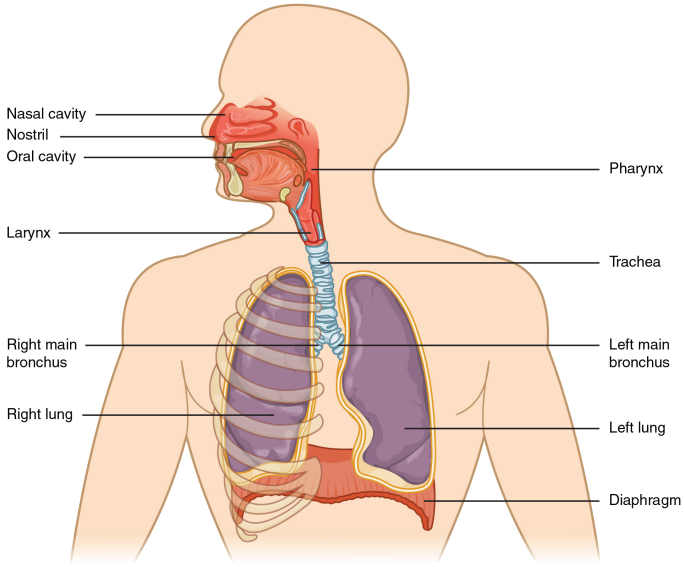

Figure 20.2.1: Major Respiratory Structures. The major respiratory structures span the nasal cavity to the diaphragm. (Image credit: "Major Respiratory Organs" by OpenStax is licensed under CC BY 3.0)

Functionally, the respiratory system can be divided into a conducting zone and a respiratory zone. The **conducting zone** of the respiratory system includes the organs and structures not directly involved in gas exchange. Gas exchange occurs in the **respiratory zone**. The conducting zone delivers air to and from the respiratory zone.

Conducting Zone

The major functions of the conducting zone are to provide a route for incoming and outgoing air, remove debris and pathogens from the incoming air, and warm and humidify the incoming air. Several structures within the conducting zone perform other functions as well. The epithelium of the nasal passages, for example, is essential to sensing odors, and the bronchial epithelium that lines the lungs can metabolize some airborne carcinogens.

The Nose and its Adjacent Structures

The primary entrance and exit for the respiratory system is through the nose. When discussing the nose, it is helpful to divide it into two major sections: the external nose, and the nasal cavity or internal nose.

The **external nose** consists of the surface and skeletal structures that result in the outward appearance of the nose and contribute to its numerous functions (Figure 20.2.2). The **root** is the region of the nose located between the eyebrows. The **bridge** is the part of the nose that connects the root to the rest of the nose. The **dorsum nasi** is the ridge that runs the length of the nose. The **apex**

is the tip of the nose. The **philtrum** is the concave surface that connects the apex of the nose to the upper lip.

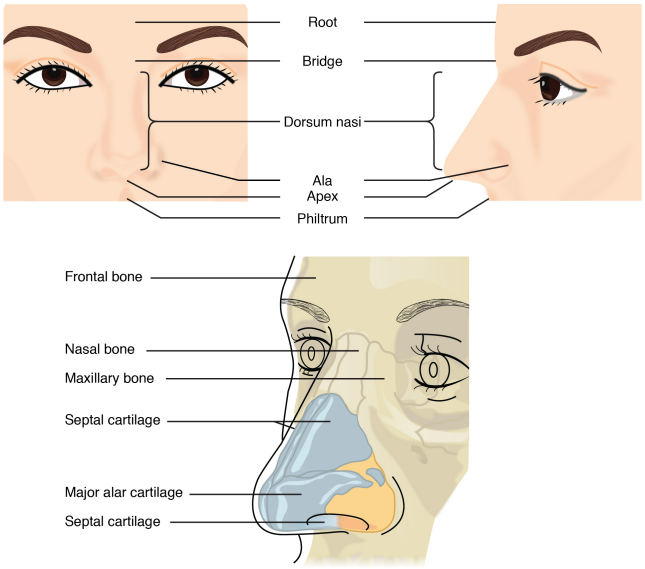

Figure 20.2.2: Nose. The features of the external nose (top) and skeletal and cartilaginous features of the nose (bottom) are illustrated. (Image credit: "External Nose" by OpenStax is licensed under CC BY 3.0)

Underneath the thin skin of the nose are its skeletal features (see Figure 20.2.2). While the root and bridge of the nose consist of bone, most of the protruding portion of the nose is composed of cartilage. As a result, when looking at a skull much of the nose is missing. The **nasal bone** is one of a pair of bones that lies under the bridge of the nose. The nasal bone articulates superiorly with the frontal bone and laterally with the maxillary bones.

On either side of the apex, the **alar cartilages**, composed of hyaline cartilage, form the medial portion of the **external nares**, the narrow openings into each nasal cavity. The **alae** (singular = ala) form the lateral portion of the external nares and lack cartilage. The external nares open into the nasal cavity, which is separated into left and right sections by the nasal septum. The **nasal septum** is formed anteriorly by a portion of the **septal cartilage**, the flexible hyaline cartilage you can move with your fingers that forms the majority of the dorsum nasi, and posteriorly by the perpendicular plate of the ethmoid bone superiorly (a cranial bone located just posterior to the nasal bones) and the thin vomer bone inferiorly (whose name refers to its plough shape).

Each lateral wall of the nasal cavity has three bony projections, called the superior, middle, and inferior nasal conchae (Figure 20.2.3). The inferior nasal conchae are separate bones, whereas the superior and middle nasal conchae are portions of the ethmoid bone. Several bones that help form the walls of the nasal cavity have hollowed air-containing spaces called the paranasal sinuses. The increased surface area of both the nasal cavities and the sinuses contribute to the richness of the tone of sounds produced, as evidenced by the change in your voice when you plug your nose or are congested. Each **paranasal sinus** is named for its associated bone: frontal sinus, maxillary sinus, sphenoidal sinus, and ethmoidal sinuses. The hollowed sinuses also lighten the weight of the skull.

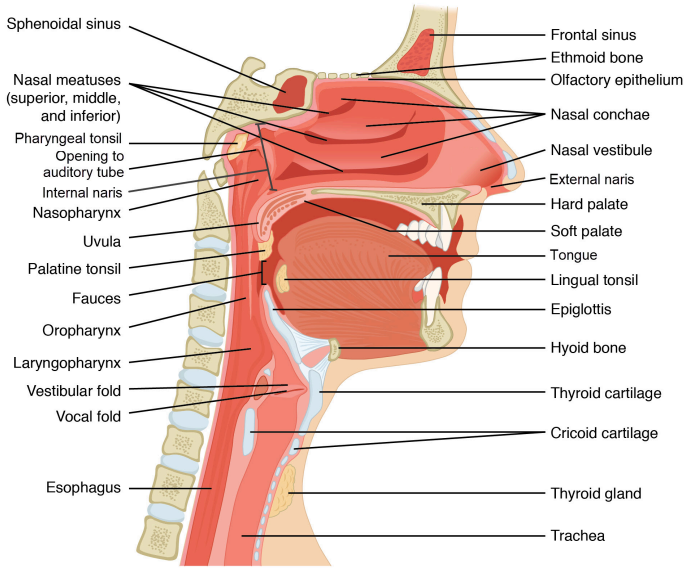

Figure 20.2.3: Upper Airway. A sagittal section of the upper airway and surrounding structures is illustrated. Air passes through the external naris and nasal vestibule as it enters the nasal cavity, which has raised nasal conchae and depressed meatuses that increase its surface area. The nasal cavity narrows at the internal naris that meets the nasopharynx. The frontal and sphenoidal sinus are shown as hollowed out spaces within the frontal and sphenoid bones, respectively. Air then passes by the tonsils as it moves through the nasopharynx above the uvula, the oropharynx posterior to the oral cavity, and the laryngopharynx before entering the larynx superior to the trachea. (Image credit: "Upper Airway" by Julie Jenks is licensed under CC BY 4.0/A derivative from the original work)

The external nares and nasal vestibule at the anterior portion of each nasal cavity are composed of skin: lined with stratified squamous epithelium and contain sebaceous glands and hair follicles embedded in the dermis that serve to prevent the passage of large debris, such as dirt, through the nasal cavity.

The conchae, meatuses, and paranasal sinuses are lined by a mucous membrane or mucosa called the **respiratory epithelium** composed of ciliated pseudostratified columnar epithelium (Figure 20.2.4 shows the same epithelium lining in the trachea). Mucous spelled with an "o" is the adjective form of the word, while mucus spelled without an "o" is the noun form used to describe the secretion produced by mucous membranes. The respiratory epithelium contains goblet cells, one of the specialized, columnar epithelial cells that produce mucus to trap debris. The cilia of the respiratory epithelium help remove the mucus and debris from the nasal cavity with a constant beating motion, sweeping materials towards the throat to be swallowed. Interestingly, cold air slows the movement of the cilia, resulting in accumulation of mucus that may in turn lead to a runny nose during cold weather. The tissue-covered nasal conchae and meatuses within the nasal cavities create turbulent airflow and provide an increased surface area to aid in filtering, warming, and humidifying air as it enters the body. Capillaries located just beneath the nasal epithelium warm the air by convection. Serous and mucus-producing cells also secrete the lysozyme enzyme and proteins called defensins, which have antibacterial properties. Immune cells that patrol the connective tissue deep to the respiratory epithelium provide additional protection.

A specialized olfactory epithelium used to detect odors (olfaction is the sense of smell) is found at the superior surface of the nasal cavity in the area of the olfactory foramina of the ethmoid bone and is covered in more detail in the chapter that includes the special senses of the nervous system.

The floor of the nasal cavity is composed of the palate. The hard palate at the anterior region of the nasal cavity is composed of mucosa covering bone, while the soft palate at the posterior portion of the nasal cavity consists of mucosa covering muscle tissue. Inhaled air moves deeper into the upper airway when it leaves the nasal cavities via the **internal nares**, also known as posterior nasal apertures, narrowings at the back of each nasal cavity, and moves into the pharynx.

Figure 20.2.4: Ciliated Pseudostratified Columnar Epithelium. The respiratory epithelium consists of a ciliated pseudostratified columnar epithelium featuring cilia at the apical surface facing the lumen of the airway and goblet cells that secrete mucus. Seromucous glands embedded in the dense irregular connective tissue of the submucosa provide additional lubricating mucus. LM × 680. (Image credit: "Pseudostratified Epithelium" by OpenStax is licensed under CC BY 3.0 / Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Pharynx

The **pharynx** is a tube formed by skeletal muscle and lined by mucous membrane that is continuous with that of the nasal cavities (see Figure 20.2.3). The pharynx is divided into three major regions: the nasopharynx, the oropharynx, and the laryngopharynx (Figure 20.2.5).

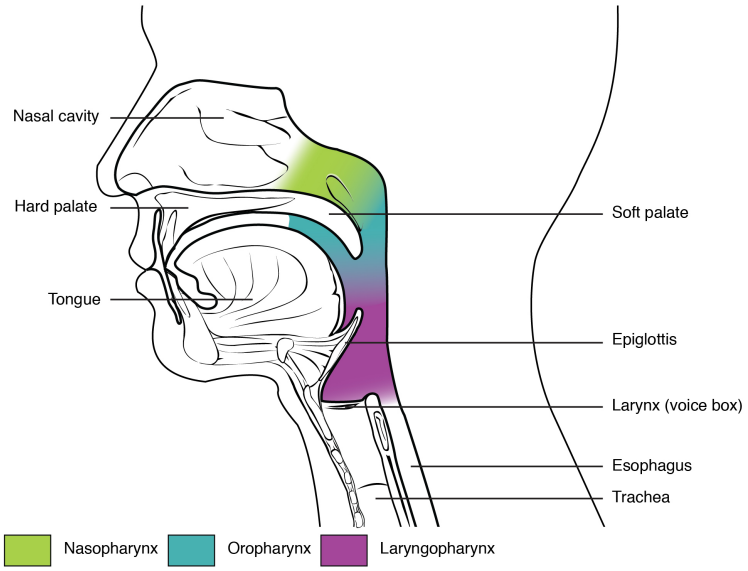

Figure 20.2.5: Divisions of the Pharynx. The pharynx a shared respiratory and digestive structure that is divided into three regions: the nasopharynx, the oropharynx, and the laryngopharynx. The nasopharynx is found between the internal naris at the posterior of the nasal cavity and the soft palate. The oropharynx extends from the soft palate (posterior to the hard palate) to the superior surface of the open epiglottis where it is continuous with the inferior region of the pharynx: the laryngopharynx. Anteriorly, the laryngopharynx opens into the larynx (which is superior to the trachea), whereas posteriorly, it enters the esophagus. (Image credit: "Divisions of the Pharynx" by OpenStax is licensed under CC BY 3.0)

The **nasopharynx** is posterior to the conchae of the nasal cavity, and it is meant to serve only as an airway. At the top of the nasopharynx is the **pharyngeal tonsil**, also called the adenoid, an aggregate of lymphoid reticular tissue. The function of the

pharyngeal tonsil is not well understood, but it contains a rich supply of lymphocytes and is covered with ciliated epithelium that traps and destroys invading pathogens that enter during inhalation. The pharyngeal tonsil is large in children, but interestingly, tends to regress with age and may even disappear. The uvula is a small bulbous, teardrop-shaped structure located at the apex of the soft palate. Both the uvula and soft palate move like a pendulum during swallowing, swinging upward to close off the nasopharynx to prevent ingested materials from entering the nasal cavity. In addition, auditory (Eustachian) tubes that connect to each middle ear cavity open into the nasopharynx. This connection is why colds may lead to ear infections.

Unlike the nasopharynx which is a passageway for air only, the **oropharynx** is a passageway for both air and food. The oropharynx is bordered superiorly by the nasopharynx and anteriorly by the oral cavity. The **fauces** is the opening at the connection between the oral cavity and the oropharynx (see Figure 20.2.3). As the nasopharynx becomes the oropharynx, the epithelium changes from ciliated pseudostratified columnar epithelium to a stratified squamous epithelium. The oropharynx contains two distinct sets of tonsils, the palatine and lingual tonsils. A **palatine tonsil** is one of a pair of structures located laterally in the oropharynx in the area of the fauces. The **lingual tonsil** is located at the base of the tongue. Similar to the pharyngeal tonsil, the palatine and lingual tonsils are composed of lymphoid tissue, and trap and destroy pathogens entering the body through the oral or nasal cavities.

The **laryngopharynx** is inferior to the oropharynx. It continues the route for ingested material and air until its inferior end, where the digestive and respiratory systems diverge. It is posterior to the open epiglottis, allowing air to move in and out of the larynx. When you swallow ingested material, the epiglottis closes and the material moves into the esophagus. The stratified squamous epithelium of the oropharynx is continuous with the laryngopharynx.

Larynx

The **larynx** is a cartilaginous structure inferior to the laryngopharynx that connects the pharynx to the trachea and helps regulate the volume of air that enters and leaves the lungs, protects the respiratory passages from ingested materials, and produces sound (Figure 20.2.6). The structure of the larynx is formed by several pieces of cartilage. With the exception of the epiglottis, the cartilages of the larynx are comprised of hyaline cartilage. Three large cartilage pieces—the thyroid cartilage (anterior), epiglottis (superior), and cricoid cartilage (inferior)—form the major structure of the larynx, which is also known as the voice box. The **thyroid cartilage** is the largest piece of cartilage that makes up the larynx and functions to form a protective shield across the anterior of the larynx. The thyroid cartilage consists of the **laryngeal prominence**, or “Adam’s apple,” which tends to be more prominent in males. The thick **cricoid cartilage** forms a continuous ring around the larynx to hold the airway open as pressure changes during ventilation. It has a taller posterior region and a shorter anterior region inferior to the thyroid cartilage. The cricoid cartilage is connected to the thyroid cartilage by the cricothyroid ligament across the midline anteriorly and is connected to the most superior cartilage of the trachea by the cricotracheal ligament. Three smaller, paired cartilages—the arytenoids, corniculates, and cuneiforms—attach to the epiglottis and the vocal cords as well as the muscle that helps move the vocal cords to produce sound.

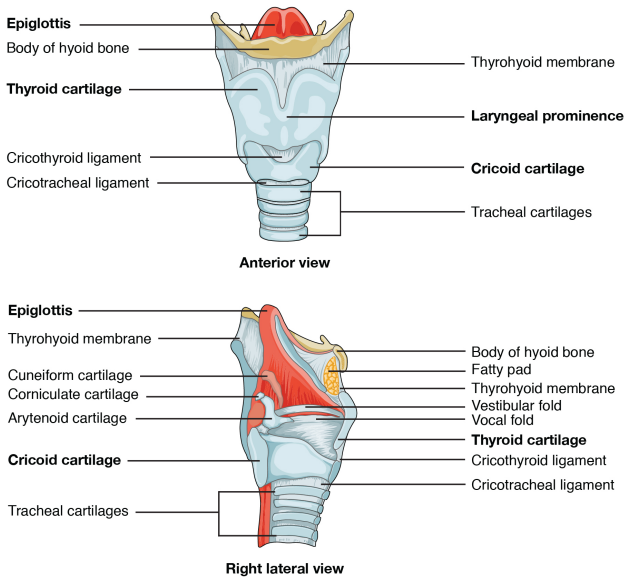

Figure 20.2.6: Larynx. The larynx is comprised of several cartilaginous structures connected by ligaments. The larynx functions to deliver air to the trachea, produce sound, and protect the respiratory passages from ingested materials. extends from the laryngopharynx and the hyoid bone to the trachea. (Image credit: "The Larynx" by OpenStax is licensed under CC BY 3.0)

The **epiglottis**, attached to the thyroid cartilage by a ligament, is a very flexible piece of elastic cartilage that is tethered to the body of the hyoid bone and remains open unless you are swallowing. The hyoid bone is also connected to the thyroid cartilage via the thyrohyoid membrane (see Figure 20.2.6). A cushioning pad of adipose connective tissue is positioned between the thyrohyoid membrane and the epiglottis. When the hyoid bone moves during swallowing, the pharynx and larynx are lifted upward, allowing the pharynx to expand and the epiglottis to swing downward to cover the glottis. These movements produce a larger area for food to pass through, while preventing ingested food and beverages from entering the trachea.

The **glottis** is composed of the vestibular folds, the true vocal cords, and the space between these folds through which air passes to and from the trachea (Figure 20.2.7). A **vestibular fold**, or false vocal cord, is one of a pair of folded sections of mucous membrane that sit superior to the vocal folds and may function to protect the vocal folds and amplify sound. A **true vocal cord (or vocal fold)** is one of the white, membranous folds attached by muscle to the thyroid and arytenoid cartilages of the larynx on their outer edges. The inner edges of the true vocal cords contain an elastic vocal ligament covered in epithelial tissue that vibrates as air moves across it to produce sound. The size of the membranous folds of the true vocal cords differs between individuals, producing voices with different pitch ranges. Folds in males tend to be larger than those in females, which create a deeper voice. Movements of the muscles attaching the folds to the thyroid and arytenoid cartilages reposition the vocal folds to adjust the pitch of sounds produced.

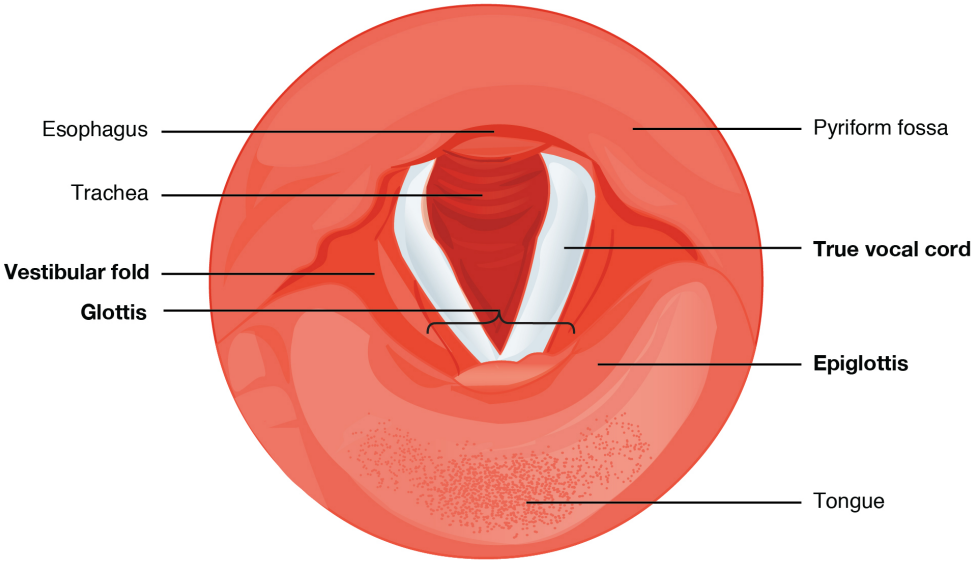

Figure 20.2.7: Glottis. The glottis inside the larynx includes the true vocal cords and the superior vestibular folds. A superior view shows the posterior of the tongue and the open epiglottis at the anterior. The trachea is inferior to the glottis, visible beyond the opening of the V-shaped true vocal cords. The pyriform fossa is a depression lateral to the glottis at the base of the laryngopharnyx. The opening to the esophagus is posterior to the glottis. (Image credit: "Cartilages of the Larynx" by OpenStax is licensed under CC BY 3.0)

Continuous with the laryngopharynx, the superior portion of the larynx is lined with stratified squamous epithelium, transitioning into ciliated pseudostratified columnar epithelium that contains goblet cells. Similar to the nasal cavity and nasopharynx, this specialized epithelium produces mucus to trap debris and pathogens as they enter the trachea. Beginning in this region and continuing throughout much of the conducting zone, cilia beat the mucus upward towards the laryngopharynx, where it can be swallowed down the esophagus into the acidic environment of the stomach that functions to kill pathogens trapped in the mucus. The action of the cilia moving the mucus upward to be swallowed is referred to as the mucous escalator.

Trachea

The **trachea** (windpipe) extends from the larynx toward the lungs (Figure 20.2.8). The mucosal layer of the wall of the trachea is lined with ciliated pseudostratified columnar epithelium featuring mucus-secreting goblet cells and covering a lamina propria of areolar connective tissue. The submucosa contains dense irregular connective tissue and houses seromucous glands that secrete a lubricating mucus that shares properties with serous fluid. The wall of the trachea contains 16 to 20 stacked, C-shaped pieces of hyaline cartilage that are positioned horizontally with the opening in the C at the back of the trachea. The incomplete rings of cartilage provide structural support that prevent the trachea from collapsing and protect it. The cartilages are connected to one another by dense connective tissue. The **fibroelastic membrane** consists of the **trachealis muscle**, made of smooth muscle, and elastic connective tissue. It is a flexible membrane that spans the gap across the the C-shaped cartilages at the posterior

of the trachea, allowing the trachea to stretch and expand slightly during inhalation and exhalation. Its flexibility also allows the trachea to accommodate ingested materials passing through the esophagus that borders the trachea posteriorly. In addition, the smooth muscle of the trachealis muscle can be contracted to force air through the trachea during exhalation. The superficial wrapping of the trachea is an adventitia of dense irregular connective tissue.

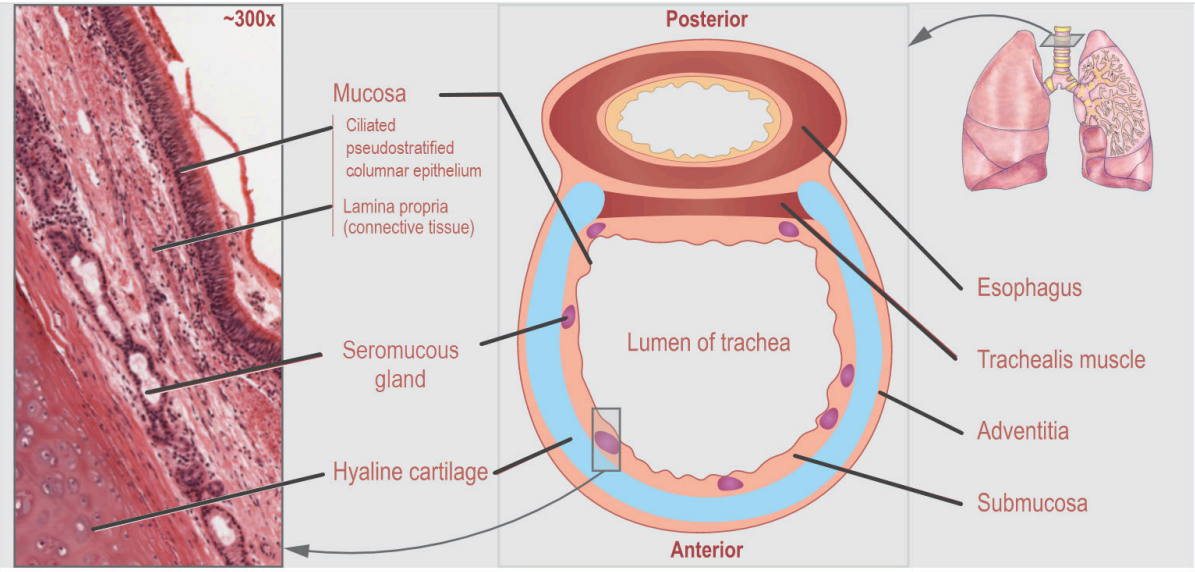

Figure 20.2.8: Trachea. The mucosa lines the hollow lumen of the trachea and is comprised of ciliated pseudostratified columnar epithelium that contains goblet cells covering a lamina propria of connective tissue. The submucosa houses seromucous glands. The C-shaped rings of hyaline cartilage are positioned deep to the mucosa with the opening at the posterior, which is spanned by the trachealis muscle and connective tissue. The superficial layer of the trachea is adventitia. The esophagus is positioned posterior to the trachea. LM × 1220. (Image credit: "Trachea" by Julie Jenks is licensed under CC BY 4.0/A derivative from the original work/Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Bronchial Tree

The trachea branches into the right and left **primary (main) bronchi** (singular = bronchus) at the **carina**. The carina is a raised structure that contains specialized nervous tissue that induces violent coughing if a foreign body, such as food, is present. These bronchi are also lined by ciliated pseudostratified columnar epithelium containing mucus-producing goblet cells (Figure 20.2.9). Rings of cartilage, similar to those of the trachea, support the structure of the bronchi and prevent their collapse. The primary bronchi branch to the **secondary (lobar) bronchi** that deliver air to the individual lobes of each lung. The secondary bronchi branch to the **tertiary (segmental) bronchi** that deliver air to the bronchopulmonary segments that comprise each lobe. The lobes and bronchopulmonary segments of the lungs will be covered in more detail in the next section.

The **bronchial tree** (or respiratory tree) is the collective term used for these highly branching bronchi, since they resemble branches of an upside-down tree. The main function of the bronchi, like other conducting zone structures, is to provide a passageway for air to move into and out of each lung. In addition, the mucous membrane traps debris and pathogens, cilia continue to work as a mucous escalator moving mucus up toward the laryngopharynx to be swallowed. Hyaline cartilage is featured within the wall of all the bronchi to reinforce the airways and help them stay open through pressure changes, but its quantity decreases with each branch point. The C-shaped rings of cartilage in the trachea become irregular plates of cartilage in the bronchi that are smaller and more sporadic in the tertiary bronchi than in the primary bronchi. A layer of smooth muscle is present in the bronchi that may **bronchoconstrict**, make the lumen diameter smaller by contracting the smooth muscle, or **bronchodilate**, make the lumen diameter larger by relaxing the smooth muscle, to adjust air flow in each passage. The quantity of smooth muscle in the wall relative to the lumen diameter increases with each branch point, meaning that the capability to adjust air flow is greater in the tertiary bronchi than in the primary bronchi.

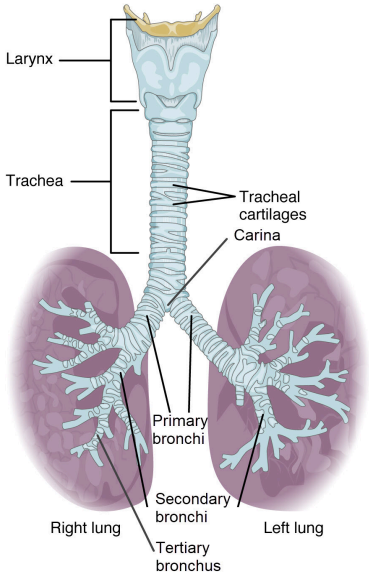

Figure 20.2.9: Bronchial Tree. The tracheal tube is formed by stacked, C-shaped pieces of hyaline cartilage. The trachea branches at the carina to the primary bronchi that deliver air to each lung. The primary bronchi branch into the secondary bronchi that deliver air to the lobes of each lung. The secondary bronchi branch into the tertiary bronchi that deliver air into the bronchopulmonary segments of each lobe. (Image credit: "Bronchial Tree" by Julie Jenks is licensed under CC BY 4.0 / A derivative from the original work)

Bronchi continue to branch from the tertiary bronchi, getting smaller and smaller. **Bronchioles**, which are 1 mm in diameter or less, further branch until they become the tiny terminal bronchioles, which lead to the structures of gas exchange. There are approximately 30,000 terminal bronchioles in each lung. As they branch, the epithelium of the bronchioles transitions from ciliated pseudostratified columnar epithelium to a thinner simple columnar epithelium to an even thinner simple cuboidal epithelium in the terminal bronchioles. Cilia and mucus-producing cells are sporadic in the largest bronchioles and then disappear as the bronchioles get smaller. The walls of the bronchioles do not contain cartilage like those of the bronchi, but they feature a significant layer of smooth muscle to change their diameter to adjust air flow.

Respiratory Zone

In contrast to the conducting zone, the respiratory zone includes structures that are directly involved in gas exchange. The respiratory zone begins where the terminal bronchioles join a **respiratory bronchiole**, the smallest type of bronchiole (Figure 20.2.10), which then leads to an alveolar duct that opens into a cluster of alveoli. Respiratory bronchioles are lined with simple cuboidal epithelium.

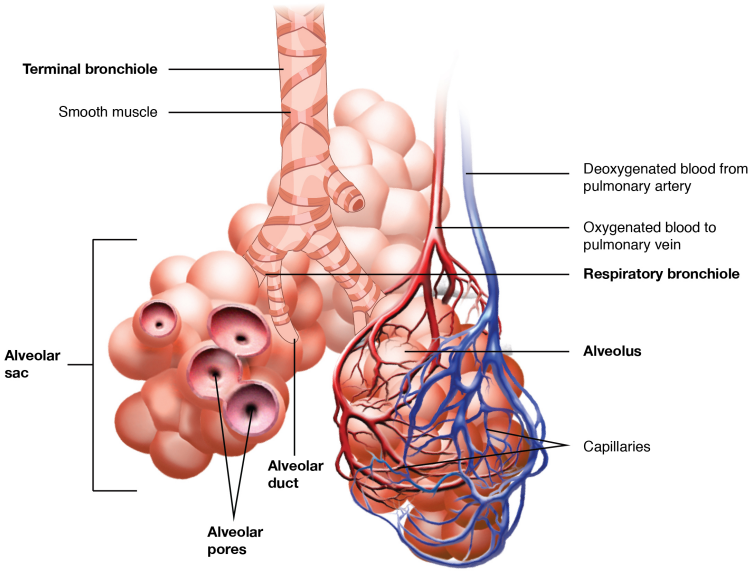

Figure 20.2.10: Respiratory Zone. Each terminal bronchiole branches to several respiratory bronchioles. Each respiratory bronchiole branches to a few alveolar ducts that connect to alveolar sacs in the respiratory zone. An alveolar sac is a cluster of alveoli wrapped in a capillary bed where gas exchange occurs, appearing as if it was caught in a net. Alveoli in each alveolar sac are interconnected by way of alveolar pores. Deoxygenated blood, shown in blue, is delivered to the capillary bed in an arteriole that branched from the pulmonary artery, while oxygenated blood, shown in red, is collected from the capillary bed by a venule that drains to the pulmonary vein. (Image credit: "The Respiratory Zone" by OpenStax is licensed under CC BY 3.0)

Alveoli

An **alveolar duct** is a tube whose wall contains smooth muscle and connective tissue and is lined with simple cuboidal epithelium. Each alveolar duct opens into a cluster of alveoli. An **alveolus** is one of the many small, grape-like sacs that are attached to the alveolar ducts. There are an average of about 480 million alveoli in the lungs, yielding an incredibly large surface area for gas exchange.

An **alveolar sac** is a cluster of many individual alveoli that are responsible for gas exchange. Each alveolar sac is surrounded by a capillary bed with a network of capillaries that distribute several capillaries to route along the outside of each alveolus in the alveolar sac (Figure 20.2.11). Deoxygenated blood is delivered to the capillary bed via an arteriole branching from the pulmonary artery and oxygenated blood is collected by a venule that drains to the pulmonary vein. An alveolus is approximately 200 µm in diameter with elastic walls that allow the alveolus to stretch during air intake like a balloon inflating, which greatly increases the surface area available for gas exchange, and then return to a smaller size to assist with expiration. Alveoli are connected to their neighbors by **alveolar pores**, which help maintain equal air pressure throughout the alveoli and lung.

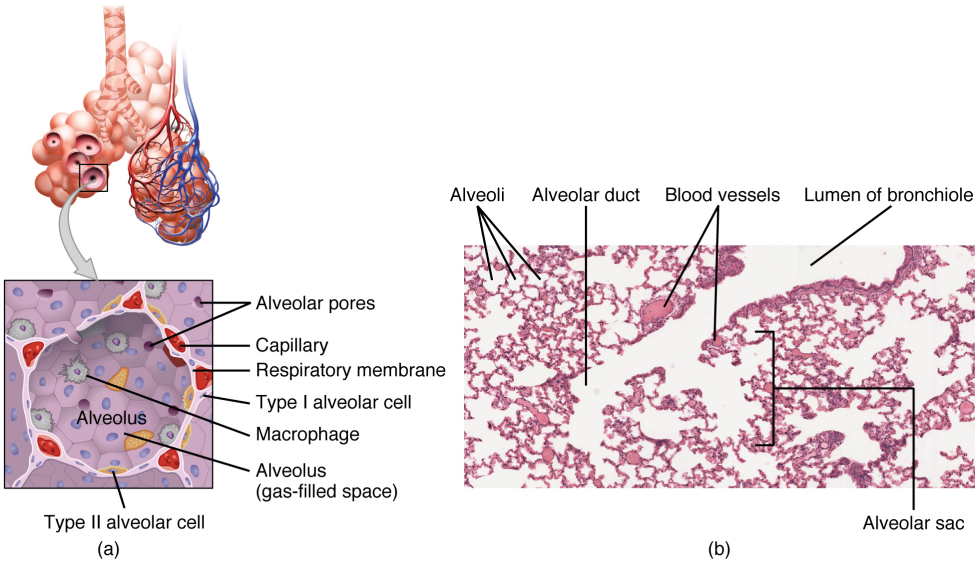

Figure 20.2.11: Structures of the Respiratory Zone. (a) The alveolus is responsible for gas exchange. (b) A micrograph shows the alveolar structures within lung tissue. LM × 178. (Image credit: "Structures of the Respiratory Zone" by OpenStax is licensed under CC BY 3.0/Micrograph provided by the Regents of University of Michigan Medical School © 2012)

The simple squamous epithelium of the alveolar wall consists of three major cell types: type I alveolar cells, type II alveolar cells, and alveolar macrophages (see Figure 20.2.11). **Type I alveolar cells** (aka type I pneumocytes or squamous alveolar cells) are squamous epithelial cells of the alveoli, which constitute up to 97 percent of the alveolar surface area. These cells are about 25 nm (there are a thousand nanometers in a millimeter!) thick and are highly permeable to gases. **Type II alveolar cells** (aka type II pneumocytes or great alveolar cells) are interspersed among the type I cells and secrete **pulmonary surfactant**, a substance composed of phospholipids and proteins that reduces the surface tension of the alveoli. Like tiny balloons, the alveoli expand when they fill with air during an inhale and deflate during an exhale. The reduced surface tension from the surfactant prevents the walls of each alveolus from sticking closed during and after exhaling. Type II alveolar cells also play an important role in initiating repair of an alveolus is damaged. Roaming around the alveolar wall is the **alveolar macrophage**, a phagocytic cell of the immune system that removes debris and pathogens that have reached the alveoli.

The simple squamous epithelium formed by type I alveolar cells is attached to a thin, elastic basement membrane. This epithelium is extremely thin and borders the endothelial membrane of capillaries. Taken together, the alveoli and capillary membranes form a **respiratory membrane** that is approximately 0.5 mm thick. The respiratory membrane allows gases to cross by simple diffusion, allowing oxygen to be picked up by the blood for transport and CO_2 to be released into the air of the alveoli to be excreted during the exhale.

DISORDERS OF THE...

Respiratory System: Asthma

Asthma is common condition that affects the lungs in both adults and children. Approximately 8.2 percent of adults (18.7 million) and 9.4 percent of children (7 million) in the United States suffer from asthma. In addition, asthma is the most frequent cause of hospitalization in children.

Asthma is a chronic disease characterized by inflammation and edema of the airway, and bronchospasms (that is, constriction of the bronchioles), which can inhibit air from entering the lungs. In addition, excessive mucus secretion can occur, which further contributes to airway occlusion (Figure 20.2.12). Cells of the immune system, such as eosinophils and macrophages, may also be involved in infiltrating the walls of the bronchi and bronchioles.

Bronchospasms occur periodically and lead to an “asthma attack.” An attack may be triggered by environmental factors such as dust, pollen, pet hair, or dander, changes in the weather, mold, tobacco smoke, and respiratory infections, or by exercise and stress.

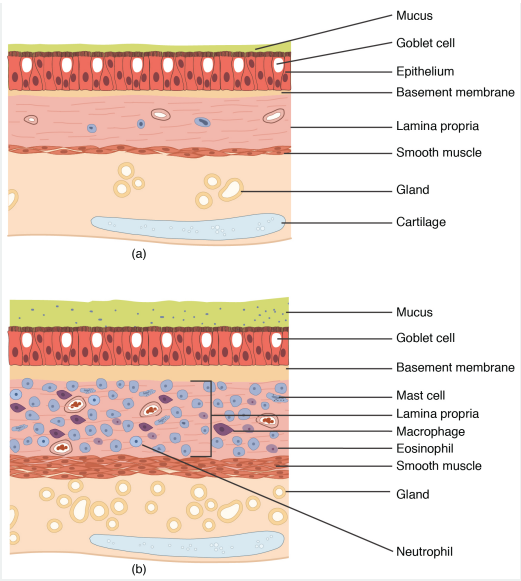

Figure 20.2.12: Normal and Asthmatic Bronchial Tissues. (a) Normal lung tissue does not have the characteristics of lung tissue during (b) an asthma attack, which include thickened mucosa, increased mucus-producing goblet cells, increased numbers of macrophages and mast cells, and eosinophil infiltrates. (Image credit: "Lung Tissue" by OpenStax is licensed under CC BY 3.0)

Symptoms of an asthma attack involve coughing, shortness of breath, wheezing, and tightness of the chest. Symptoms of a severe asthma attack that requires immediate medical attention would include difficulty breathing that results in blue (cyanotic) lips or face, confusion, drowsiness, a rapid pulse, sweating, and severe anxiety. The severity of the condition, frequency of attacks, and identified triggers influence the type of medication that an individual may require. Longer-term treatments are used for those with more severe asthma. Short-term, fast-acting drugs that are used to treat an asthma attack are typically administered via an inhaler. For young children or individuals who have difficulty using an inhaler, asthma medications can be administered via a nebulizer.

In many cases, the underlying cause of the condition is unknown. However, recent research has demonstrated that certain viruses, such as human rhinovirus C (HRVC), and the bacteria *Mycoplasma pneumoniae* and *Chlamydia pneumoniae* that are contracted in infancy or early childhood, may contribute to the development of many cases of asthma.

Concept Review

The respiratory system is responsible for obtaining oxygen and getting rid of carbon dioxide, and aiding in speech production and in sensing odors. From a functional perspective, the respiratory system can be divided into two major areas: the conducting zone and the respiratory zone. The conducting zone consists of all of the structures that provide passageways for air to travel into and out of the lungs: the nasal cavity, pharynx, larynx, trachea, bronchi, and most bronchioles. The nasal passages contain the conchae and meatuses that expand the surface area of the cavity, which helps to warm and humidify incoming air, while removing debris and pathogens. The pharynx is composed of three major sections: the nasopharynx, which is continuous with the nasal cavity; the oropharynx, which borders the nasopharynx and the oral cavity; and the laryngopharynx, which connects the oropharynx to the larynx and esophagus.

The larynx is a cartilaginous structure involved in passing air to and from the trachea. The epiglottis closes during swallowing to prevent ingested materials from passing to the trachea. The true vocal cords within the glottis of the larynx function in the production of sound. The trachea delivers air to and from the bronchial tree, a pathway of branching tubes with several levels of bronchi and tiny bronchioles that conduct air to the respiratory zone. The respiratory zone includes the structures of the lung that are directly involved in gas exchange: the respiratory bronchioles and alveoli. The lining of the conducting zone is composed mostly of ciliated pseudostratified columnar epithelium with goblet cells. The mucus secreted by goblet cells traps pathogens and debris, whereas beating cilia move the mucus superiorly via the mucous escalator toward the throat, where it is swallowed. As the bronchioles become smaller and smaller, and nearer the alveoli, the epithelium thins and is simple squamous epithelium in the alveoli. The endothelium of the surrounding capillaries, together with the alveolar epithelium, forms the respiratory membrane. This is a blood-air barrier through which gas exchange occurs by simple diffusion.

Review Questions

Q. Which of the following anatomical structures is *not* part of the conducting zone?

A. pharynx

B. nasal cavity

C. alveoli

D. bronchi

Answer

C

Q. What is the function of the conchae in the nasal cavity?

A. increase surface area

B. exchange gases

C. maintain surface tension

D. maintain air pressure

Answer

A

Q. The fauces connects which of the following structures to the oropharynx?

A. nasopharynx

B. laryngopharynx

C. nasal cavity

D. oral cavity

Answer

D

Q. Which of the following are structural features of the trachea?

A. C-shaped cartilage

B. smooth muscle fibers

C. cilia

D. all of the above

Answer

D

Q. Which of the following structures is *not* part of the conducting zone?

A. trachea

B. bronchi

C. terminal bronchioles

D. respiratory bronchioles

Answer

D

Q. What is the role of alveolar macrophages?

A. to secrete pulmonary surfactant

B. to secrete antimicrobial proteins

C. to remove pathogens and debris

D. to facilitate gas exchange

Answer

C

Critical Thinking Questions

Q. Describe the three regions of the pharynx and their functions.

Answer

The pharynx has three major regions. The first region is the nasopharynx, which is connected to the posterior nasal cavity. The second region is the oropharynx, which is continuous with the nasopharynx and is connected to the oral cavity at the fauces. The laryngopharynx is connected to the oropharynx and the esophagus and trachea. Both the oropharynx and laryngopharynx are passageways for air and food and drink, while the nasopharynx is designed only for air. The epithelium of the nasopharynx is a ciliated pseudostratified columnar epithelium with mucus-secreting goblet cells to help trap debris and pathogens from air, whereas the oropharynx and laryngopharynx are lined with a stratified squamous epithelium for extra protection from abrasion and exposures related to swallowing ingested food and drink.

Q. If a person sustains an injury to the epiglottis, what would be the functional consequence?

Answer

The epiglottis is a region of the larynx that is important during the swallowing of food or drink. As a person swallows, the pharynx moves upward and the epiglottis closes over the trachea, preventing food or drink from entering the trachea. If a person's epiglottis were injured, this mechanism would be impaired. As a result, the person may have problems with food or drink entering the trachea, and possibly, the lungs. Over time, this may cause infections such as pneumonia to set in.

Q. Compare and contrast the conducting and respiratory zones.

Answer

The conducting zone of the respiratory system includes the organs and structures that are not directly involved in gas exchange, but perform other duties such as providing a passageway for air, trapping and removing debris and pathogens, and warming and humidifying incoming air. Such structures include the nasal cavity, pharynx, larynx, trachea, and most of the bronchial tree. The respiratory zone includes all the organs and structures that are directly

involved in gas exchange, including the respiratory bronchioles, alveolar ducts, and alveoli.

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Glossary

ala
: (plural = alae) small, flaring structure of a nostril that forms the lateral side of the external naris

alar cartilage
: cartilage that supports the apex of the nose and helps shape the nares; it is connected to the septal cartilage and connective tissue of the alae

alveolar duct
: small tube that leads from the terminal bronchiole to the respiratory bronchiole and is the point of attachment for alveoli

alveolar macrophage
: immune system cell of the alveolus that removes debris and pathogens

alveolar pore
: opening that allows airflow between neighboring alveoli

alveolar sac
: cluster of alveoli

alveolus
: small, grape-like sac that performs gas exchange in the lungs

apex
: tip of the external nose

bronchial tree
: collective name for the multiple branches of the bronchi and bronchioles of the respiratory system

bridge
: portion of the external nose that lies in the area of the nasal bones

bronchiole
: branch of bronchi that are 1 mm or less in diameter and terminate at alveolar sacs

bronchoconstriction
: contraction of the smooth muscle in the wall of a bronchus or bronchiole to reduce the volume of the lumen and adjust air flow

bronchodilation
: relaxation of the smooth muscle in the wall of a bronchus or bronchiole to increase the volume of the lumen and adjust air flow

bronchus
tube connected to the trachea that branches into many subsidiaries and provides a passageway for air to enter and leave the lungs

carina
raised structure at the divergence of the left and right main bronchi from the trachea that induces coughing if a foreign body (such as food) is detected

conducting zone
region of the respiratory system that includes the organs and structures that provide passageways for air and are not directly involved in gas exchange

cricoid cartilage
portion of the larynx composed of a ring of cartilage with a wide posterior region and a thinner anterior region; attached to the esophagus

dorsum nasi
intermediate portion of the external nose that connects the bridge to the apex and is supported by the nasal bone

epiglottis
leaf-shaped piece of elastic cartilage that is a portion of the larynx that swings to close the trachea during swallowing

external naris
(plural = external nares) opening of the nostril to the nasal cavity

external nose
region of the nose that is easily visible to others

fauces
portion of the posterior oral cavity that connects the oral cavity to the oropharynx

fibroelastic membrane
specialized membrane that connects the ends of the C-shape cartilage in the trachea; contains smooth muscle fibers

glottis
opening between the vocal folds through which air passes when producing speech

laryngeal prominence
region where the two lamina of the thyroid cartilage join, forming a protrusion known as “Adam’s apple”

laryngopharynx
portion of the pharynx bordered by the oropharynx superiorly and esophagus and trachea inferiorly; serves as a route for both air and food

larynx
cartilaginous structure that produces the voice, prevents food and beverages from entering the trachea, and regulates the volume of air that enters and leaves the lungs

lingual tonsil
lymphoid tissue located at the base of the tongue

meatus
one of three recesses (superior, middle, and inferior) in the nasal cavity attached to the conchae that increase the surface area of the nasal cavity

nasal bone
bone of the skull that lies under the root and bridge of the nose and is connected to the frontal and maxillary bones

nasal septum
wall composed of bone and cartilage that separates the left and right nasal cavities

nasopharynx
portion of the pharynx flanked by the conchae and oropharynx that serves as an airway

oropharynx
portion of the pharynx flanked by the nasopharynx, oral cavity, and laryngopharynx that is a passageway for both air and food

palatine tonsil
one of the paired structures composed of lymphoid tissue located anterior to the uvula at the roof of isthmus of the fauces

paranasal sinus
one of the cavities within the skull that is connected to the conchae that serve to warm and humidify incoming air, produce mucus, and lighten the weight of the skull; consists of frontal, maxillary, sphenoidal, and ethmoidal sinuses

pharyngeal tonsil
structure composed of lymphoid tissue located in the nasopharynx; also known as the adenoid

pharynx
region of the conducting zone that forms a tube of skeletal muscle lined with respiratory epithelium; located between the nasal conchae and the esophagus and trachea

philtrum
concave surface of the face that connects the apex of the nose to the top lip

primary bronchus (main bronchus)
passageway of the conducting zone branching directly off the trachea that delivers air to each lung

pulmonary surfactant
substance composed of phospholipids and proteins that reduces the surface tension of the alveoli; made by type II alveolar cells

respiratory bronchiole
specific type of bronchiole that leads to alveolar sacs

respiratory epithelium
ciliated lining of much of the conducting zone that is specialized to remove debris and pathogens, and produce mucus

respiratory membrane
alveolar and capillary wall together, which form an air-blood barrier that facilitates the simple diffusion of gases

respiratory zone
includes structures of the respiratory system that are directly involved in gas exchange

root
region of the external nose between the eyebrows

secondary bronchus (lobar bronchus)
passageway of the conducting zone branching directly off the primary bronchi that delivers air to a lobe of either lung

septal cartilage
flexible hyaline cartilage that forms the anterior portion of the nasal septum

tertiary bronchus (segmental bronchus)
passageway of the conducting zone branching directly off the secondary bronchi that delivers air to a

bronchopulmonary segment within a lobe of either lung

thyroid cartilage
largest piece of cartilage that makes up the larynx and consists of two lamina

trachea
tube composed of cartilaginous rings and supporting tissue that connects the lung bronchi and the larynx; provides a route for air to enter and exit the lung

trachealis muscle
smooth muscle located in the fibroelastic membrane of the trachea

true vocal cord
one of the pair of folded, white membranes that have a free inner edge that oscillates as air passes through to produce sound

type I alveolar cell
squamous epithelial cells that are the major cell type in the alveolar wall; highly permeable to gases

type II alveolar cell
cuboidal epithelial cells that are the minor cell type in the alveolar wall; secrete pulmonary surfactant

vestibular fold
part of the folded region of the glottis composed of mucous membrane; supports the epiglottis during swallowing

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20.3: The Lungs

By the end of this section, you will be able to:

- Describe the overall function of the lungs
- Outline the anatomy of the blood supply to the lungs
- Describe the pleurae of the lungs and their function

A major organ of the respiratory system, each **lung** houses structures of both the conducting and respiratory zones. The main function of the lungs is to perform the exchange of oxygen and carbon dioxide with air from the atmosphere. To this end, the lungs exchange respiratory gases across a very large epithelial surface area—about 70 square meters—that is highly permeable to gases.

Gross Anatomy of the Lungs

The lungs are pyramid-shaped, paired organs that are connected to the trachea by the right and left bronchi; on the inferior surface, the lungs are bordered by the diaphragm. The diaphragm is the flat, dome-shaped muscle located at the base of the lungs and thoracic cavity. The lungs are enclosed by the pleurae, which are attached to the mediastinum. The right lung is shorter and wider than the left lung, and the left lung occupies a smaller volume than the right. The **cardiac notch** is an indentation on the medial surface of the left lung that allows space for the heart (Figure 20.3.1). The apex of the lung is the superior region, whereas the base is the opposite region near the diaphragm. The costal surface of the lung borders the ribs. The mediastinal surface faces the midline. The primary bronchi enter the lungs at the **hilum**, a concave region facing the mediastinum where blood vessels, lymphatic vessels, and nerves also enter the lungs. Collectively this grouping of the bronchi, vessels, and nerves is known as the **lung root**.

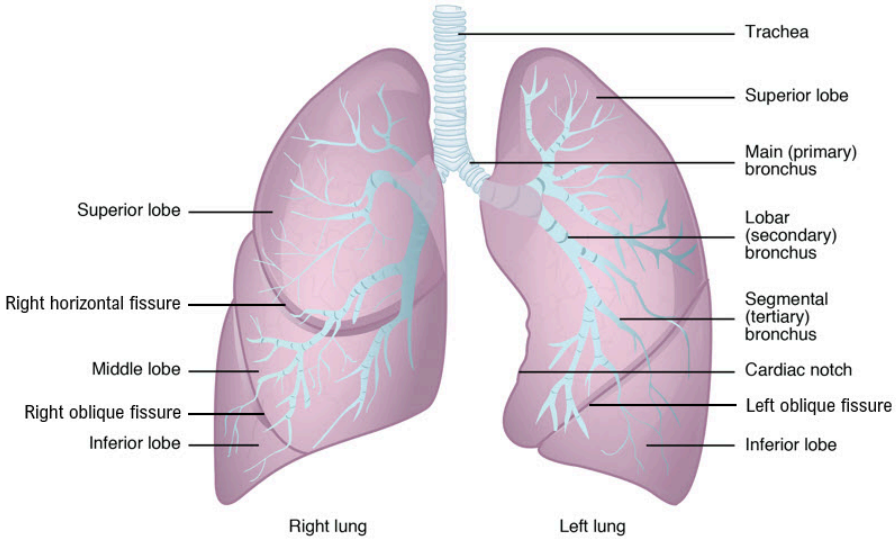

Figure 20.3.1: Gross Anatomy of the Lungs. The left lung is divided into just two lobes and has less mass due to the cardiac notch while the right lung is divided into three lobes. The right superior lobe is separated from the right middle lobe by the right horizontal fissure. The right middle lobe is separated from the right inferior lobe by the right oblique fissure. The left superior lobe is separated from the right inferior lobe by the left oblique fissure. The main (primary) bronchi deliver air from the trachea into each lung. The lobar (secondary) bronchi deliver air into the lobes of each lung. The segmental (tertiary) bronchi deliver air into the bronchopulmonary segments of each lobe. (Image credit: "Gross Anatomy of the Lungs" by Julie Jenks is licensed under CC BY 4.0 / A derivative from the original work)

Each lung is composed of smaller units called **lobes**. Deep grooves called **fissures** separate these lobes from each other; the lobes are only connected near the mediastinum where connective tissue anchors the lungs in place as well as the major pulmonary arteries and veins routing into each lung. The right lung consists of three lobes: the superior, middle, and inferior lobes. The right

superior and middle lobes are separated by the right horizontal fissure, while the right middle and inferior lobes are separated by the right oblique fissure. The left lung consists of two lobes: the superior and inferior lobes, separated by the left oblique fissure. A **bronchopulmonary segment** is a division of a lobe, and each lobe houses multiple bronchopulmonary segments. Each segment receives air from its own tertiary bronchus and is supplied with blood by its own artery. Some diseases of the lungs typically affect one or more bronchopulmonary segments, and in some cases, the diseased segments can be surgically removed with little influence on neighboring segments. A **pulmonary lobule** is a subdivision formed as the bronchi branch into bronchioles. Each lobule receives its own large bronchiole that has multiple branches. An interlobular septum is a wall, composed of connective tissue, which separates lobules from one another.

Blood Supply and Nervous Innervation of the Lungs

The blood supply of the lungs plays an important role in gas exchange and serves as a transport system for gases throughout the body. In addition, innervation by both the parasympathetic and sympathetic nervous systems provides an important level of control through dilation and constriction of the airways.

Blood Supply

The major function of the lungs is to perform gas exchange, which requires blood from the pulmonary circulation. This blood supply contains deoxygenated blood and travels to the lungs where erythrocytes, also known as red blood cells, pick up oxygen to be transported to tissues throughout the body. The **pulmonary arteries** are arteries that arise from the pulmonary trunk and carry deoxygenated, arterial blood to each lung. Each pulmonary artery branches multiple times as it follows the bronchi, and each branch becomes progressively smaller in diameter. One arteriole and an accompanying venule supply and drain one pulmonary lobule. As they near the alveoli, the pulmonary arterioles become the pulmonary capillary network. The pulmonary capillary network consists of tiny vessels with very thin walls that lack smooth muscle fibers. The capillaries branch and follow the bronchioles and structure of the alveoli. It is at this point that the capillary wall meets the alveolar wall, creating the respiratory membrane. Once the blood is oxygenated, it drains from the alveoli by way of multiple pulmonary veins, which exit the lungs through the hilum.

Nervous Innervation

Dilation and constriction of the airway are achieved through nervous control by the parasympathetic and sympathetic nervous systems. The parasympathetic system causes **bronchoconstriction**, whereas the sympathetic nervous system stimulates **bronchodilation**. Reflexes such as coughing, and the ability of the lungs to regulate oxygen and carbon dioxide levels, also result from this autonomic nervous system control. Sensory nerve fibers arise from the vagus nerve, and from the second to fifth thoracic ganglia. The **pulmonary plexus** is a region on the lung root formed by the entrance of the nerves at the hilum. The nerves then follow the bronchi in the lungs and branch to innervate muscle fibers, glands, and blood vessels.

Pleurae of the Lungs

Each lung is enclosed within a cavity that is surrounded by the pleurae. The pleura (plural = pleurae) is a serous membrane that surrounds each lung. The right and left pleurae, which enclose the right and left lungs, respectively, are separated by the mediastinum. The pleurae consist of two layers. The **visceral pleura** is the layer that is superficial to the lungs, and extends into and lines the lung fissures (Figure $20.3.2$). In contrast, the **parietal pleura** is the outer layer that connects to the thoracic wall, the mediastinum, and the diaphragm. The visceral and parietal pleurae connect to each other at the hilum. The **pleural cavity** is the space between the visceral and parietal layers.

The pleurae perform two major functions: They produce pleural fluid (serous fluid) and create cavities that separate the lungs from each other and other thoracic structures. **Pleural fluid** is secreted by mesothelial cells from both pleural layers and acts to lubricate their surfaces. This lubrication reduces friction between the two layers to prevent trauma during breathing, and creates surface tension that helps maintain the position of the lungs against the thoracic wall. This adhesive characteristic of the pleural fluid causes the lungs to enlarge when the thoracic wall expands during ventilation, allowing the lungs to fill with air. The pleurae also create a division between major organs that prevents interference due to the movement of the organs, while preventing the spread of infection.

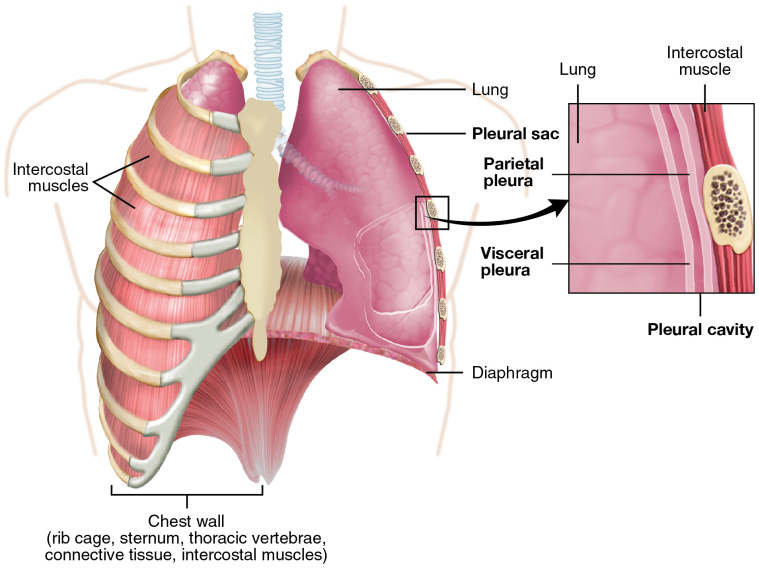

Figure 20.3.2: Parietal and Visceral Pleurae of the Lungs. The pleural sac is formed by the parietal and visceral pleura of the lungs. The parietal pleura is attached to the deep surface of the chest wall, which includes the ribs, sternum, thoracic vertebrae, connective tissue of the mediastinum, internal intercostal muscles, and the superior surface of the diaphragm. The visceral pleura covers the superficial surface of the lobes of the lungs. The pleural cavity is the potential space between the layers that is filled with lubricating serous fluid. (Image credit: "The Lung Pleurae" by OpenStax is licensed under CC BY 3.0)

DISORDERS OF THE...

Respiratory System: Pneumothorax

A pneumothorax is a condition in which a rupture caused by trauma or disease introduces air into the pleural cavity. The air increases pressure on the surface of the lung on the affected side, breaking the surface tension that adheres the visceral pleura to the parietal pleura throughout increases and decreases in the volume of the thoracic cavity during ventilation. With the surface tension between the pleurae broken, the lung collapses due to elastic recoil (Figure 20.3.3). Treatment may include manual aspiration of the air, along with treatment of the underlying cause of the pneumothorax.

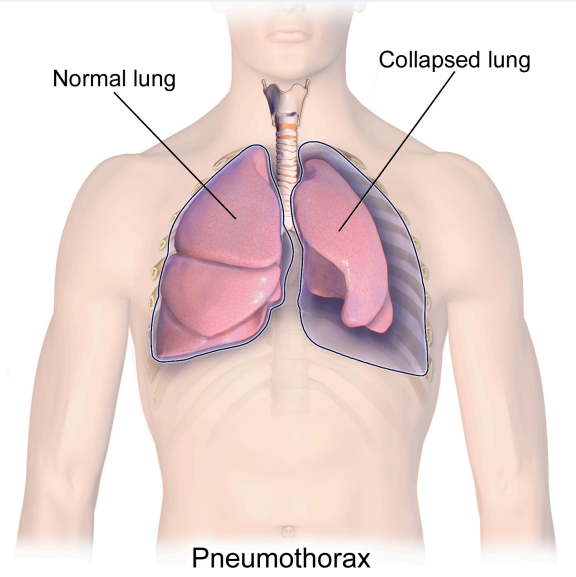

Figure 20.3.3: Pneumothorax. A pneumothorax is caused by air in the pleural cavity, which increases pressure on the lung, causing it to collapse. (Image credit: "Blausen 0742 Pneumothorax" by Bruce Blaus Blausen.com staff, Medical gallery of Blausen Medical is licensed under CC BY 3.0)

EVERYDAY CONNECTION

The Effects of Second-Hand Tobacco Smoke

The burning of a tobacco cigarette creates multiple chemical compounds that are released through mainstream smoke, which is inhaled by the smoker, and through sidestream smoke, which is the smoke that is given off by the burning cigarette. Second-hand smoke, which is a combination of sidestream smoke and the mainstream smoke that is exhaled by the smoker, has been demonstrated by numerous scientific studies to cause disease. At least 40 chemicals in sidestream smoke have been identified that negatively impact human health, leading to the development of cancer or other conditions, such as immune system dysfunction, liver toxicity, cardiac arrhythmias, pulmonary edema, and neurological dysfunction. Furthermore, second-hand smoke has been found to harbor at least 250 compounds that are known to be toxic, carcinogenic, or both. Some major classes of carcinogens in second-hand smoke are polyaromatic hydrocarbons (PAHs), N-nitrosamines, aromatic amines, formaldehyde, and acetaldehyde.

Tobacco and second-hand smoke are considered to be carcinogenic. Exposure to second-hand smoke can cause lung cancer in individuals who are not tobacco users themselves. It is estimated that the risk of developing lung cancer is increased by up to 30 percent in nonsmokers who live with an individual who smokes in the house, as compared to nonsmokers who are not regularly exposed to second-hand smoke. Children are especially affected by second-hand smoke. Children who live with an individual who smokes inside the home have a larger number of lower respiratory infections, which are associated with hospitalizations, and higher risk of sudden infant death syndrome (SIDS). Second-hand smoke in the home has also been linked to a greater number of ear infections in children, as well as worsening symptoms of asthma.

Concept Review

The lungs are the major organs of the respiratory system and are responsible for performing gas exchange. The lungs are paired and separated into lobes; The left lung consists of two lobes, whereas the right lung consists of three lobes. Blood circulation is very important, as blood is required to transport oxygen from the lungs to other tissues throughout the body and deliver carbon dioxide to the lungs for removal. The function of the pulmonary circulation is to aid in gas exchange. The pulmonary artery provides deoxygenated blood to the capillaries that form respiratory membranes with the alveoli, and the pulmonary veins return newly oxygenated blood to the heart for further transport throughout the body. The lungs are innervated by the parasympathetic and sympathetic nervous systems, which coordinate bronchodilation and bronchoconstriction of the airways. The lungs are enclosed by the pleurae, a membrane that is composed of visceral and parietal pleural layers. The space between these two layers is called the pleural cavity. The mesothelial cells of the pleural membrane create pleural (serous) fluid, which serves as both a lubricant (to reduce friction during breathing) and as an adhesive to adhere the lungs to the thoracic wall (to facilitate movement of the lungs during ventilation).

Review Questions

Q. Which of the following structures separates the lung into lobes?

A. mediastinum

B. fissure

C. root

D. pleura

Answer

B

Q. A section of the lung that receives its own tertiary bronchus is called the _____.

A. bronchopulmonary segment

B. pulmonary lobule

C. interpulmonary segment

D. respiratory segment

Answer

A

Q. The _____ circulation picks up oxygen for cellular use and drops off carbon dioxide for removal from the body.

A. pulmonary

B. interlobular

C. respiratory

D. bronchial

Answer

A

Q. The pleura that surrounds the lungs consists of two layers, the _____.

A. visceral and parietal pleurae

B. mediastinum and parietal pleurae

C. visceral and mediastinum pleurae

D. none of the above

Answer

A

Critical Thinking Questions

Q. Compare and contrast the right and left lungs.

Answer

The right and left lungs differ in size and shape to accommodate other organs that encroach on the thoracic region. The right lung consists of three lobes separated by two fissures. The left lung consists of two lobes separated by one fissure and it has a concave region on the mediastinal surface called the cardiac notch that allows space for the heart.

Q. Why doesn't the change in size of the lungs during normal breathing damage the pleurae?

Answer

There is a cavity, called the pleural cavity, between the parietal and visceral layers of the pleura. Mesothelial cells produce and secrete pleural (serous) fluid into the pleural cavity that acts as a lubricant and also creates surface tension that adheres the layers so they stay together as the lungs expand and contract.

Glossary

bronchoconstriction
: decrease in the size of the bronchiole due to contraction of the muscular wall

bronchodilation
: increase in the size of the bronchiole due to contraction of the muscular wall

bronchopulmonary segment
: division of a lobe of the lung that receives air from a single tertiary (segmental) bronchus

cardiac notch
: indentation on the surface of the left lung that allows space for the heart

hilum
: concave structure on the mediastinal surface of the lungs where blood vessels, lymphatic vessels, nerves, and a bronchus enter the lung

lobe
: large division of lung tissue receiving air from a single secondary (lobar) bronchus

lung
: organ of the respiratory system that performs gas exchange

lung root
: collection of the primary bronchus, blood vessels, lymphatic vessels, and nerves that enters each lung at the hilum

parietal pleura
: outermost layer of the pleura that connects to the thoracic wall, mediastinum, and diaphragm

pleural cavity
: space between the visceral and parietal pleurae

pleural fluid
: substance that acts as a lubricant for the visceral and parietal layers of the pleura during the movement of breathing

pulmonary artery
: artery that arises from the pulmonary trunk and carries deoxygenated, arterial blood to the alveoli

pulmonary lobule
: subdivision of lung that receives air from a single large bronchiole as it branches from a bronchus

pulmonary plexus
: network of autonomic nervous system fibers found near the hilum of the lung

visceral pleura
: innermost layer of the pleura that is superficial to the lungs and extends into the lung fissures

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McKnight CL, Burns B. Pneumothorax. 2020 Nov 16. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2021 Jan–. PMID: 28722915. Licensed under CC BY 4.0. [Accessed 30 Apr 2021]

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20.4: The Processes of the Respiratory System

By the end of this section, you will be able to:

- Describe how the relationship between pressure and volume drives pulmonary ventilation
- Compare and contrast ventilation, the transport of gases, and the specific types of respiration

The processes of the respiratory system follow oxygen from its origin in the air you inhale to its use by cells of the body to convert glucose to cellular energy in the form of adenosine triphosphate (ATP). Since the conversion of glucose to ATP produces carbon dioxide as a waste, carbon dioxide originates at the cells of the body and takes the same journey in reverse to be eliminated form the body when you inhale. The processes of the respiratory system are pulmonary ventilation, external respiration, transport of gases, internal respiration, and cellular respiration.

Pulmonary Ventilation

Pulmonary ventilation is the act of breathing, which can be described as the movement of air into and out of the lungs. When you take a deep breath, notice the expansion of your rib cage. Contraction of the diaphragm and external intercostal muscles increases the volume in the chest cavity, which in turn lowers the pressure and draws air into the lungs for **inspiration**. The process for **expiration** (or exhalation) is similar only in the reverse (Figure 20.4.1). Boyle's Law describes the relationship between volume and pressure in a gas at a constant temperature. Boyle discovered that the pressure of a gas is inversely proportional to its volume: If volume increases, pressure decreases. Likewise, if volume decreases, pressure increases.

The lungs themselves are passive during breathing, meaning they are not involved in creating the movement that helps inspiration and expiration. This is because of the adhesive nature of the pleural fluid, which allows the lungs to be pulled outward when the thoracic wall moves during inspiration. The recoil of the thoracic wall, partly due to lung elasticity, during expiration causes compression of the lungs. While typical expiration is a passive process caused by relaxation of muscles and elasticity of tissues, a forced or maximal expiration can involve contraction of the internal intercostals and other muscles that compress the rib cage.

The difference in pressures drives pulmonary ventilation because air flows down a pressure gradient, that is, air flows from an area of higher pressure to an area of lower pressure. By expanding the thoracic cavity and thus the lungs, the increased volume results in a decrease in the lung air pressure. At this time, atmospheric pressure is greater than pressure within the lungs and air flows in (inhalation). Air flows out of the lungs during expiration based on the same principle; when the lungs recoil, pressure within the lungs becomes greater than the atmospheric pressure.

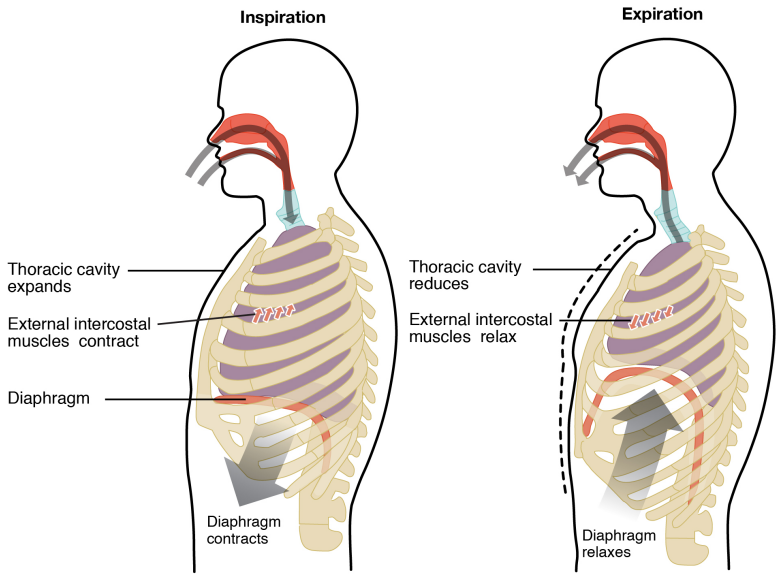

Figure 20.4.1: Inspiration and Expiration. During inspiration, the diaphragm and external intercostal muscles contract, expanding the volume in the thoracic cavity, creating a pressure gradient with lower air pressure in the lungs that draws air in. During expiration, the diaphragm and external intercostal muscles relax, reducing the volume in the thoracic cavity and reversing the pressure gradient with higher air pressure in the lungs that forces air out. (Image credit: "Inspiration and Expiration" by OpenStax is licensed under CC BY 3.0)

DISORDERS OF THE...

Respiratory System: Chronic Obstructive Pulmonary Disorder (COPD)

Chronic Obstructive Pulmonary Disorder (COPD) is used to describe a number of closely related respiratory conditions including chronic bronchitis and emphysema. COPD is often associated with heavy smokers, although it can affect individuals that never smoked. In chronic bronchitis, the walls of the bronchioles are chronically inflamed, reducing the volume of the lumen and marked by an over-production of mucus that can obstruct the movement of air during ventilation. In emphysema, the alveolar walls lose their elasticity and are destroyed, often by a build-up of damage and debris being cleaned up by alveolar macrophages (Figure 20.4.2). The damage leads to fibrosis in which normal tissue is replaced by scar tissue, further reducing the elasticity of the alveolar walls and perpetuating the progression fo the disease.

Patients with COPD can have shortness of breath and can have difficulty in particular with expiration, which affects the efficiency of ventilation. Coupled with alveolar damage, the result is reduced oxygen levels in the blood, which can affect the function of many systems of the body. Bronchodilators and anti-inflammatory medications are typically used to treat COPD. Eventually, in those with severe COPD, even treatment with supplemental oxygen will not be sufficient to prevent respiratory failure.

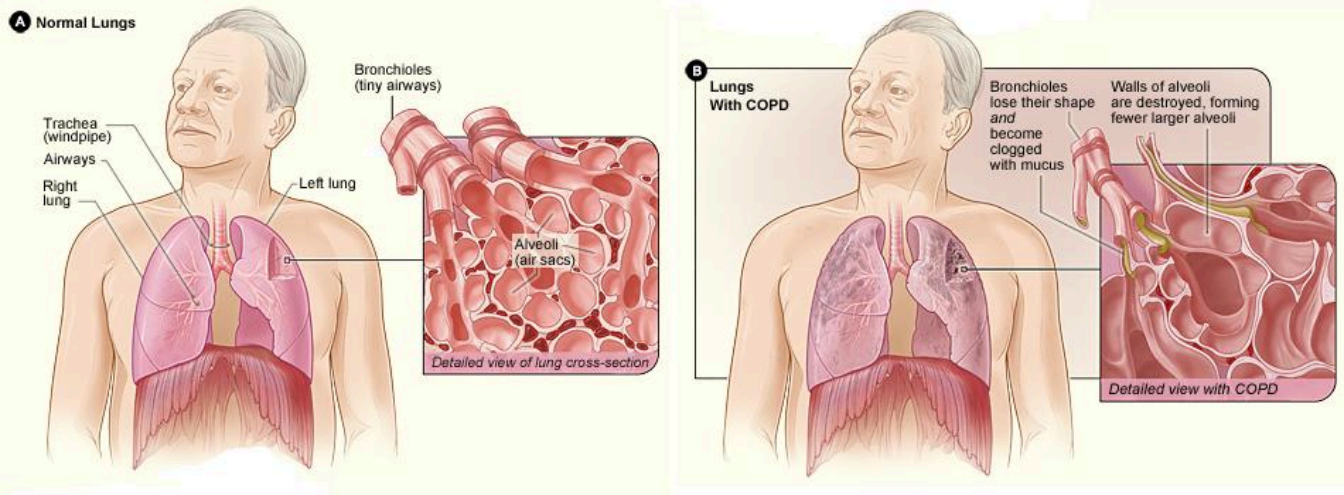

Figure 20.4.2: Chronic Obstructive Pulmonary Disorder. Lungs with COPD contain fewer alveoli after the walls between adjacent alveoli are destroyed, forming fewer, larger alveoli and reducing the surface area for gas exchange. Bronchioles lose their shape and are clogged with excessive mucus. (Image credit: "COPD_2010Side" by National Heart Lung and Blood Institute is in the Public Domain)

Respiratory Rate and Control of Ventilation

Breathing usually occurs without thought, although at times you can consciously control it, such as when you swim under water, sing a song, or blow bubbles. The **respiratory rate** is the total number of breaths, or respiratory cycles, that occur each minute. Respiratory rate can be an important indicator of disease, as the rate may increase or decrease during an illness or in a disease condition. The respiratory rate is controlled by the respiratory center located within the medulla oblongata in the brain, which responds primarily to input received from central and peripheral chemoreceptors that sense carbon dioxide and blood pH. While blood oxygen levels are not the primary drive of respiratory rate, the respiratory center will receive input if they get dangerously low.

The normal respiratory rate of a child decreases from birth to adolescence. A child under 1 year of age has a normal respiratory rate between 30 and 60 breaths per minute, but by the time a child is about 10 years old, the normal rate is closer to 18 to 30. By adolescence, the normal respiratory rate is similar to that of adults, 12 to 18 breaths per minute.

DISORDERS OF THE...

Respiratory System: Sleep Apnea

Sleep apnea is a chronic disorder that can occur in children or adults, and is characterized by the cessation of breathing during sleep. These episodes may last for several seconds or several minutes, and may differ in the frequency with which they are experienced. Sleep apnea leads to poor sleep, which is reflected in the symptoms of fatigue, evening napping, irritability, memory problems, and morning headaches. In addition, many individuals with sleep apnea experience a dry throat in the morning after waking from sleep, which may be due to excessive snoring.

There are two types of sleep apnea: obstructive sleep apnea and central sleep apnea. Obstructive sleep apnea is caused by an obstruction of the airway during sleep, which can occur at different points in the airway, depending on the underlying cause of the obstruction. For example, the tongue and throat muscles of some individuals with obstructive sleep apnea may relax excessively, causing the muscles to push into the airway. Another example is obesity, which is a known risk factor for sleep apnea, as excess adipose tissue in the neck region can push the soft tissues towards the lumen of the airway, causing the trachea to narrow.

In central sleep apnea, the respiratory centers of the brain do not respond properly to rising carbon dioxide levels and therefore do not stimulate the contraction of the diaphragm and intercostal muscles regularly. As a result, inspiration does not occur and breathing stops for a short period. In some cases, the cause of central sleep apnea is unknown. However,

some medical conditions, such as stroke and congestive heart failure, may cause damage to the pons or medulla oblongata. In addition, some pharmacologic agents, such as morphine, can affect the respiratory centers, causing a decrease in the respiratory rate. The symptoms of central sleep apnea are similar to those of obstructive sleep apnea.

A diagnosis of sleep apnea is usually done during a sleep study, where the patient is monitored in a sleep laboratory for several nights. The patient's blood oxygen levels, heart rate, respiratory rate, and blood pressure are monitored, as are brain activity and the volume of air that is inhaled and exhaled. Treatment of sleep apnea commonly includes the use of a device called a continuous positive airway pressure (CPAP) machine during sleep. The CPAP machine has a mask that covers the nose, or the nose and mouth, and forces air into the airway at regular intervals. This pressurized air can help to gently force the airway to remain open, allowing more normal ventilation to occur. Other treatments include lifestyle changes to decrease weight, eliminate alcohol and other sleep apnea–promoting drugs, and changes in sleep position. In addition to these treatments, patients with central sleep apnea may need supplemental oxygen during sleep.

Respiration and Transport of Gases

External respiration is the process of **gas exchange** between the air in the alveoli of the lungs and the blood in capillaries wrapped around them. Oxygen moves by simple diffusion from an area of higher concentration in the air across two simple squamous epithelium linings: the first lining the alveolus and the second lining the blood capillary. The oxygen then moves into an erythrocyte and binds to a molecule of hemoglobin. In exchange, carbon dioxide moves from the blood into the alveolus by the same process in the reverse direction.

Once oxygen binds to hemoglobin in the bloodstream of the pulmonary circuit, it is transported back to the heart and then delivered to another capillary bed at a tissue of the body via the systemic circuit. Carbon dioxide is a metabolic waste product that travels through the bloodstream from the tissues so it may be eliminated from the body during expiration. Some carbon dioxide travels in erythrocytes, but most of it travels in the plasma and may be in the form of carbonic acid (a weak acid) or sodium bicarbonate (a weak base) to help balance the pH of the blood. Thereby, levels of carbon dioxide eliminated during expiration may be adjusted to help balance blood pH. In these ways, blood acts as the medium of **transport of respiratory gases**.

Internal respiration is the process of gas exchange between the blood in capillaries at the cells of the tissues of the body. The process is similar to that of external respiration, but in the reverse direction: oxygen moves by simple diffusion from the capillary into the cells while carbon dioxide moves by simple diffusion from the cells into the capillary. The mitochondria of the cells in the destination tissue will use the oxygen to complete **cellular respiration**, the chemical process by which glucose is converted to ATP cellular energy to power various activities of the cell. Carbon dioxide is produced as a metabolic waste product of cellular respiration and must be removed from the tissue and transported for elimination from the body.

Concept Review

Pulmonary ventilation is the process of breathing, which is driven by pressure differences between the lungs and the atmosphere. Pulmonary ventilation consists of the process of inspiration (or inhalation), where air enters the lungs, and expiration (or exhalation), where air leaves the lungs. During inspiration, the diaphragm and external intercostal muscles contract, causing the rib cage to expand and move outward, and expanding the thoracic cavity and lung volume. This creates a lower pressure within the lung than that of the atmosphere, causing air to be drawn into the lungs. During expiration, the diaphragm and intercostals relax, causing the thorax and lungs to recoil. The air pressure within the lungs increases to above the pressure of the atmosphere, causing air to be forced out of the lungs. However, during forced exhalation, the internal intercostals and abdominal muscles may be involved in forcing air out of the lungs.

Both respiratory rate and depth are controlled by the respiratory centers of the brain, which are stimulated by factors such as chemical and pH changes in the blood. A rise in carbon dioxide or a decline in oxygen levels in the blood stimulates an increase in respiratory rate and depth.

External respiration is the process of gas exchange that occurs between the alveoli and the bloodstream. Transport of gases describes the movement of oxygen and carbon dioxide through the bloodstream from where each gas originates to its destination in the body. Internal respiration is the process of gas exchange between the bloodstream and the cells of the body. Cellular respiration is the metabolic process of consuming oxygen to convert glucose into ATP energy.

Review Questions

Q. Which of the following processes does atmospheric pressure play a role in?

A. pulmonary ventilation

B. production of pulmonary surfactant

C. resistance

D. surface tension

Answer

A

Q. A decrease in volume leads to a(n) _____ pressure.

A. decrease in

B. equalization of

C. increase in

D. zero

Answer

C

Critical Thinking Questions

Q. What is respiratory rate and how is it controlled?

Answer

Respiratory rate is defined as the number of breaths taken per minute. Respiratory rate is controlled by the respiratory center, located in the medulla oblongata. Conscious thought can alter the normal respiratory rate through control by skeletal muscle, although one cannot consciously stop the rate altogether. A typical resting respiratory rate is about 14 breaths per minute.

Glossary

atmospheric pressure
amount of force that is exerted by gases in the air surrounding any given surface

Boyle's law
relationship between volume and pressure as described by the formula: $P_1V_1 = P_2V_2$

expiration
(also, exhalation) process that causes the air to leave the lungs

inspiration
(also, inhalation) process that causes air to enter the lungs

pulmonary ventilation
exchange of gases between the lungs and the atmosphere; breathing

respiratory rate
: total number of breaths taken each minute

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20.5: Embryonic Development of the Respiratory System

By the end of this section, you will be able to:

- Create a timeline of the phases of respiratory development in the fetus
- Propose reasons for fetal breathing movements
- Explain how the lungs become inflated after birth

Development of the respiratory system begins early in the fetus. It is a complex process that includes many structures, most of which arise from the endoderm. Towards the end of development, the fetus can be observed making breathing movements. Until birth, however, the mother provides all of the oxygen to the fetus as well as removes all of the fetal carbon dioxide via the placenta.

Time Line

The development of the respiratory system begins at about week 4 of gestation. By week 28, enough alveoli have matured that a baby born prematurely at this time can usually breathe on its own. The respiratory system, however, is not fully developed until early childhood, when a full complement of mature alveoli is present.

Weeks 4–7

Respiratory development in the embryo begins around week 4. Ectodermal tissue from the anterior head region invaginates posteriorly to form olfactory pits, which fuse with endodermal tissue of the developing pharynx. An **olfactory pit** is one of a pair of structures that will enlarge to become the nasal cavity. At about this same time, the lung bud forms. The **lung bud** is a dome-shaped structure composed of tissue that bulges from the foregut. The **foregut** is endoderm just inferior to the pharynx, surrounded by splanchnic mesoderm. Eventually, the epithelial tissues of the trachea, bronchi, and lungs form from the endoderm while the smooth muscle and connective tissues of the trachea, bronchi, and lungs, as well as the visceral pleura, develop from the splanchnic mesoderm. The **laryngotracheal tube** is a structure that forms from the longitudinal extension of the lung bud as development progresses. The portion of this structure nearest the pharynx becomes the trachea, whereas the distal end becomes more bulbous and bifurcates, forming bronchial buds. A **bronchial bud** is one of a pair of structures that will eventually become the bronchi and all other lower respiratory structures (Figure 20.5.1).

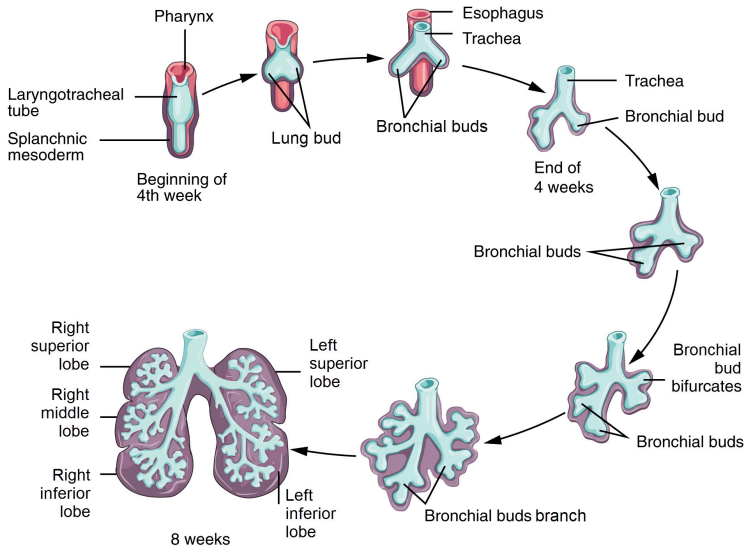

Figure 20.5.1: Development of the Lower Respiratory System. The respiratory passages begin to develop from the developing pharynx during week 4 of gestation when the laryngotracheal tube forms and then elongates, forming the trachea and bronchial buds. In the weeks that follow, the bronchial buds continue to elongate and branch further, forming the branches of the bronchial tree. Superficial tissues of the respiratory passages and the lobes of the lungs develop from splanchnic mesoderm. (Image credit: "Development of the Lower Respiratory System" by Julie Jenks is licensed under CC BY 4.0 / A derivative from the original work)

Weeks 7–16

Bronchial buds continue to branch as development progresses until all of the segmental bronchi have been formed. Beginning around week 13, the lumens of the bronchi begin to expand in diameter. By week 16, respiratory bronchioles form. The fetus now has the beginnings of all major lung structures involved in the airway.

Weeks 16–24

Once the respiratory bronchioles form, further development includes extensive vascularization, or the development of the blood vessels, as well as the formation of alveolar ducts and alveolar precursors. At about week 19, the respiratory bronchioles have formed. In addition, cells lining the respiratory structures begin to differentiate to form type I and type II alveolar cells. Once type II alveolar cells have differentiated, they begin to secrete small amounts of pulmonary surfactant. Around week 20, fetal breathing movements may begin.

Weeks 24–Term

Major growth and maturation of the respiratory system occurs from week 24 until term. More alveolar precursors develop, and larger amounts of pulmonary surfactant are produced. Surfactant levels are not generally adequate to create effective lung compliance, or a change in lung volume as the result of a change in pressure, until about the eighth month of pregnancy. The respiratory system continues to expand, and the surfaces that will form the respiratory membrane develop further. At this point, pulmonary capillaries have formed and continue to expand, creating a large surface area for gas exchange. The major milestone of respiratory development occurs at around week 28, when sufficient alveolar precursors have matured so that a baby born prematurely at this time can usually breathe on its own. However, alveoli continue to develop and mature into childhood. A full complement of functional alveoli does not form until around 8 years of age.

Fetal “Breathing”

Although the function of fetal breathing movements is not entirely clear, they can be observed starting at 20–21 weeks of development. Fetal breathing movements involve muscle contractions that cause the inhalation of amniotic fluid and exhalation of the same fluid, with pulmonary surfactant and mucus. Fetal breathing movements are not continuous and may include periods of frequent movements and periods of no movements. Maternal factors can influence the frequency of breathing movements. For

example, high blood glucose levels, called hyperglycemia, can boost the number of breathing movements. Conversely, low blood glucose levels, called hypoglycemia, can reduce the number of fetal breathing movements. Tobacco use is also known to lower fetal breathing rates. Fetal breathing may help tone the muscles in preparation for breathing movements once the fetus is born. It may also help the alveoli to form and mature. Fetal breathing movements are considered a sign of robust health.

Birth

Prior to birth, the lungs are filled with amniotic fluid, mucus, and surfactant. As the fetus is squeezed through the birth canal, the fetal thoracic cavity is compressed, expelling much of this fluid. Some fluid remains, however, but is rapidly absorbed by the body shortly after birth. The first inhalation occurs within 10 seconds after birth and not only serves as the first inspiration, but also acts to inflate the lungs. Pulmonary surfactant is critical for inflation to occur, as it reduces the surface tension of the alveoli. Preterm birth around 26 weeks frequently results in severe respiratory distress, although with current medical advancements, some babies may survive. Prior to 26 weeks, sufficient pulmonary surfactant is not produced, and the surfaces for gas exchange have not formed adequately; therefore, survival is low.

DISORDERS OF THE...

Respiratory System: Respiratory Distress Syndrome

Respiratory distress syndrome (RDS) primarily occurs in infants born prematurely. Up to 50 percent of infants born between 26 and 28 weeks and fewer than 30 percent of infants born between 30 and 31 weeks develop RDS. RDS results from insufficient production of pulmonary surfactant, thereby preventing the lungs from properly inflating at birth. A small amount of pulmonary surfactant is produced beginning at around 20 weeks; however, this is not sufficient for inflation of the lungs. As a result, dyspnea occurs and gas exchange cannot be performed properly. Blood oxygen levels are low, whereas blood carbon dioxide levels and pH are high.

The primary cause of RDS is premature birth, which may be due to a variety of known or unknown causes. Other risk factors include gestational diabetes, cesarean delivery, second-born twins, and family history of RDS. The presence of RDS can lead to other serious disorders, such as septicemia (infection of the blood) or pulmonary hemorrhage. Therefore, it is important that RDS is immediately recognized and treated to prevent death and reduce the risk of developing other disorders.

Medical advances have resulted in an improved ability to treat RDS and support the infant until proper lung development can occur. At the time of delivery, treatment may include resuscitation and intubation if the infant does not breathe on his or her own. These infants would need to be placed on a ventilator to mechanically assist with the breathing process. If spontaneous breathing occurs, application of nasal continuous positive airway pressure (CPAP) may be required. In addition, a laboratory synthesized form of pulmonary surfactant is typically administered. Death due to RDS has been reduced by 50 percent due to the introduction of pulmonary surfactant therapy. Other therapies may include corticosteroids, supplemental oxygen, and assisted ventilation. Supportive therapies, such as temperature regulation, nutritional support, and antibiotics, may be administered to the premature infant as well.

Concept Review

The development of the respiratory system in the fetus begins at about 4 weeks and continues into childhood. Ectodermal tissue in the anterior portion of the head region invaginates posteriorly, forming olfactory pits, which ultimately fuse with endodermal tissue of the early pharynx. At about this same time, a protrusion of endodermal tissue extends anteriorly from the foregut, producing a lung bud, which continues to elongate until it forms the laryngotracheal bud. The proximal portion of this structure will mature into the trachea, whereas the bulbous end will branch to form two bronchial buds. These buds then branch repeatedly, so that at about week 16, all major airway structures are present. Development progresses after week 16 as respiratory bronchioles and alveolar ducts form, and extensive vascularization occurs. Type I alveolar cells also begin to take shape. Type II alveolar cells develop and begin to produce small amounts of surfactant. As the fetus grows, the respiratory system continues to expand as more alveoli develop and more surfactant is produced. Beginning at about week 36 and lasting into childhood, alveolar precursors mature to become fully functional alveoli. At birth, compression of the thoracic cavity forces much of the fluid in the lungs to be expelled. The first inhalation inflates the lungs. Fetal breathing movements begin around week 20 or 21, and occur when contractions of the respiratory muscles cause the fetus to inhale and exhale amniotic fluid. These movements continue until birth, which may help to tone the muscles in preparation for breathing after birth, and are a sign of good health.

Review Questions

Q. The olfactory pits form from which of the following?

A. mesoderm

B. cartilage

C. ectoderm

D. endoderm

Answer

C

Q. A full complement of mature alveoli are present by _____.

A. early childhood, around 8 years of age

B. birth

C. 37 weeks

D. 16 weeks

Answer

A

Q. If a baby is born prematurely before type II alveolar cells produce sufficient pulmonary surfactant, which of the following might you expect?

A. difficulty expressing fluid

B. difficulty inflating the lungs

C. difficulty with pulmonary capillary flow

D. no difficulty as type I alveolar cells can provide enough surfactant for normal breathing

Answer

B

Q. When do fetal breathing movements begin?

A. around week 20

B. around week 37

C. around week 16

D. after birth

Answer

A

Critical Thinking Questions

Q. During what timeframe does a fetus have enough mature structures to breathe on its own if born prematurely? Describe the other structures that develop during this phase.

Answer

At about week 28, enough alveolar precursors have matured so that a baby born prematurely at this time can usually breathe on its own. Other structures that develop about this time are pulmonary capillaries, expanding to create a large surface area for gas exchange. Alveolar ducts and alveolar precursors have also developed.

Q. Describe fetal breathing movements and their purpose.

Answer

Fetal breathing movements occur due to the contraction of respiratory muscles, causing the fetus to inhale and exhale amniotic fluid. It is thought that these movements are a way to “practice” breathing, which results in toning the muscles in preparation for breathing after birth. In addition, fetal breathing movements may help alveoli to form and mature.

Glossary

bronchial bud
structure in the developing embryo that forms when the laryngotracheal tube extends and branches to form two bulbous structures

foregut
endoderm of the embryo towards the head region

laryngotracheal tube
tube that forms from the lung bud, has a tracheal end and bulbous bronchial buds at the distal end

lung bud
median dome that forms from the endoderm of the foregut

olfactory pit
invaginated ectodermal tissue in the anterior portion of the head region of an embryo that will form the nasal cavity

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21: DIGESTIVE SYSTEM

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21.1: Introduction to the Digestive System

21.2: Organs of the Digestive System

21.3: Digestive System Processes and Regulation

21.4: Mouth, Pharynx, and Esophagus

21.5: Stomach

21.6: Small and Large Intestines

21.7: Accessory Organs in Digestion- Liver, Pancreas, and Gallbladder

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21.1: Introduction to the Digestive System

Chapter Learning Objectives:

After studying this chapter, you will be able to:

- List and describe the functional anatomy of the organs and accessory organs of the digestive system
- Discuss how food moves through the digestive tract
- Discuss the anatomy of the accessory organs of the digestive system, which include liver, pancreas, and gallbladder

The digestive system is continually at work, yet people seldom appreciate the complex tasks it performs in a choreographed biologic symphony. Consider what happens when you eat an apple. Of course, you enjoy the apple's taste as you chew it, but in the hours that follow, unless something goes amiss and you get a stomachache, you don't notice that your digestive system is working. You may be taking a walk or studying or sleeping, having forgotten all about the apple, but your stomach and intestines are busy digesting it and absorbing its vitamins and other nutrients. By the time any waste material is excreted, the body has appropriated all it can use from the apple. In short, whether you pay attention or not, the organs of the digestive system perform their specific functions, allowing you to use the food you eat to keep you going. This chapter examines the structure of these organs, and explores the mechanics of the digestive system processes.

Figure 21.1.1: Eating Apples. Eating may be one of the simple pleasures in life, but digesting even one apple requires the coordinated work of many organs. (credit: "Aimanness Photography"/Flickr)

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21.2: Organs of the Digestive System

By the end of the section, you will be able to:

- Identify the organs of the alimentary canal from proximal to distal, and briefly state their functions
- Identify the accessory digestive organs and briefly state their primary function
- Describe the four fundamental tissue layers of the alimentary canal
- Contrast the contributions of the enteric and autonomic nervous systems to digestive system functioning
- Describe the structure and function of the peritoneum and mesenteries

The function of the digestive system is to break down the foods you eat by secreting enzymes to mix with food, release their nutrients, and absorb those nutrients into the body. Although the small intestine is the workhorse of the system, where the majority of digestion occurs, and where most of the released nutrients are absorbed into the blood or lymph, each of the digestive system organs makes a vital contribution to this process (Figure 21.2.1). The picture below shows all the organs of the digestive tract, a long tube that starts with the mouth, to the esophagus, stomach, small intestine, large intestine, and ending at the anus. The picture also shows some accessory digestive organs, such as the salivary glands, liver, gall bladder, and pancreas. The different organs and structures are briefly discussed below. The rest of this chapter will cover the details of each organ.

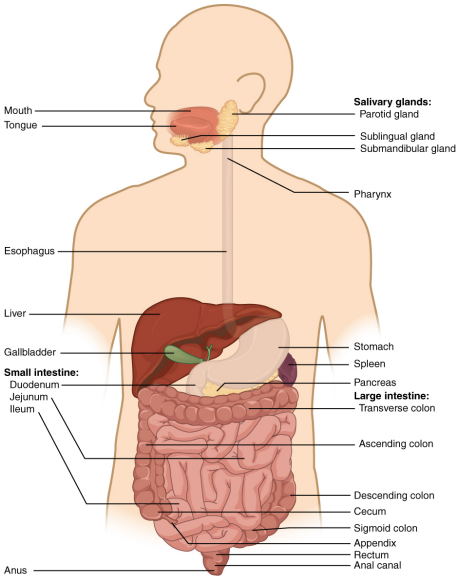

Figure 21.2.1: Structures of the Digestive System. The image displays the major organs of the digestive tract, as well as the accessory organs (liver, pancreas and gallbladder). All digestive organs play integral roles in the life-sustaining process of digestion. (Image credit: "Components of the Digestive System" by OpenStax is licensed under CC BY 3.0)

As is the case with all body systems, the digestive system does not work in isolation; it functions cooperatively with the other systems of the body. Consider for example, the interrelationship between the digestive and cardiovascular systems. Arteries supply the digestive organs with oxygen and processed nutrients, and veins drain the digestive tract. These intestinal veins, constituting the hepatic portal system, are unique; they do not return blood directly to the heart. Rather, this blood is diverted to the liver where its nutrients are off-loaded for processing before blood completes its circuit back to the heart. At the same time, the digestive system provides nutrients to the heart muscle and vascular tissue to support their functioning. The interrelationship of the digestive and endocrine systems is also critical. Hormones secreted by several endocrine glands, as well as endocrine cells of the pancreas, the stomach, and the small intestine, contribute to the control of digestion and nutrient metabolism. In turn, the digestive system provides the nutrients to fuel endocrine function. Table 21.2.1 gives a quick glimpse at how these other systems contribute to the functioning of the digestive system.

Table 21.2.1: Contribution of Other Body Systems to the Digestive System

Body system	Benefits received by the digestive system
Cardiovascular	Blood supplies digestive organs with oxygen and processed nutrients
Endocrine	Endocrine hormones help regulate secretion in digestive glands and accessory organs
Integumentary	Skin helps protect digestive organs and synthesizes vitamin D for calcium absorption
Lymphatic	Mucosa-associated lymphoid tissue (MALT) and other lymphatic tissue defend against entry of pathogens; lacteals absorb lipids; and lymphatic vessels transport lipids to bloodstream
Muscular	Skeletal muscles support and protect abdominal organs
Nervous	Sensory and motor neurons help regulate secretions and muscle contractions in the digestive tract
Respiratory	Respiratory organs provide oxygen and remove carbon dioxide
Skeletal	Bones help protect and support digestive organs
Urinary	Kidneys convert vitamin D into its active form, allowing calcium absorption in the small intestine

Digestive System Organs

The easiest way to understand the digestive system is to divide its organs into two main categories. The first group is the organs that make up the alimentary canal, also known as the digestive tract or gastrointestinal (GI) tract. Accessory digestive organs comprise the second group and are critical for orchestrating the breakdown of food and the assimilation of its nutrients into the body. Accessory digestive organs, despite their name, are critical to the function of the digestive system.

Alimentary Canal Organs

Also called the digestive tract, gastrointestinal (GI) tract or gut, the alimentary canal (aliment- = "to nourish") is a one-way tube about 7.62 meters (25 feet) in length during life and closer to 10.67 meters (35 feet) in length when measured after death, once smooth muscle tone is lost. The main function of the organs of the alimentary canal is to nourish the body. This tube begins at the mouth and terminates at the anus. Between those two points, the canal is modified as the pharynx, esophagus, stomach, and small and large intestines to fit the functional needs of the body. In this system, relative locations closer to the mouth are considered "proximal" and further from the mouth (closer to the anus) are considered "distal". Both the mouth and anus are open to the external environment; thus, food and wastes within the alimentary canal are technically considered to be outside the body. Only through the process of absorption, moving from digestive organs into the blood, do the nutrients in food enter into and nourish the body's "inner space."

Accessory Structures

Each accessory digestive organ aids in the breakdown of food (Figure 21.2.1. Within the mouth, the teeth and tongue begin mechanical digestion, whereas the salivary glands begin chemical digestion. Once food products enter the small intestine, the gallbladder, liver, and pancreas release secretions—such as bile and enzymes—essential for digestion to continue. Together, these are called accessory organs because they sprout from the lining cells of the developing gut (mucosa) and augment its function; indeed, you could not live without the vital contributions from the liver and pancreas, and many significant diseases result from their malfunction. Even after development is complete, they maintain a connection to the gut by way of ducts.

Histology of the Alimentary Canal

Throughout its length, the alimentary tract is composed of the same four tissue layers; the details of their structural arrangements vary to fit the specific functions of each organ or region. Starting from the lumen and moving outwards, these layers are the mucosa, submucosa, muscularis, and serosa, which is continuous with the mesentery (see Figure 21.2.2. The picture below also shows the details in each layer, which will be discussed in the paragraphs below. The image also shows the blood vessels and nerve sandwiched between the two layers called mesentery. More details about mesentery are found in upcoming paragraphs in this section.

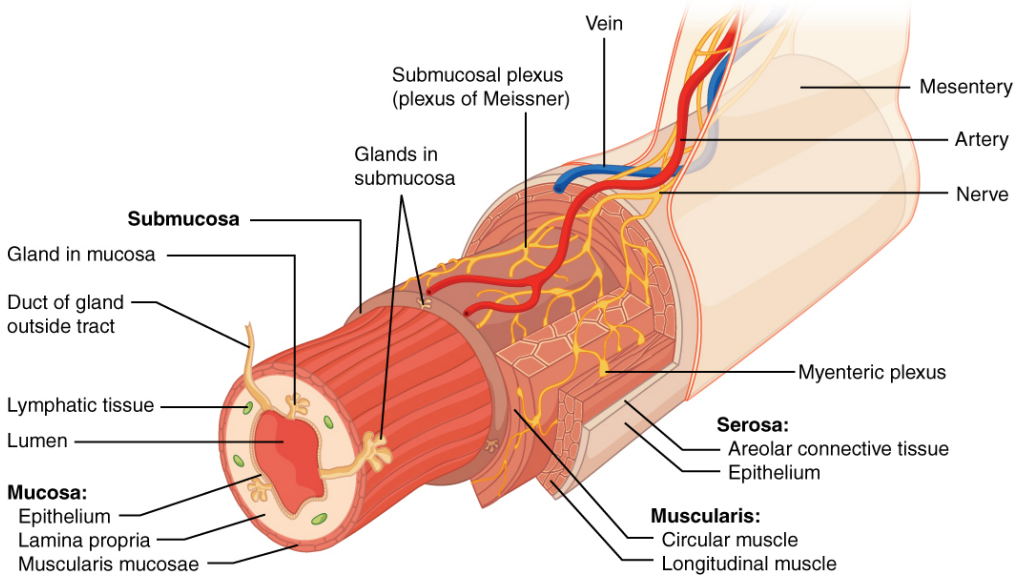

Figure 21.2.2: Layers of the Alimentary Canal. From inner to outer, the wall of the alimentary canal has four basic tissue layers: the mucosa, submucosa, muscularis, and serosa. Mesentery is seen with vessels and nerves sandwiched in between. (Image credit: "Layers of the Gastrointestinal Tract" by OpenStax is licensed under CC BY 3.0)

The **mucosa** is referred to as a mucous membrane, because mucus production is a characteristic feature of gut epithelium. The membrane consists of epithelium, which is in direct contact with ingested food, and the lamina propria, a layer of dense irregular connective tissue analogous to the dermis. In addition, the mucosa has a thin, smooth muscle layer, called the muscularis mucosa (not to be confused with the muscularis layer, described below).

Epithelium—In the mouth, pharynx, esophagus, and anal canal, the epithelium is primarily a non-keratinized, stratified squamous epithelium. In the stomach and intestines, it is a simple columnar epithelium. Notice that the epithelium is in direct contact with the lumen, the space inside the alimentary canal. Interspersed among its epithelial cells are goblet cells, which secrete mucus and fluid into the lumen, and enteroendocrine cells, which secrete hormones into the interstitial spaces between cells. Epithelial cells have a very brief lifespan, averaging from only a couple of days (in the mouth) to about a week (in the gut). This process of rapid renewal helps preserve the health of the alimentary canal, despite the wear and tear resulting from continued contact with foodstuffs.

Lamina propria—In addition to loose connective tissue, the lamina propria contains numerous blood and lymphatic vessels that transport nutrients absorbed through the alimentary canal to other parts of the body. The lamina propria also serves an immune function by housing clusters of lymphocytes, making up the mucosa-associated lymphoid tissue (MALT). These lymphocyte clusters are particularly substantial in the distal ileum where they are known as Peyer's patches. When you consider that the alimentary canal is exposed to foodborne bacteria and other foreign matter, it is not hard to appreciate why the immune system has evolved a means of defending against the pathogens encountered within it.

Muscularis mucosa—This thin layer of smooth muscle is in a constant state of tension, pulling the mucosa of the stomach and small intestine into undulating folds. These folds dramatically increase the surface area available for digestion and absorption.

As its name implies, the **submucosa** lies immediately beneath the mucosa. A broad layer of dense irregular connective tissue, it lies between the mucosa and the muscularis. It includes blood and lymphatic vessels (which transport absorbed nutrients), and a scattering of submucosal glands that release digestive secretions. Additionally, it serves as a conduit for a dense branching network of nerves, the submucosal plexus, which functions as described below.

The third layer of the alimentary canal is the **muscularis** (also called the **muscularis externa**). The muscularis in the small intestine is made up of a double layer of smooth muscle: an inner circular layer, forming a ring around the tube, and an outer longitudinal layer that runs the length of the tube. The contractions of these layers promote mechanical digestion, expose more of the food to digestive chemicals, and move the food along the canal. In the most proximal and distal regions of the alimentary canal, including the mouth, pharynx, anterior part of the esophagus, and external anal sphincter, the muscularis is made up of skeletal muscle, which gives you voluntary control over swallowing and defecation. The basic two-layer structure found in the small intestine is modified in the organs proximal and distal to it. The stomach is equipped for its churning function by the addition of a third layer, the oblique muscle. While the colon has two layers like the small intestine, its longitudinal layer is segregated into

three narrow parallel bands, the teniae coli, which make it look like a series of pouches rather than a simple tube. The myenteric plexus (plexus of Auerbach) is a network of nerves to stimulate the muscles, lies in the muscularis layer.

The **serosa** is the portion of the alimentary canal superficial to the muscularis. Present only in the region of the alimentary canal within the abdominal cavity, it consists of a layer of visceral peritoneum overlying a layer of loose connective tissue. Instead of serosa, the mouth, pharynx, and esophagus have a dense sheath of collagen fibers called the adventitia. These tissues serve to hold the alimentary canal in place near the ventral surface of the vertebral column.

Nerve Supply

As soon as food enters the mouth, it is detected by receptors that send impulses along the sensory neurons of cranial nerves. Without these nerves, not only would your food be without taste, but you would also be unable to feel either the food or the structures of your mouth. Without these nerves, you would could bite yourself as you chew, an action enabled by the motor branches of cranial nerves.

Intrinsic (within) innervation of much of the alimentary canal is provided by the enteric nervous system, which runs from the esophagus to the anus, and contains approximately 100 million motor, sensory, and interneurons (unique to this system compared to all other parts of the peripheral nervous system). These enteric neurons are grouped into two plexuses. The myenteric plexus (plexus of Auerbach) lies in the muscularis layer of the alimentary canal and is responsible for motility, especially the rhythm and force of the contractions of the muscularis. The submucosal plexus (plexus of Meissner) lies in the submucosal layer and is responsible for regulating digestive secretions and reacting to the presence of food (see Figure 21.2.2.

Extrinsic innervations of the alimentary canal are provided by the autonomic nervous system communicating with the enteric nervous system. In general, sympathetic activation (the fight-or-flight response) restricts the activity of enteric neurons, thereby decreasing GI secretion and motility. In contrast, parasympathetic activation (the rest-and-digest response) increases GI secretion and motility by stimulating neurons of the enteric nervous system.

Blood Supply

The blood vessels serving the digestive system have two functions. They transport the protein and carbohydrate nutrients absorbed by mucosal cells after food is digested in the lumen. Lipids are absorbed via lacteals, tiny structures of the lymphatic system. The blood vessels' second function is to supply the organs of the alimentary canal with the nutrients and oxygen needed to drive their cellular processes.

Specifically, the more anterior parts of the alimentary canal are supplied with blood by arteries branching off the aortic arch and thoracic aorta. Below this point, the alimentary canal is supplied with blood by arteries branching from the abdominal aorta. The celiac trunk services the liver, stomach, and duodenum, whereas the superior and inferior mesenteric arteries supply blood to the remaining small and large intestines.

The veins that collect nutrient-rich blood from the small intestine (where most absorption occurs) and the spleen, empty into the hepatic portal system. This venous network takes the blood into the liver where the nutrients are either processed or stored for later use. Only then does the blood drained from the alimentary canal viscera and the spleen (not a digestive organ) circulate back to the heart. To appreciate just how demanding the digestive process is on the cardiovascular system, consider that while you are "resting and digesting," about one-fourth of the blood pumped with each heartbeat enters arteries serving the intestines.

Peritoneum

The digestive organs within the abdominal cavity are held in place by the peritoneum, a broad serous membranous sac made up of squamous epithelial tissue, also known as mesothelium, surrounded by areolar connective tissue. It is composed of two different regions: the parietal peritoneum, which lines the abdominal wall, and the visceral peritoneum, which envelopes the abdominal organs (Figure 21.2.3). This image shows a cross-section of the upper abdomen with organs labeled as vertebra, kidney, pancreas, liver, gallbladder, stomach, and spleen. The membrane adhering to the liver, small intestine, large intestine, stomach, and spleen is highlighted and labeled visceral peritoneum. The parietal peritoneum, also highlighted, is continuous with the visceral peritoneum and runs immediately external to the visceral peritoneum. The peritoneal cavity is the space bounded by the visceral and parietal peritoneal surfaces, filled with a small amount of water. A few milliliters of watery fluid act as a lubricant to minimize friction between the serosal surfaces of the peritoneum.

The serosa, mentioned above, is also called the visceral peritoneum. The visceral peritoneum includes multiple large folds, also called mesenteries, that connect various abdominal organs, holding them to the dorsal surface of the body (trunk) wall and in some cases, each other. The folds are created by visceral peritoneum leaving the wall of an organ to form a double layer of mesothelium sandwiching areolar connective tissue, adipose tissue, blood vessels, lymphatic vessels, and nerves that innervate the organs with which they are in contact. General functions of the peritoneal folds are to provide routes for vessels and nerves to reach intraperitoneal (within the peritoneum) organs, hold these organs to a relative location and in some cases insulate and protect other nearby organs. The five major peritoneal folds are described in Table 21.2.2 and are shown in Figure 21.2.4, Figure 21.2.5, and Figure 21.2.6. Note that during fetal development, certain digestive structures, including the first portion of the small intestine (called the duodenum), the pancreas, and portions of the large intestine (the ascending and descending colon, and the rectum) remain completely or partially posterior to the peritoneum. Thus, the location of these organs is described as retroperitoneal.

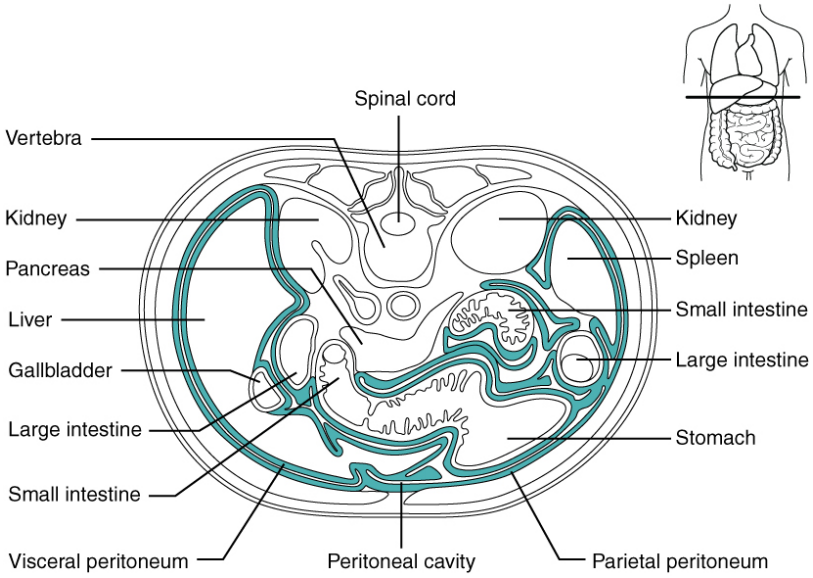

Figure 21.2.3: Peritoneum. A cross-section of the abdomen shows the relationship between abdominal organs and the peritoneum (thick blue lines). (Image credit: "The Peritoneum" by OpenStax is licensed under CC BY 3.0)

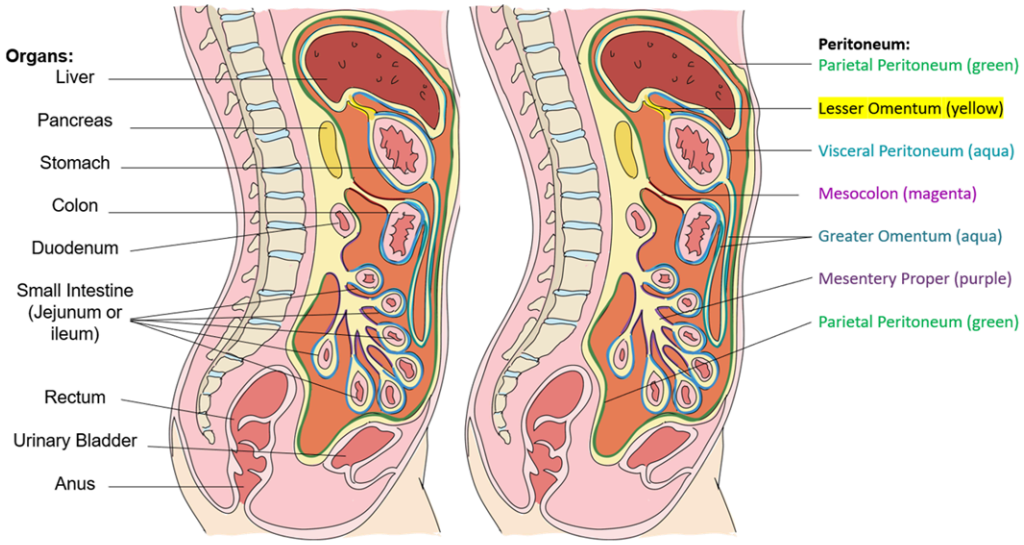

Figure 21.2.4: Midsagittal View of Peritoneum. Different regions of the peritoneum are outlined in different colors. On the left, the organs are labeled. On the right, the peritoneum and mesenteries are labeled. (Image credit: “Midsagittal View of Peritoneum" by KL Nguyen is a derivative from the original work of Daniel Donnelly is licensed under CC BY 4.0)

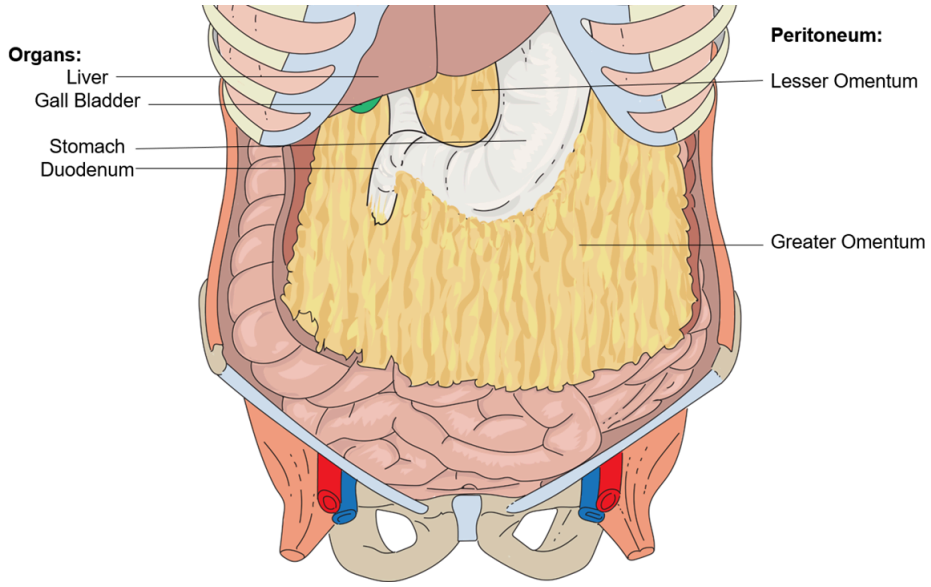

Figure 21.2.5: Anterior View of Omentum. Drawing showing the greater omentum descending from the stomach, covering most of the abdominal organs inferior to the stomach and lesser omentum extending superiorly from stomach to liver. (Image credit: "Anterior View of Omentum" by KL Nguyen is a derivative from the original work of Daniel Donnelly is licensed under CC BY 4.0)

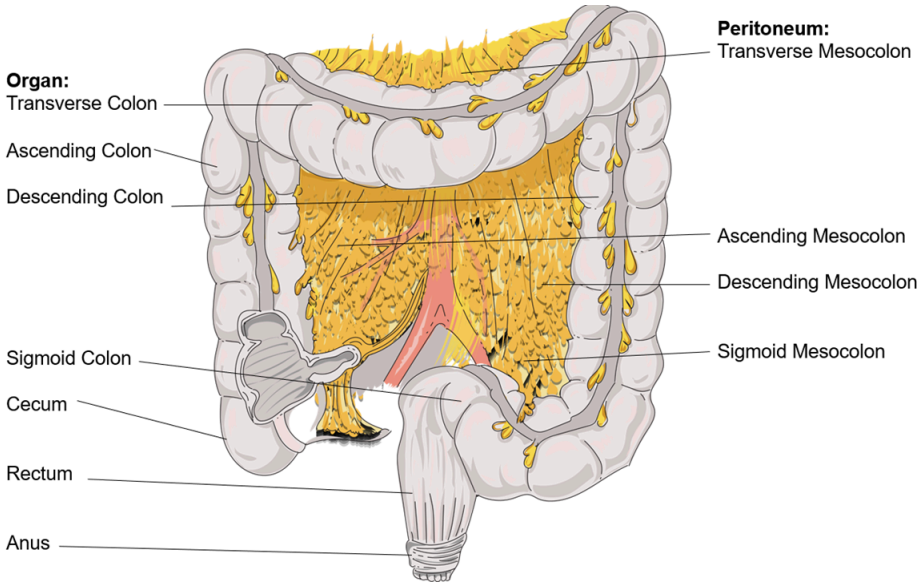

Figure 21.2.6: Mesocolon. Anterior view of abdomen posterior to greater omentum, with the stomach and small intestine reomoved, showing mesenteries attached to colon. Notice, different parts of the large intestine and the mesocolon connecting to each region share the same name. (Image credit: "Mesocolon" by KL Nguyen is a derivative from the original work of Daniel Donnelly is licensed under CC BY 4.0)

DISORDERS OF THE...

Digestive System: Peritonitis

Inflammation of the peritoneum is called peritonitis. Chemical peritonitis can develop any time the wall of the alimentary canal is breached, allowing the contents of the lumen entry into the peritoneal cavity. For example, when an ulcer perforates the stomach wall, gastric juices spill into the peritoneal cavity. Hemorrhagic peritonitis occurs after a ruptured tubal pregnancy or traumatic injury to the liver or spleen fills the peritoneal cavity with blood. Even more severe peritonitis is associated with bacterial infections seen with appendicitis, colonic diverticulitis, and pelvic inflammatory disease (infection of uterine tubes, usually by sexually transmitted bacteria). Peritonitis is life threatening and often results in emergency surgery to correct the underlying problem and intensive antibiotic therapy. When your great grandparents and even your

parents were young, the mortality from peritonitis was high. Aggressive surgery, improvements in anesthesia safety, the advance of critical care expertise, and antibiotics have greatly improved the mortality rate from this condition. Even so, the mortality rate for peritonitis still ranges from 30 to 40 percent.

Table 21.2.2: The Five Major Peritoneal Folds

Fold	Description
Greater omentum	Apron-like structure that lies superficial to the small intestine and transverse colon; a site of fat deposition in people who are overweight
Falciform ligament	Anchors the liver to the anterior abdominal wall and inferior border of the diaphragm
Lesser omentum	Suspends the stomach from the inferior border of the liver; provides a pathway for structures connecting to the liver
Mesentery proper	Vertical band of tissue anterior to the lumbar vertebrae and anchoring all of the small intestine except the initial portion (the duodenum)
Mesocolon	Attaches two portions of the large intestine (the transverse and sigmoid colon) to the posterior abdominal wall

Concept Review

The digestive system includes the organs of the alimentary canal and accessory structures. The alimentary canal forms a continuous tube that is open to the outside environment at both ends. The organs of the alimentary canal are the mouth, pharynx, esophagus, stomach, small intestine, and large intestine. The accessory digestive structures include the teeth, tongue, salivary glands, liver, pancreas, and gallbladder. The wall of the alimentary canal is composed of four basic tissue layers: mucosa, submucosa, muscularis, and serosa. The enteric nervous system provides intrinsic innervation, and the autonomic nervous system provides extrinsic innervation. Organs of the digestive system receive oxygenated blood from the abdominal aorta and send deoxygenated, nutrient rich blood, to the liver through the hepatic portal vein. The peritoneum, a serous membrane, functions to anchor abdominal organs and provides routes for vessels and nerves along with insulation in specialized regions called peritoneal folds (mesenteries).

Review Questions

Q. Which of these organs is not considered an accessory digestive structure?

A. mouth

B. salivary glands

C. pancreas

D. liver

Answer

Answer: A

Q. Which of the following organs is supported by a layer of adventitia rather than serosa?

A. esophagus

B. stomach

C. small intestine

D. large intestine

Answer

Answer: A

Q. Which of the following membranes covers the stomach?

A. falciform ligament

B. mesocolon

C. parietal peritoneum

D. visceral peritoneum

Answer

Answer: D

Critical Thinking Questions

Q. Explain how the enteric nervous system supports the digestive system. What might occur that could result in the autonomic nervous system having a negative impact on digestion?

Answer

A. The enteric nervous system helps regulate alimentary canal motility and the secretion of digestive juices, thus facilitating digestion. If a person becomes overly anxious, sympathetic innervation of the alimentary canal is stimulated, which can result in a slowing of digestive activity.

Q. What layer of the alimentary canal tissue is capable of helping to protect the body against disease, and through what mechanism?

Answer

A. The lamina propria of the mucosa contains lymphoid tissue that makes up the MALT and responds to pathogens encountered in the alimentary canal.

Glossary

accessory digestive organ
includes teeth, tongue, salivary glands, gallbladder, liver, and pancreas

alimentary canal
continuous muscular digestive tube that extends from the mouth to the anus

motility
movement of food through the GI tract

mucosa
innermost lining of the alimentary canal

muscularis
muscle (skeletal or smooth) layer of the alimentary canal wall

myenteric plexus
(plexus of Auerbach) major nerve supply to alimentary canal wall; controls motility

retroperitoneal
located posterior to the peritoneum

serosa
: outermost layer of the alimentary canal wall present in regions within the abdominal cavity

submucosa
: layer of dense connective tissue in the alimentary canal wall that binds the overlying mucosa to the underlying muscularis

submucosal plexus
: (plexus of Meissner) nerve supply that regulates activity of glands and smooth muscle

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21.3: Digestive System Processes and Regulation

By the end of the section, you will be able to:

- Discuss seven fundamental activities of the digestive system, giving an example of each
- Describes the functions of each digestive organs
- Describe the difference between mechanical digestion and chemical digestion
- Describe the difference between peristalsis and segmentation

The digestive system uses mechanical and chemical activities to break food down into absorbable substances during its journey through the digestive system. Table 21.3.1 provides an overview of the basic functions of the digestive organs.

Table 21.3.1: Functions of the Digestive Organs

Organ	Major functions	Other functions
Mouth	• Ingests food • Chews and mixes food • Begins chemical breakdown of carbohydrates with secretion of saliva • Moves food into the pharynx • Begins breakdown of lipids via lingual lipase	• Moistens and dissolves food, allowing you to taste it • Cleans and lubricates the teeth and oral cavity • Has some antimicrobial activity
Pharynx	• Propels food from the oral cavity to the esophagus	• Lubricates food and passageways
Esophagus	• Propels food to the stomach	• Lubricates food and passageways
Stomach	• Mixes and churns food with gastric juices secreted from epithelium to form chyme • Begins chemical breakdown of proteins • Releases food into the duodenum as chyme • Absorbs some fat-soluble substances (for example, alcohol, aspirin) • Possesses antimicrobial functions	• Stimulates protein-digesting enzymes • Secretes intrinsic factor required for vitamin B_{12} absorption in small intestine
Small intestine	• Mixes chyme with digestive juices secreted from pancreas, gallbladder, and small intestine • Propels food at a rate slow enough for digestion and absorption • Absorbs breakdown products of carbohydrates, proteins, lipids, and nucleic acids, along with vitamins, minerals, and water • Performs physical digestion via segmentation	• Provides optimal medium for enzymatic activity

Organ	Major functions	Other functions
Accessory organs	• Liver: produces bile salts, which emulsify lipids, aiding their digestion and absorption • Gallbladder: stores, concentrates, and releases bile • Pancreas: produces digestive enzymes and bicarbonate	• Bicarbonate-rich pancreatic juices help neutralize acidic chyme and provide optimal environment for enzymatic activity
Large intestine	• Further breaks down food residues • Absorbs most residual water, electrolytes, and vitamins produced by enteric bacteria • Propels feces toward rectum • Eliminates feces	• Food residue is concentrated and temporarily stored prior to defecation • Mucus eases passage of feces through colon

Digestive Processes

The processes of digestion include seven activities: ingestion, propulsion, mechanical or physical digestion, chemical digestion, secretion, absorption, and defecation.

The first of these processes, **ingestion**, refers to the entry of food into the alimentary canal through the mouth. There, the food is chewed and mixed with saliva secreted by salivary glands, which contains enzymes that begin breaking down the carbohydrates in the food plus some lipid digestion via lingual lipase. Chewing increases the surface area of the food and allows an appropriately sized bolus (chunk) to be produced.

Food leaves the mouth when the tongue and pharyngeal muscles propel it into the esophagus. This act of swallowing, the last voluntary act until defecation, is an example of **propulsion**, which refers to the movement of food through the digestive tract. It includes both the voluntary process of swallowing and the involuntary process of peristalsis. **Peristalsis** consists of sequential, alternating waves of contraction and relaxation of of circular and longitudinal layers of the muscularis externa (alimentary wall smooth muscles), which act to propel food along (Figure 21.3.1). These waves also play a role in mixing food with digestive juices. Peristalsis is so powerful that foods and liquids you swallow enter your stomach even if you are standing on your head.

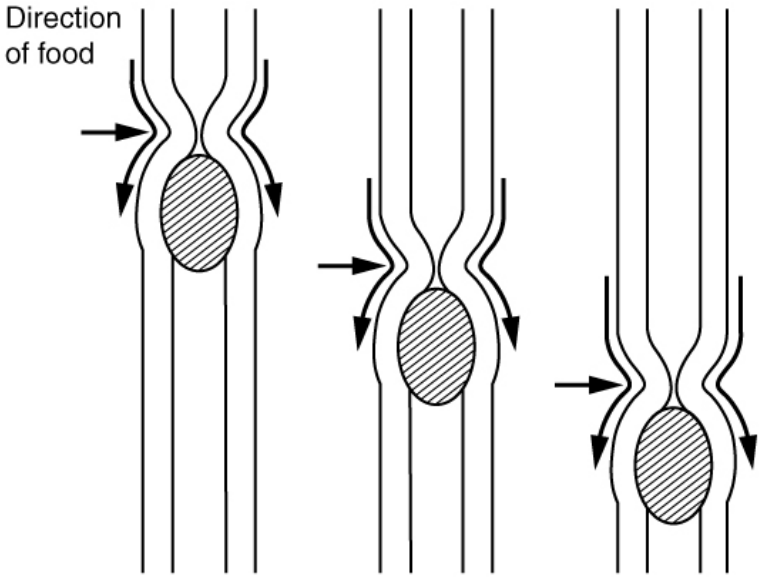

Figure 21.3.1: Peristalsis. Peristalsis moves food through the digestive tract with alternating waves of muscle contraction and relaxation. (Image credit: "Peristalsis" by OpenStax is licensed under CC BY 3.0)

Digestion includes both mechanical and chemical processes. **Mechanical digestion** is a purely physical process that does not change the chemical nature of the food. Instead, it makes the food smaller to increase both surface area and mobility. It includes

mastication, or chewing, as well as tongue movements that help break food into smaller bits and mix food with saliva. Although there may be a tendency to think that mechanical digestion is limited to the first steps of the digestive process, it occurs after the food leaves the mouth, as well. The mechanical churning of food in the stomach serves to further break it apart and expose more of its surface area to digestive juices, creating an acidic "soup" called **chyme**. **Segmentation**, which occurs mainly in the small intestine, consists of localized contractions of circular muscle of the muscularis layer of the alimentary canal. These contractions isolate small sections of the intestine, moving their contents back and forth while continuously subdividing, breaking up, and mixing the contents. By moving food back and forth in the intestinal lumen, segmentation mixes food with digestive juices and facilitates absorption.

Chemical digestion is aided by **secretion** of enzymes. Starting in the mouth, digestive secretions break down complex food molecules into their chemical building blocks (for example, proteins into separate amino acids). These secretions vary in composition, but typically contain water, various enzymes, acids, and salts. The process is completed in the small intestine.

Food that has been broken down is of no value to the body unless it enters the bloodstream and its nutrients are put to work. This occurs through the process of **absorption**, which takes place primarily within the small intestine. There, most nutrients are absorbed from the lumen of the alimentary canal into the bloodstream through the epithelial cells that make up the mucosa. Lipids are absorbed into lacteals and are transported via the lymphatic vessels to the bloodstream (the subclavian veins near the heart). The details of these processes will be discussed later.

In **defecation**, the final step in digestion, undigested materials are removed from the body as feces.

AGING AND THE...

Digestive System: From Appetite Suppression to Constipation

Age-related changes in the digestive system begin in the mouth and can affect virtually every aspect of the digestive system. Taste buds become less sensitive, so food isn't as appetizing as it once was. A slice of pizza is a challenge, not a treat, when you have lost teeth, your gums are diseased, and your salivary glands aren't producing enough saliva. Swallowing can be difficult, and ingested food moves slowly through the alimentary canal because of reduced strength and tone of muscular tissue. Neurosensory feedback is also dampened, slowing the transmission of messages that stimulate the release of enzymes and hormones.

Pathologies that affect the digestive organs—such as hiatal hernia, gastritis, and peptic ulcer disease—can occur at greater frequencies as you age. Problems in the small intestine may include duodenal ulcers, maldigestion, and malabsorption. Problems in the large intestine include hemorrhoids, diverticular disease, and constipation. Conditions that affect the function of accessory organs—and their abilities to deliver pancreatic enzymes and bile to the small intestine—include jaundice, acute pancreatitis, cirrhosis, and gallstones.

In some cases, a single organ is in charge of a digestive process. For example, ingestion occurs only in the mouth and defecation from the anus. However, most digestive processes involve the interaction of several organs and occur gradually as food moves through the alimentary canal (Figure 21.3.2). Figure 21.3.2 shows the digestive tract with the locations of propulsion, chemical digestion, mechanical digestion, and absorption in different organs.

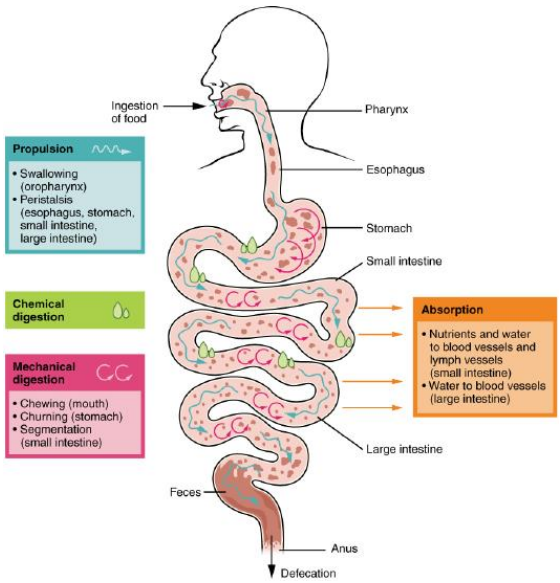

Figure 21.3.2: Digestive Processes. The digestive processes are ingestion (mouth), propulsion (GI tract), mechanical digestion (mouth, stomach, and small intestine), chemical digestion (mouth, stomach, and small intestine), absorption (stomach, small intestine, and large intestine), and defecation (anus). (Image credit: "Digestive Process" by OpenStax is licensed under CC BY 3.0)

While most chemical digestion occurs in the small intestine, some occurs in the mouth (carbohydrates and lipids) and stomach (proteins). Absorption, also largely carried out by the small intestine, some can occur in the mouth, stomach, and large intestine. For example, alcohol and aspirin are absorbed by the stomach and water and many ions are absorbed by the large intestine.

Regulatory Mechanisms

Neural and endocrine regulatory mechanisms work to maintain the optimal conditions in the lumen needed for digestion and absorption. These regulatory mechanisms, which stimulate digestive activity through mechanical and chemical activity, are controlled both extrinsically and intrinsically.

Neural Controls

The walls of the alimentary canal contain a variety of sensors that help regulate digestive functions. These include mechanoreceptors, chemoreceptors, and osmoreceptors, which are capable of detecting mechanical, chemical, and osmotic stimuli, respectively. For example, these receptors can sense when the presence of food has caused the stomach to expand, whether food particles have been sufficiently broken down, how much liquid is present, and the type of nutrients in the food (lipids, carbohydrates, and/or proteins). Stimulation of these receptors provokes an appropriate reflex that furthers the process of digestion. This may entail sending a message that activates the glands that secrete digestive juices into the lumen, or it may mean the stimulation of muscles within the alimentary canal, thereby activating peristalsis and segmentation that move food along the intestinal tract.

The walls of the entire alimentary canal are embedded with nerve plexuses (enteric nervous system, submucosal and myenteric plexuses) that interact with the central nervous system and other nerve plexuses—either within the same digestive organ or in different ones. These interactions prompt several types of reflexes. Extrinsic nerve plexuses orchestrate long reflexes, which involve the central and autonomic nervous systems and work in response to stimuli from outside the digestive system. Short reflexes, on the other hand, are orchestrated by intrinsic nerve plexuses within the alimentary canal wall. These two plexuses and their connections were introduced earlier as the enteric nervous system. Short reflexes regulate activities in one area of the digestive tract and may coordinate local peristaltic movements and stimulate digestive secretions. For example, the sight, smell, and taste of food initiate long reflexes that begin with a sensory neuron delivering a signal to the medulla oblongata. The response to the signal is to stimulate cells in the stomach to begin secreting digestive juices in preparation for incoming food. In contrast, food that distends the stomach initiates short reflexes that cause cells in the stomach wall to increase their secretion of digestive juices.

Hormonal Controls

A variety of hormones are involved in the digestive process. The main digestive hormone of the stomach is gastrin, which is secreted in response to the presence of food. Gastrin stimulates the secretion of gastric acid by the parietal cells of the stomach mucosa. Other GI hormones are produced and act upon the gut and its accessory organs. Hormones produced by the duodenum include secretin, which stimulates a watery secretion of bicarbonate by the pancreas; cholecystokinin (CCK), which stimulates the secretion of pancreatic enzymes and bile from the liver and release of bile from the gallbladder; and gastric inhibitory peptide, which inhibits gastric secretion and slows gastric emptying and motility. These GI hormones are secreted by specialized epithelial cells, called enteroendocrine cells, located in the mucosal epithelium of the stomach and small intestine. These hormones then enter the bloodstream, through which they can reach their target organs.

Concept Review

The digestive system ingests and digests food, absorbs released nutrients, and excretes food components that are indigestible. The six activities involved in this process are ingestion (mouth), motility (GI tract), mechanical digestion (mouth, stomach, small intestine), chemical digestion (mouth, stomach, small intestine), absorption (mouth, stomach, small and large intestines), and defecation (anus). Contractions of smooth muscles (muscularis externa) result in peristalsis to push contents along in the GI tract and segmentation to mix the content with enzymes. These processes are regulated by neural and hormonal mechanisms.

Review Questions

Q. Which of these processes occurs in the mouth?

A. ingestion

B. mechanical digestion

C. chemical digestion

D. all of the above

Answer

Answer: D

Q. Which of these processes occurs throughout most of the alimentary canal?

A. ingestion

B. propulsion

C. segmentation

D. absorption

Answer

Answer: B

Q. Which of the following occur(s) in the mouth?

A. mechanical digestion

B. chemical digestion

C. mastication

D. all of the above

Answer

Answer: D

Q. Which of these statements about the colon is false?

A. Chemical digestion occurs in the colon.

B. Absorption occurs in the colon.

C. Peristalsis occurs in the colon.

D. Diverticular disease occurs in the colon.

Answer

Answer: A

Critical Thinking Questions

Q. Offer a theory to explain why segmentation occurs and peristalsis slows in the small intestine.

Answer

A. The majority of digestion and absorption occurs in the small intestine. By slowing the transit of chyme, segmentation and a reduced rate of peristalsis allow time for these processes to occur.

Q. Which organ is mostly responsible for diarrhea and constipation and why?

Answer

A. The colon absorbs water. If it absorbs too much water, then the remaining contents (stool) may be hard and constipation may result. If it absorbs very little water or even secretes water, then the remaining contents will be loose and watery, resulting in diarrhea.

Glossary

absorption
passage of digested products from the intestinal lumen through mucosal cells and into the bloodstream or lacteals

chemical digestion
enzymatic breakdown of food

chyme
soupy liquid created when food is mixed with digestive juices

defecation
elimination of undigested substances from the body in the form of feces

ingestion
taking food into the GI tract through the mouth

mastication
chewing

mechanical digestion
chewing, mixing, and segmentation that prepares food for chemical digestion

peristalsis
muscular contractions and relaxations that propel food through the GI tract

propulsion
: voluntary process of swallowing and the involuntary process of peristalsis that moves food through the digestive tract

segmentation
: alternating contractions and relaxations of non-adjacent segments of the intestine that move food forward and backward, breaking it apart and mixing it with digestive juices

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21.4: Mouth, Pharynx, and Esophagus

By the end of the section, you will be able to:

- Describe the structures of the mouth, including its three accessory digestive organs
- Group the 32 adult teeth according to name, location, and function
- Describe the process of swallowing, including the roles of the tongue, upper esophageal sphincter, and epiglottis
- Trace the pathway food follows from ingestion into the mouth through release into the stomach

In this section, you will examine the anatomy and functions of the three main organs of the upper alimentary canal—the mouth, pharynx, and esophagus—as well as three associated accessory organs—the tongue, salivary glands, and teeth.

Mouth

The cheeks, tongue, and palate frame the mouth, which is also called the **oral cavity** (or buccal cavity). The structures of the mouth are illustrated in Figure 21.4.1. Teeth, hard and soft palate, fauces, arches, and uvula form the roof of the mouth. The floor of the mouth has the different types of teeth labeled, tongue, and lingual frenulum attached to the tongue. Below the tongue are openings of the ducts of submandibular glands. The image also shows the upper and lower lips attached by the upper and lower labial frenula (singular: frenulum).

At the entrance to the mouth are the lips, or **labia** (singular = labium). Their outer covering is skin, which transitions to a mucous membrane in the mouth proper. Lips are very vascular with a thin layer of keratin; hence, the reason they are "red." They have a huge representation on the cerebral cortex, which probably explains the human fascination with kissing! The lips cover the orbicularis oris muscle, which regulates what comes in and goes out of the mouth. The **labial frenulum** is a midline fold of mucous membrane that attaches the inner surface of each lip to the **gingiva** (gum). The cheeks make up the oral cavity's sidewalls. While their outer covering is skin, their inner covering is mucous membrane. This membrane is made up of non-keratinized, stratified squamous epithelium. Between the skin and mucous membranes are connective tissue and buccinator muscles. The next time you eat some food, notice how the buccinator muscles in your cheeks and the orbicularis oris muscle in your lips contract, helping you keep the food from falling out of your mouth. Additionally, notice how these muscles work when you are speaking.

The pocket-like part of the mouth that is framed on the inside by the gingivae and teeth, and on the outside by the cheeks and lips is called the **oral vestibule**. Moving farther into the mouth, the opening between the oral cavity and throat (oropharynx) is called the **fauces** (like the kitchen "faucet"). The main open area of the mouth, or oral cavity proper, runs from the gums and teeth to the fauces.

When you are chewing, you do not find it difficult to breathe simultaneously. The next time you have food in your mouth, notice how the arched shape of the roof of your mouth allows you to handle both ingestion and respiration at the same time. This arch is called the palate. The anterior region of the palate serves as a wall (or septum) between the oral and nasal cavities as well as a rigid shelf against which the tongue can push food. It is created by the maxillary and palatine bones of the skull and, given its bony structure, is known as the hard palate. If you run your tongue along the roof of your mouth, you'll notice that the hard palate ends in the posterior oral cavity, and the tissue becomes fleshier. This part of the palate, known as the **soft palate**, is composed mainly of skeletal muscle. You can therefore manipulate, subconsciously, the soft palate—for instance, to yawn, swallow, or sing (see Figure 21.4.1).

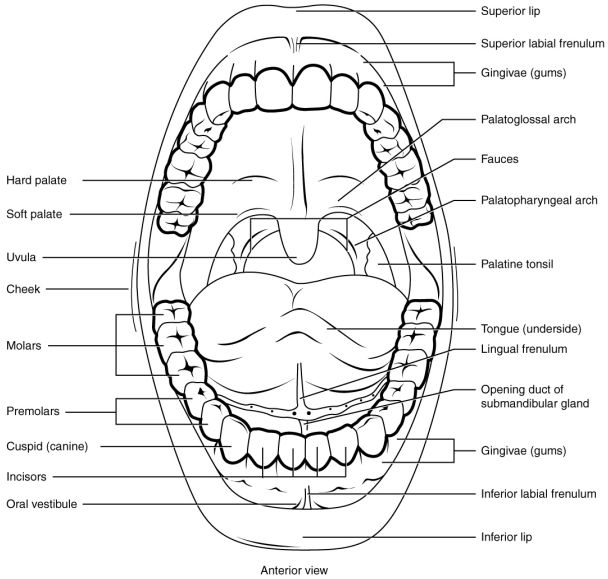

Figure 21.4.1: Mouth. The mouth includes the lips, tongue, palate, gums, and teeth. (Image credit: "Structures of the Mouth" by OpenStax is licensed under CC BY 3.0)

A fleshy bead of tissue called the uvula drops down from the center of the posterior edge of the soft palate. Although some have suggested that the uvula is a vestigial (a structure in our ancestors that has over time lost its original function) organ, it serves an important purpose. When you swallow, the soft palate and uvula move upward, helping to keep foods and liquid from entering the nasal cavity. Unfortunately, it can also contribute to the sound produced by snoring. Two muscular folds extend downward from the soft palate, on either side of the uvula. Toward the front (anterior), the **palatoglossal arch** lies next to the base of the tongue; behind (posterior) it, the **palatopharyngeal arch** forms the superior and lateral margins of the fauces. Between these two arches are the palatine tonsils, clusters of lymphoid tissue that protect the pharynx. The lingual tonsils are located at the base of the tongue.

Tongue

Perhaps you have heard it said that the **tongue** is the strongest muscle in the body. Those who stake this claim cite its strength proportionate to its size. Although it is difficult to quantify the relative strength of different muscles, it remains indisputable that the tongue is a workhorse, facilitating ingestion, mechanical digestion, chemical digestion (lingual lipase), sensation (of taste, texture, and temperature of food), swallowing, and vocalization.

The tongue is attached to the mandible, the styloid processes of the temporal bones, and the hyoid bone. The hyoid is unique in that it only distantly/indirectly articulates with other bones. The tongue is positioned over the floor of the oral cavity. A medial septum extends the entire length of the tongue, dividing it into symmetrical halves.

Beneath its mucous membrane covering, each half of the tongue is composed of the same number and type of intrinsic and extrinsic skeletal muscles. The intrinsic muscles (those within the tongue) are the longitudinalis inferior, longitudinalis superior, transversus linguae, and verticalis linguae muscles. These allow you to change the size and shape of your tongue, as well as to stick it out, if you wish. Having such a flexible tongue facilitates both swallowing and speech.

As you learned in your study of the muscular system, the extrinsic muscles of the tongue are the mylohyoid, hyoglossus, styloglossus, and genioglossus muscles. These muscles originate outside the tongue and insert into connective tissues within the tongue. The mylohyoid is responsible for raising the tongue, the hyoglossus pulls it down and back, the styloglossus pulls it up and back, and the genioglossus pulls it forward. Working in concert, these muscles perform three important digestive functions in the mouth: (1) position food for optimal chewing, (2) gather food into a **bolus** (rounded mass), and (3) position food so it can be swallowed.

The top and sides of the tongue are studded with papillae (round mounds), extensions of lamina propria of the mucosa, which are covered in stratified squamous epithelium (Figure 21.4.2). This picture also shows the epiglottis posterior to the tongue, palatine tonsil lateral to the tongue, and lingual tonsil at the root of the tongue. The image also shows the different type of papillae and the terminal sulcus separating the lingual tonsil (posterior) from the foliate papillae (anterior). Fungiform papillae , which are

mushroom shaped, cover a large area of the tongue; they tend to be larger toward the rear of the tongue and smaller on the tip and sides. In contrast, filiform papillae are long and thin. Fungiform papillae contain taste buds, and filiform papillae have touch receptors that help the tongue move food around in the mouth. The filiform papillae create an abrasive surface that performs mechanically, much like a cat's rough tongue that is used for grooming. Lingual glands in the lamina propria of the tongue secrete mucus and a watery serous fluid that contains the enzyme **lingual lipase**, which plays a minor role in breaking down triglycerides (fats) but does not begin working until it is activated in the stomach. A fold of mucous membrane on the underside of the tongue, the **lingual frenulum**, tethers the tongue to the floor of the mouth. People with the congenital anomaly ankyloglossia, also known by the non-medical term "tongue tie," have a lingual frenulum that is too short or otherwise malformed. Severe ankyloglossia can impair speech and must be corrected with surgery.

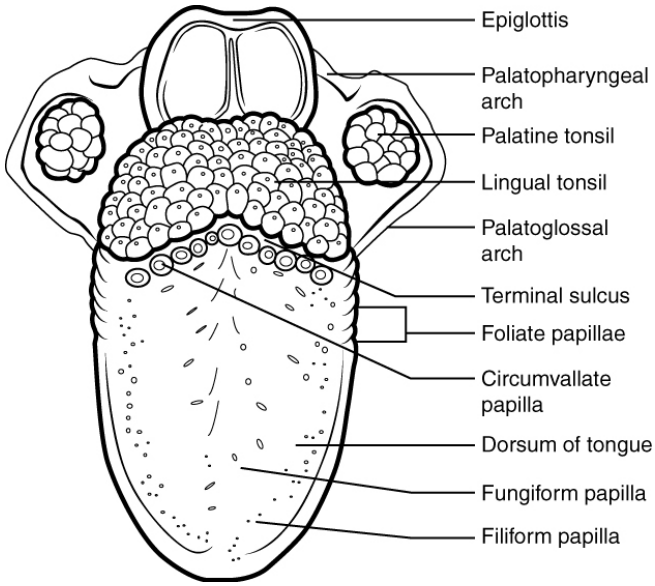

Figure 21.4.2: Tongue. This superior view of the tongue shows the locations and types of lingual papillae. (Image credit: "Tongue" by OpenStax is licensed under CC BY 3.0)

Salivary Glands

Many small **salivary glands** are housed within the mucous membranes of the mouth and tongue. These minor exocrine glands are constantly secreting saliva, either directly into the oral cavity or indirectly through ducts, even while you sleep. In fact, an average of 1 to 1.5 liters of saliva is secreted each day. Usually just enough saliva is present to moisten the mouth and teeth. Reflexes stimulated by presence or thoughts of food increase secretion when you eat, because saliva is essential to moisten food and initiate the chemical breakdown of carbohydrates. Small amounts of saliva are also secreted by the labial glands in the lips. In addition, the buccal glands in the cheeks, palatal glands in the palate, and lingual glands in the tongue help ensure that all areas of the mouth are supplied with adequate saliva.

Major Salivary Glands

Outside the oral mucosa are three pairs of major salivary glands, which secrete the majority of saliva into ducts that open into the mouth (Figure 21.4.3).

- The **submandibular glands**, which are in the floor of the mouth, secrete saliva into the mouth through the submandibular ducts, one on each side of the lingual frenulum.
- The **sublingual glands**, which lie below the tongue, use the multiple lesser sublingual ducts to secrete saliva into the oral cavity.
- The **parotid glands** lie between the skin and the masseter muscle, near the ears. They secrete saliva into the mouth through the parotid duct, which is located near the second upper molar tooth.

Saliva is essentially water (95.5%). The remaining 4.5 percent is a complex mixture of ions, glycoproteins, enzymes, growth factors, and waste products. Perhaps the most important ingredient in saliva from the perspective of digestion is the enzyme **salivary amylase**, which initiates the breakdown of carbohydrates. Food does not spend enough time in the mouth to allow all

the carbohydrates to break down, but salivary amylase continues acting until it is inactivated by stomach acids. Bicarbonate and phosphate ions function as chemical buffers, maintaining saliva at a pH between 6.35 and 6.85. Salivary mucus helps lubricate food, facilitating movement in the mouth, bolus formation, and swallowing. Saliva contains immunoglobulin A (antibodies), which prevents microbes from penetrating the epithelium, and lysozyme, which makes saliva antimicrobial. Saliva also contains epidermal growth factor, which might have given rise to the adage “a mother’s kiss can heal a wound.”

Each of the major salivary glands secretes a unique formulation of saliva according to its cellular makeup. For example, the parotid glands secrete a watery solution that contains salivary amylase. The submandibular glands have cells similar to those of the parotid glands, as well as mucus-secreting cells. Therefore, saliva secreted by the submandibular glands also contains amylase but in a liquid thickened with mucus. The sublingual glands contain mostly mucous cells, and they secrete the thickest saliva with the least amount of salivary amylase.

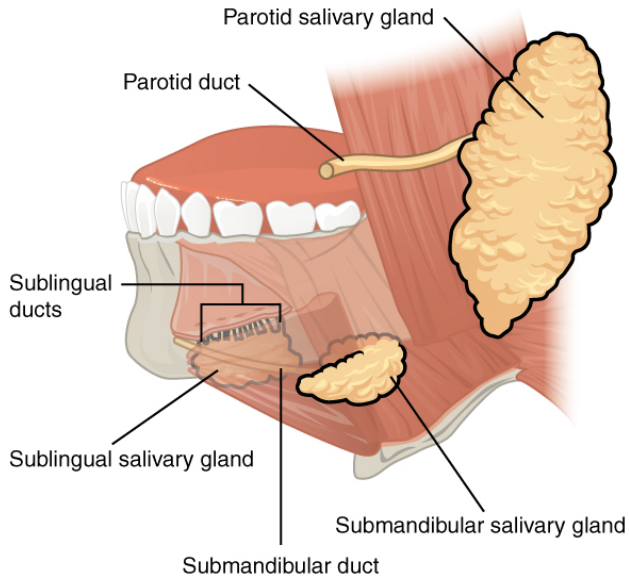

Figure 21.4.3: Salivary glands. The major salivary glands are located outside the oral mucosa and deliver saliva into the mouth through ducts. (Image credit: “Salivary Glands” by OpenStax is licensed under CC BY 3.0)

DISORDER OF THE...

Digestive System: Mumps in Parotid Glands

Infections of the nasal passages and pharynx can attack any salivary gland. The parotid glands are the usual site of infection with the virus that causes mumps (paramyxovirus). Mumps manifests as enlargement and inflammation of the parotid glands, causing a characteristic swelling between the ears and the jaw. Symptoms include fever and throat pain, which can be severe when swallowing acidic substances such as orange juice.

In about one-third of men who are past puberty, mumps also causes testicular inflammation, typically affecting only one testis and rarely resulting in sterility. With the increasing use and effectiveness of mumps vaccines, the incidence of mumps has decreased dramatically. According to the U.S. Centers for Disease Control and Prevention (CDC), the number of mumps cases dropped from more than 150,000 in 1968 to fewer than 1700 in 1993 to only 11 reported cases in 2011.

Regulation of Salivation

The autonomic nervous system regulates **salivation** (the secretion of saliva). In the absence of food, parasympathetic stimulation keeps saliva flowing at just the right level for comfort as you speak, swallow, sleep, and generally go about life. Over-salivation can occur, for example, if you are stimulated by the smell of food, but that food is not available for you to eat. Drooling is an extreme instance of the overproduction of saliva. During times of stress, such as before speaking in public, sympathetic stimulation takes over, reducing salivation and producing the symptom of dry mouth often associated with anxiety. When you are dehydrated, salivation is reduced, causing the mouth to feel dry and prompting you to take action to quench your thirst.

Salivation can be stimulated by the sight, smell, and taste of food. It can even be stimulated by thinking about food. You might notice whether reading about food and salivation right now has had any effect on your production of saliva.

How does the salivary process work while you are eating? Food contains chemicals that stimulate taste receptors on the tongue, which send impulses to the superior and inferior salivatory nuclei in the brain stem. These two nuclei then send back parasympathetic impulses through fibers in the glossopharyngeal and facial nerves, which stimulate salivation. Even after you swallow food, salivation is increased to cleanse the mouth and to water down and neutralize any irritating chemical remnants, such as that hot sauce in your burrito. Most saliva is swallowed along with food and is reabsorbed, so that fluid is not lost.

Teeth

The teeth, or **dentes** (singular = dens), are organs similar to bones that you use to tear, grind, and otherwise mechanically break down food.

Types of Teeth

During the course of your lifetime, you have two sets of teeth (one set of teeth is a **dentition**). Your 20 **deciduous teeth**, or baby teeth, first begin to appear at about 6 months of age. Between approximately age 6 and 12, these teeth are replaced by 32 **permanent teeth**. Figure 21.4.4 shows both the deciduous and permanent set of teeth, upper and lower, with the different types of teeth labeled and the age range in which they are seen. Moving from the center of the mouth toward the side, these are as follows:

- The eight **incisors**, four top and four bottom, are the sharp front teeth you use for biting into food.
- The four **cuspids** (or canines) flank the incisors and have a pointed edge (cusp) to tear up food. These fang-like teeth are superb for piercing tough or fleshy foods.
- Posterior to the cuspids are the eight **premolars** (or bicuspids), which have an overall flatter shape with two rounded cusps useful for mashing foods.
- The most posterior and largest are the 12 **molars**, which have several pointed cusps used to crush food so it is ready for swallowing. The third members of each set of three molars, top and bottom, are commonly referred to as the wisdom teeth, because their eruption is commonly delayed until early adulthood. It is not uncommon for wisdom teeth to fail to erupt; that is, they remain impacted. In these cases, the teeth are typically removed by orthodontic surgery.

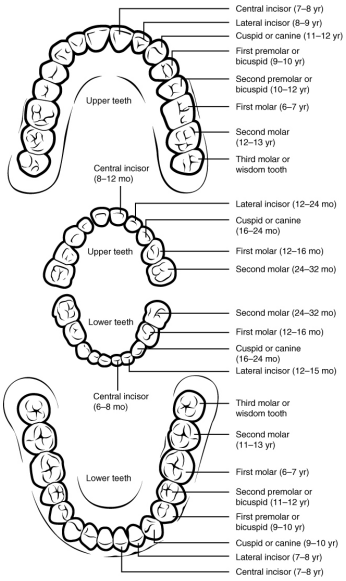

Figure 21.4.4: Permanent and Deciduous Teeth. This figure of two human dentitions shows the arrangement of teeth in the maxilla and mandible, and the relationship between the deciduous and permanent teeth. (Image credit: “Permanent and Deciduous Teeth” by OpenStax is licensed under CC BY 3.0)

Anatomy of a Tooth

The teeth are secured in the alveolar processes (sockets) of the maxilla and the mandible. **Gingivae** (commonly called the gums) are soft tissues that line the alveolar processes and surround the necks of the teeth. Teeth are also held in their sockets by dense connective tissue called the periodontal ligament.

The two main parts of a tooth are the **crown**, which is the portion projecting above the gum line, and the **root**, which is embedded within the maxilla or mandible. Both parts contain an inner **pulp cavity**, containing loose connective tissue through which runs nerves and blood vessels. The region of the pulp cavity that runs through the root of the tooth is called the root canal. Surrounding the pulp cavity is **dentin**, a bone-like tissue. In the root of each tooth, the dentin is covered by an even harder bone-like layer called **cementum**. In the crown of each tooth, the dentin is covered by an outer layer of **enamel**, the hardest substance in the body (Figure 21.4.5).

Although enamel protects the underlying dentin and pulp cavity, it is still nonetheless susceptible to mechanical and chemical erosion, or what is known as tooth decay. The most common form, dental caries (cavities) develops when colonies of bacteria feeding on sugars in the mouth release acids that cause soft tissue inflammation and degradation of the calcium crystals of the enamel.

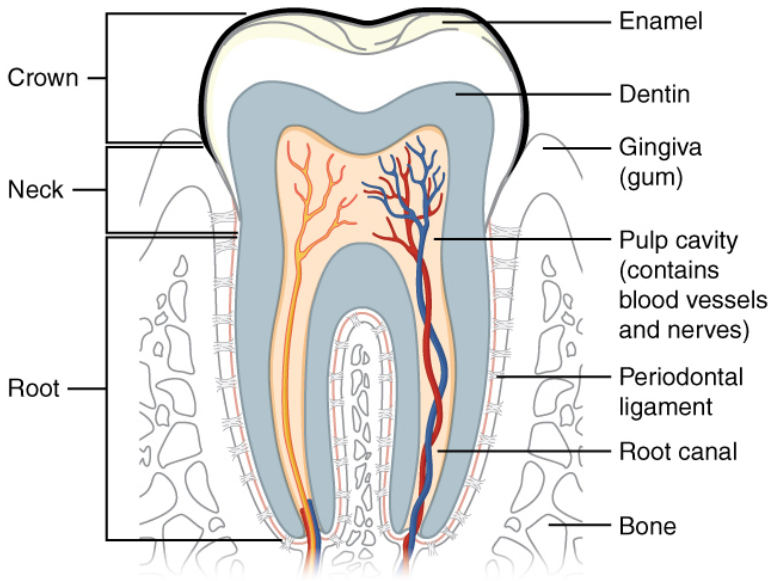

Figure 21.4.5: The Structure of the Tooth. This longitudinal section through a molar in its alveolar socket shows the relationships between enamel, dentin, and pulp. (Image credit: “Tooth” by OpenStax is licensed under CC BY 3.0)

The digestive functions of the mouth are summarized in Table 21.4.1.

Table 21.4.1: Digestive Functions of the Mouth

Structure	Action	Outcome
Lips and cheeks	Confine food between teeth	• Food is chewed evenly during mastication
Salivary glands	Secrete saliva	• Moisten and lubricate the lining of the mouth and pharynx • Moisten, soften, and dissolve food • Clean the mouth and teeth • Salivary amylase breaks down starch

Structure	Action	Outcome
Tongue's extrinsic muscles	Move tongue sideways, and in and out	• Manipulate food for chewing • Shape food into a bolus • Manipulate food for swallowing
Tongue's intrinsic muscles	Change tongue shape	• Manipulate food for swallowing
Taste buds	Sense food in mouth and sense taste	• Nerve impulses from taste buds are conducted to salivary nuclei in the brain stem and then to salivary glands, stimulating saliva secretion
Lingual glands	Secrete lingual lipase	• Activated in the stomach • Break down triglycerides into fatty acids and diglycerides
Teeth	Shred and crush food	• Break down solid food into smaller particles for deglutition

Pharynx

The **pharynx** (throat) is involved in both digestion and respiration. It receives food and air from the mouth, and air from the nasal cavities. When food enters the pharynx, involuntary muscle contractions close off the air passageways.

A short tube of skeletal muscle lined with a mucous membrane, the pharynx runs from the posterior oral and nasal cavities to the opening of the esophagus and larynx. There are three subdivisions of the pharynx. The most superior, the nasopharynx, is involved only in breathing and speech. Nasopharynx is separated from the oral cavity by the hard and soft palate. The other two subdivisions, the **oropharynx** and the **laryngopharynx**, are used for both breathing and digestion. The oropharynx begins inferior to the nasopharynx and is continuous below with the laryngopharynx (Figure 21.4.6). Oropharynx is separated from the oral cavity by the uvula.The inferior border of the laryngopharynx connects to the esophagus, whereas the anterior portion connects to the larynx, allowing air to flow into the bronchial tree. Figure 21.4.6 also shows the epiglottis and glottis to signal the beginning of the larynx.

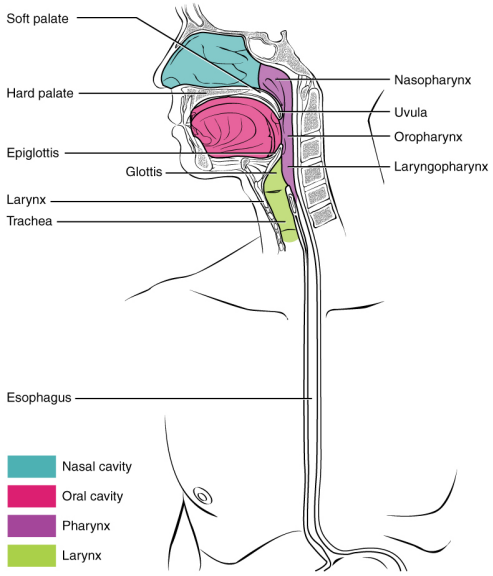

Figure 21.4.6: Pharynx. The pharynx runs from the nostrils to the esophagus and the larynx. (Image credit: "Pharynx" by OpenStax is licensed under CC BY 3.0)

Histologically, the wall of the oropharynx is similar to that of the oral cavity. The mucosa includes a stratified squamous epithelium that is endowed with mucus-producing glands. During swallowing, the elevator skeletal muscles of the pharynx contract, raising and expanding the pharynx to receive the bolus of food. Once received, these muscles relax and the constrictor muscles of the pharynx contract, forcing the bolus into the esophagus and initiating peristalsis.

Usually during swallowing, the soft palate and uvula rise reflexively to close off the entrance to the nasopharynx. At the same time, the larynx is pulled superiorly and the cartilaginous epiglottis, its most superior structure, folds inferiorly, covering the glottis (the opening to the larynx); this process effectively blocks access to the trachea and bronchi. When the food "goes down the wrong way," it goes into the trachea. When food enters the trachea, the reaction is to cough, which usually forces the food up and out of the trachea, and back into the pharynx.

Esophagus

The **esophagus** is a muscular tube that connects the pharynx to the stomach. It is approximately 25.4 cm (10 in) in length, located posterior to the trachea, and remains in a collapsed form when not engaged in swallowing (Figure 21.4.7) The esophagus runs a mainly straight route through the mediastinum of the thorax. To enter the abdomen, the esophagus penetrates the diaphragm through an opening called the esophageal hiatus. The esophagus has two sphincters: the upper esophageal sphincter at the inferior border of the laryngopharynx and the lower esophageal sphincter by the diaphragm.

Passage of Food through the Esophagus

The **upper esophageal sphincter**, which is continuous with the inferior pharyngeal constrictor, controls the movement of food from the pharynx into the esophagus. The upper two-thirds of the esophagus consists of both smooth and skeletal muscle fibers, with the latter fading out in the bottom third of the esophagus. Rhythmic waves of peristalsis, which begin in the upper esophagus, propel the bolus of food toward the stomach. Meanwhile, secretions from the esophageal mucosa lubricate the esophagus and food. Food passes from the esophagus into the stomach at the **lower esophageal sphincter** (also called the gastroesophageal or cardiac sphincter). Recall that sphincters are muscles that surround tubes and serve as valves, closing the tube when the sphincters contract and opening it when they relax. In the alimentary canal, involuntary sphincters are created by a thickening of the circular layer of the muscularis externa. The lower esophageal sphincter relaxes to let food pass into the stomach, and then contracts to prevent stomach acids from backing up into the esophagus. Surrounding this sphincter is the muscular diaphragm (the opening is the esophageal hiatus), which helps close off the sphincter when no food is being swallowed. When the lower esophageal sphincter does not completely close, the stomach's contents can reflux (that is, back up into the esophagus), causing heartburn or gastroesophageal reflux disease (GERD).

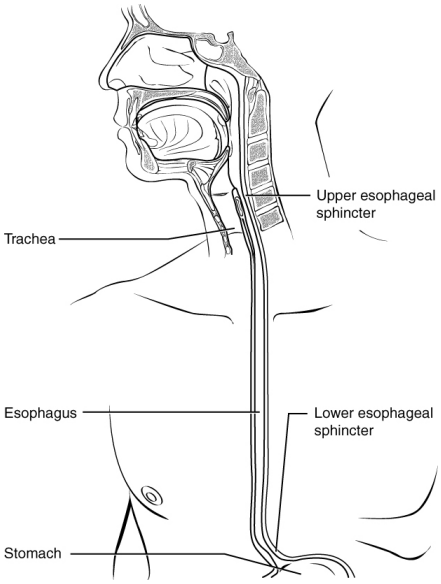

Figure 21.4.7: Esophagus. The upper esophageal sphincter controls the movement of food from the pharynx to the esophagus. The lower esophageal sphincter controls the movement of food from the esophagus to the stomach. (Image credit: "Esophagus" by OpenStax is licensed under CC BY 3.0)

Histology of the Esophagus

The mucosa of the esophagus is made up of an epithelial lining that contains non-keratinized, stratified squamous epithelium, with a layer of basal and parabasal cells. This epithelium protects against erosion from food particles. The mucosa's lamina propria contains mucus-secreting glands. The muscularis layer changes according to location: In the upper third of the esophagus, the muscularis is skeletal muscle. In the middle third, it is both skeletal and smooth muscle. In the lower third, it is smooth muscle. As mentioned previously, the most superficial layer of the esophagus is called the adventitia, not the serosa. In contrast to the stomach and intestines, the connective tissue of the adventitia is not covered by a fold of visceral peritoneum. The digestive functions of the esophagus are identified in Table 21.4.2.

Table 21.4.2: Digestive Functions of the Esophagus

Action	Outcome
Upper esophageal sphincter relaxation	Allows the bolus to move from the laryngopharynx to the esophagus
Peristalsis	Propels the bolus through the esophagus
Lower esophageal sphincter relaxation	Allows the bolus to move from the esophagus into the stomach and prevents chyme from entering the esophagus
Mucus secretion	Lubricates the esophagus, allowing easy passage of the bolus

Deglutition

Deglutition is another word for swallowing—the movement of food from the mouth to the stomach. The entire process takes about 4 to 8 seconds for solid or semisolid food, and about 1 second for very soft food and liquids. Although this sounds quick and effortless, deglutition is, in fact, a complex process that involves both the skeletal muscle of the tongue and the muscles of the pharynx and esophagus. It is aided by the presence of mucus and saliva. There are three stages in deglutition: the voluntary phase, the pharyngeal phase, and the esophageal phase (Figure 21.4.8). This picture shows the sequence of activities seen in swallowing, described in the next paragraphs, moving the food from the oral cavity down to the esophagus. The autonomic nervous system controls the latter two phases.

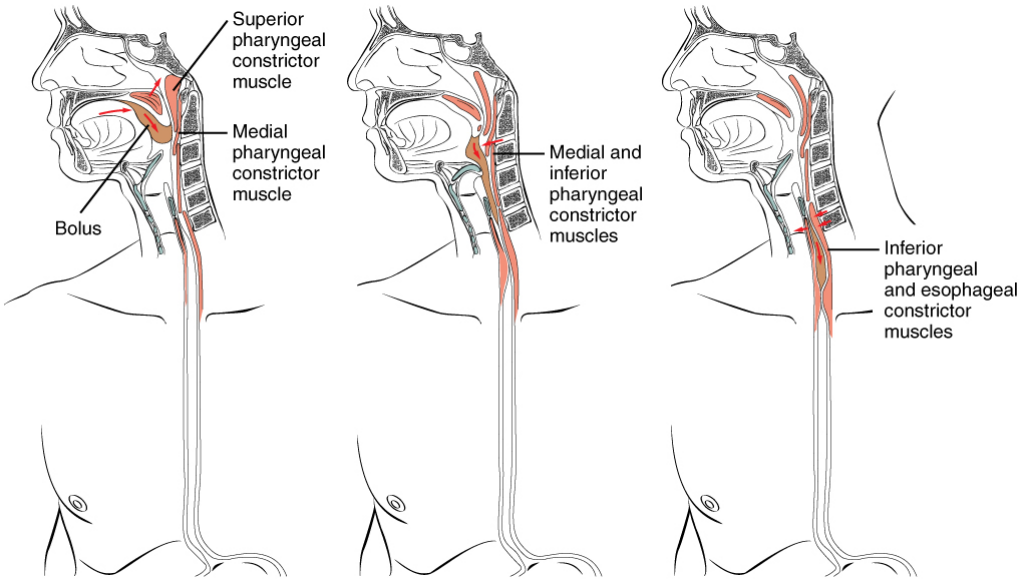

Figure 21.4.8: Deglutition. Deglutition includes the voluntary phase and two involuntary phases: the pharyngeal phase and the esophageal phase. (Image credit: "Deglutition" by OpenStax is licensed under CC BY 3.0)

Voluntary Phase

The **voluntary phase** of deglutition (also known as the oral or buccal phase) is so called because you can control when you swallow food. In this phase, chewing has been completed and swallowing is set in motion. The tongue moves upward and backward against the palate, pushing the bolus to the back of the oral cavity and into the oropharynx. Other muscles keep the mouth closed and prevent food from falling out. At this point, the two involuntary phases of swallowing begin.

Pharyngeal Phase

In the pharyngeal phase, stimulation of receptors in the oropharynx sends impulses to the deglutition center (a collection of neurons that controls swallowing) in the medulla oblongata. Impulses are then sent back to the uvula and soft palate, causing them to move upward and close off the nasopharynx. The laryngeal muscles also constrict to prevent aspiration of food into the trachea. At this point, deglutition apnea takes place, which means that breathing ceases for a very brief time. Contractions of the pharyngeal constrictor muscles move the bolus through the oropharynx and laryngopharynx. Relaxation of the upper esophageal sphincter then allows food to enter the esophagus.

Esophageal Phase

The entry of food into the esophagus marks the beginning of the esophageal phase of deglutition and the initiation of peristalsis. As in the previous phase, the complex neuromuscular actions are controlled by the medulla oblongata. Peristalsis propels the bolus through the esophagus and toward the stomach. The circular muscle layer of the muscularis contracts, pinching the esophageal wall and forcing the bolus forward. At the same time, the longitudinal muscle layer of the muscularis also contracts, shortening this area and pushing out its walls to receive the bolus. In this way, a series of contractions keeps moving food toward the stomach. When the bolus nears the stomach, distention of the esophagus initiates a short reflex relaxation of the lower esophageal sphincter that allows the bolus to pass into the stomach. During the esophageal phase, esophageal glands secrete mucus that lubricates the bolus and minimizes friction.

Concept Review

In the mouth, the tongue and the teeth begin mechanical digestion, and saliva begins chemical digestion and helps form the bolus, and protects the oral cavity. The pharynx, which plays roles in breathing and vocalization as well as digestion, runs from the nasal and oral cavities superiorly to the esophagus inferiorly (for digestion) and to the larynx anteriorly (for respiration). During deglutition (swallowing), the soft palate rises to close off the nasopharynx, the larynx elevates, and the epiglottis folds over the glottis. The esophagus includes an upper esophageal sphincter made of skeletal muscle, which regulates the movement of food

from the pharynx to the esophagus. It also has a lower esophageal sphincter, made of smooth muscle, which controls the passage of food from the esophagus to the stomach. Cells in the esophageal wall secrete mucus that eases the passage of the food bolus.

Review Questions

Q. Which describes the epithelium of the mouth, pharynx and esophagus?

A. squamous

B. keratinized

C. columnar

D. simple

Answer

Answer: A

Q. Which of these statements about the pharynx is true?

A. It extends from the nasal and oral cavities superiorly to the esophagus anteriorly.

B. The oropharynx is continuous superiorly with the nasopharynx.

C. The nasopharynx is involved in digestion.

D. The laryngopharynx is composed partially of cartilage.

Answer

Answer: B

Q. Which structure is located where the esophagus penetrates the diaphragm?

A. esophageal hiatus

B. cardiac orifice

C. upper esophageal sphincter

D. lower pharyngeal sphincter

Answer

Answer: A

Q. Which phase of deglutition involves contraction of the longitudinal muscle layer of the muscularis?

A. voluntary phase

B. buccal phase

C. pharyngeal phase

D. esophageal phase

Answer

Answer: D

Critical Thinking Questions

Q. The composition of saliva varies from gland to gland. Discuss how saliva produced by the parotid gland differs in action from saliva produced by the sublingual gland.

Answer

A. Parotid gland saliva is watery with little mucus but a lot of amylase, which allows it to mix freely with food during mastication and begin the digestion of carbohydrates. In contrast, sublingual gland saliva has a lot of mucus with the least amount of amylase of all the salivary glands. The high mucus content serves to lubricate the food for swallowing.

Q. During a hockey game, the puck hits a player in the mouth, knocking out all eight of his most anterior teeth. Which teeth did the player lose and how does this loss affect food ingestion?

Answer

A. The incisors. Since these teeth are used for tearing off pieces of food during ingestion, the player will need to ingest foods that have already been cut into bite-sized pieces until the broken teeth are replaced.

Q. What prevents swallowed food from entering the airways?

Answer

A. Usually when food is swallowed, involuntary muscle contractions cause the soft palate to rise and close off the nasopharynx. The larynx also is pulled up, and the epiglottis folds over the glottis. These actions block off the air passages.

Q. Explain the mechanism responsible for gastroesophageal reflux.

Answer

A. If the lower esophageal sphincter does not close completely, the stomach's acidic contents can back up into the esophagus, a phenomenon known as GERD.

Q. Explain why the histology in the esophagus is suitable for that location.

Answer

A. The epithelium in the esophagus is non-keratinized stratified squamous epithelium. The many layers of flat cells permits the apical cells to shed (and quickly be replaced by other squamous cells) as food move down and yet, these many flat cells are not bulky to obstruct passage of food. The many layers may also be protective against acid reflux. The glands secrete mucus to lubricate the bolus and ease the passage. The change from all skeletal muscles superiorly to all smooth muscle inferiorly is logical b/c swallowing is voluntary superiorly and peristalsis is involuntary inferiorly.

References

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Glossary

bolus
mass of chewed food

cementum
bone-like tissue covering the root of a tooth

crown
portion of tooth visible superior to the gum line

cuspid
(also, canine) pointed tooth used for tearing and shredding food

deciduous tooth
one of 20 “baby teeth”

deglutition
three-stage process of swallowing

dens
tooth

dentin
bone-like tissue immediately deep to the enamel of the crown or cementum of the root of a tooth

dentition
set of teeth

enamel
covering of the dentin of the crown of a tooth

esophagus
muscular tube that runs from the pharynx to the stomach

fauces
opening between the oral cavity and the oropharynx

gingiva
gum

incisor
midline, chisel-shaped tooth used for cutting into food

labium
lip

labial frenulum
midline mucous membrane fold that attaches the inner surface of the lips to the gums

laryngopharynx
part of the pharynx that functions in respiration and digestion

lingual frenulum
mucous membrane fold that attaches the bottom of the tongue to the floor of the mouth

lingual lipase
digestive enzyme from glands in the tongue that acts on triglycerides

lower esophageal sphincter
smooth muscle sphincter that regulates food movement from the esophagus to the stomach

molar
tooth used for crushing and grinding food

oral cavity
(also, buccal cavity) mouth

oral vestibule
part of the mouth bounded externally by the cheeks and lips, and internally by the gums and teeth

oropharynx
part of the pharynx continuous with the oral cavity that functions in respiration and digestion

palatoglossal arch
muscular fold that extends from the lateral side of the soft palate to the base of the tongue

palatopharyngeal arch
muscular fold that extends from the lateral side of the soft palate to the side of the pharynx

parotid gland
one of a pair of major salivary glands located inferior and anterior to the ears

permanent tooth
one of 32 adult teeth

pharynx
throat

premolar
(also, bicuspid) transitional tooth used for mastication, crushing, and grinding food

pulp cavity
deepest portion of a tooth, containing nerve endings and blood vessels

root
portion of a tooth embedded in the alveolar processes beneath the gum line

saliva
aqueous solution of proteins and ions secreted into the mouth by the salivary glands

salivary amylase
digestive enzyme in saliva that acts on starch

salivary gland
an exocrine gland that secretes a digestive fluid called saliva

salivation
secretion of saliva

soft palate
posterior region of the bottom portion of the nasal cavity that consists of skeletal muscle

sublingual gland
one of a pair of major salivary glands located beneath the tongue

submandibular gland
one of a pair of major salivary glands located in the floor of the mouth

tongue
accessory digestive organ of the mouth, the bulk of which is composed of skeletal muscle

upper esophageal sphincter
skeletal muscle sphincter that regulates food movement from the pharynx to the esophagus

voluntary phase
initial phase of deglutition, in which the bolus moves from the mouth to the oropharynx

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21.5: Stomach

By the end of the section, you will be able to:

- Label on a diagram the four main regions of the stomach, its curvatures, and its sphincter
- Identify the four main types of secreting cells in gastric glands, and their important products
- Explain why the stomach does not digest itself
- Describe the mechanical and chemical digestion of food entering the stomach

Although a minimal amount of carbohydrate digestion occurs in the mouth, chemical digestion really gets underway in the stomach. An expansion of the alimentary canal that lies immediately inferior to the esophagus, the stomach links the esophagus to the first part of the small intestine (the duodenum) and is relatively fixed in place at its esophageal and duodenal ends. In between, however, it can be a highly active structure, contracting and continually changing position and size. These contractions provide mechanical assistance to digestion. The empty stomach is only about the size of your fist, but can stretch to hold as much as 4 liters of food and fluid, or more than 75 times its empty volume, and then return to its resting size when empty. Although you might think that the size of a person's stomach is related to how much food that individual consumes, body weight does not correlate with stomach size. Rather, when you eat greater quantities of food—such as at holiday dinner—you stretch the stomach more than when you eat less.

Popular culture tends to refer to the stomach as the location where all digestion takes place. Of course, as you have already begun to learn, this is not true; the bulk of digestion occurs in the small intestine. An important function of the stomach is to serve as a temporary holding chamber. You can ingest a meal far more quickly than it can be digested and absorbed by the small intestine. Thus, the stomach holds food and parses only small amounts into the small intestine at a time. Foods are not processed in the order they are eaten; rather, they are mixed together with digestive juices in the stomach until they are converted into chyme, which is released into the small intestine.

As you will see in the sections that follow, the stomach plays several important roles in chemical digestion, including the continued digestion of carbohydrates and the initial digestion of proteins and triglycerides. Little,if any, nutrient absorption occurs in the stomach, with the exception of the negligible amount of nutrients in alcohol.

Structure

There are four main regions in the **stomach**: the cardia, fundus, body, and pylorus (Figure 21.5.1). It is unique with three layers of the muscularis externa: outer longitudinal layer, middle circular layer, and inner oblique layer. The **cardia** (or cardiac region) is the point where the esophagus connects to the stomach and through which food passes into the stomach. Located inferior to the diaphragm, above and to the left of the cardia, is the dome-shaped **fundus**. Below the fundus is the **body**, the main part of the stomach. The funnel-shaped **pylorus** connects the stomach to the duodenum. The wider end of the funnel, the **pyloric antrum**, connects to the body of the stomach. The narrower end is called the **pyloric canal**, which connects to the duodenum. The smooth muscle **pyloric sphincter** is located at this latter point of connection and controls stomach emptying. In the absence of food, the stomach deflates inward, and its mucosa and submucosa fall into large folds called **rugae**.

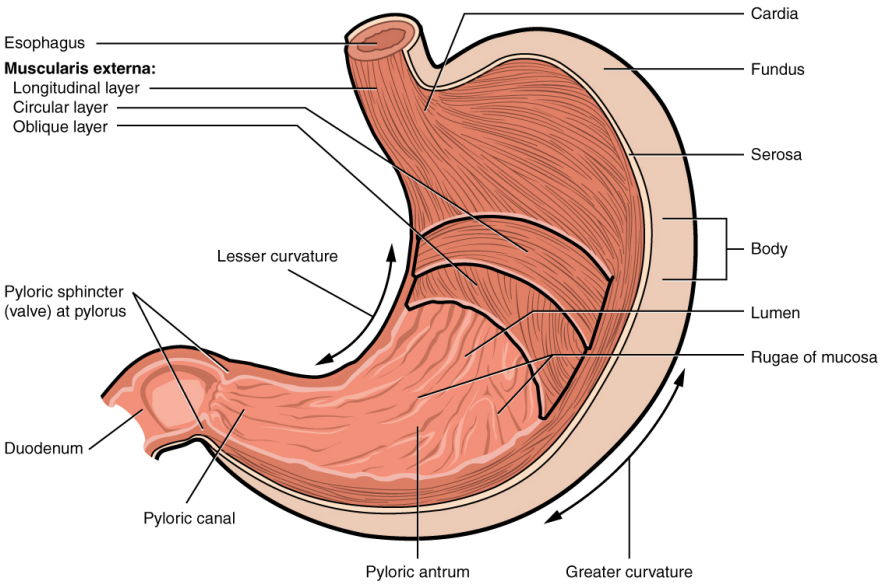

Figure 21.5.1: Stomach. The stomach has four major regions: the cardia, fundus, body, and pylorus. The addition of an inner oblique smooth muscle layer gives the muscularis the ability to vigorously churn and mix food. (Image credit: "Stomach" by OpenStax is licensed under CC BY 3.0)

The convex lateral surface of the stomach is called the greater curvature; the concave medial border is the lesser curvature. The stomach is held in place by the lesser omentum, which extends from the liver to the lesser curvature, and the greater omentum, which runs from the greater curvature, down the anterior abdominal cavity, forming a large, insulating fold and then connecting to the transverse colon.

Histology

The wall of the stomach is made of the same four layers as most of the rest of the alimentary canal, but with adaptations to the mucosa and muscularis for the unique functions of this organ. In addition to the typical circular and longitudinal smooth muscle layers, the muscularis has an inner oblique smooth muscle layer (Figure 21.5.2). As a result, in addition to moving food through the canal, the stomach can vigorously churn food, mechanically breaking it down into smaller particles.

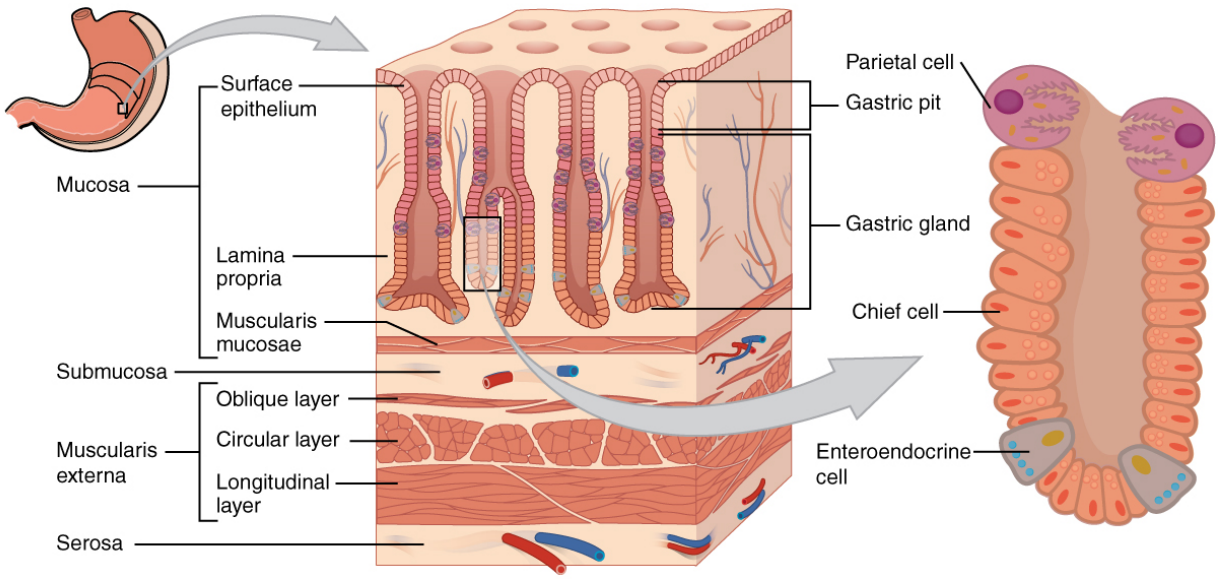

Figure 21.5.2: Histology of the Stomach. The stomach wall is adapted for the functions of the stomach. In the epithelium, gastric pits lead to gastric glands that secrete gastric juice. The gastric glands (one gland is shown enlarged on the right) contain different types of cells that secrete a variety of enzymes, including hydrochloric acid, which activates the protein-digesting enzyme, pepsin. (Image credit: "Histology of the Stomach" by OpenStax is licensed under CC BY 3.0)

Figure 21.5.2 also shows the different types of gastric gland in the epithelial lining. The stomach mucosa's simple columnar epithelial lining consists only of surface **mucous cells**, which secrete a protective coat of alkaline mucus. A vast number of **gastric pits** dot the surface of the epithelium, giving it the appearance of a well-used pincushion, and mark the entry to deeper exocrine tubules called **gastric glands**, which secrete a complex digestive fluid referred to as gastric juice.

Although the walls of the gastric pits are made up primarily of mucous cells, the gastric glands are made up of different types of cells. The glands of the cardia and pylorus are composed primarily of mucus-secreting cells. Cells that make up the pyloric antrum secrete mucus and a number of hormones, including the majority of the stimulatory hormone, **gastrin**. The much larger glands of the fundus and body of the stomach, the site of most chemical digestion, produce most of the gastric secretions. These glands are made up of a variety of secretory cells. These include parietal cells, chief cells, mucous neck cells, and enteroendocrine cells.

Parietal cells—Located primarily in the middle region of the gastric glands are **parietal cells**, which are among the most highly differentiated of the body's epithelial cells. These relatively large cells produce both **hydrochloric acid (HCl)** and **intrinsic factor**. HCl is responsible for the high acidity (pH 1.5 to 3.5) of the stomach contents and is needed to activate the protein-digesting enzyme, pepsin. The acidity also kills much of the bacteria you ingest with food and helps to denature proteins, making them more available for enzymatic digestion. Intrinsic factor is a glycoprotein necessary for the absorption of vitamin B_{12} in the small intestine.

Chief cells—Located primarily in the basal regions of gastric glands are **chief cells**, which secrete **pepsinogen**, the inactive proenzyme form of pepsin. HCl is necessary for the conversion of pepsinogen to pepsin, an enzyme to digest proteins.

Mucous neck cells—Gastric glands in the upper part of the stomach contain **mucous neck cells** that secrete thin, acidic mucus that is much different from the mucus secreted by the goblet cells of the surface epithelium. The role of this mucus is not currently known.

Enteroendocrine cells—Finally, enteroendocrine cells found in the gastric glands secrete various hormones into the interstitial fluid of the lamina propria. These include gastrin, which is released mainly by enteroendocrine **G cells**.

The mucosa of the stomach is exposed to the highly corrosive acidity of gastric juice. Gastric enzymes that can digest protein can also digest the stomach itself. The stomach is protected from self-digestion by the **mucosal barrier**. This barrier has several components. First, the stomach wall is covered by a thick coating of bicarbonate-rich mucus. This mucus forms a physical barrier, and its bicarbonate ions neutralize acid. Second, the epithelial cells of the stomach's mucosa meet at tight junctions, which block gastric juice from penetrating the underlying tissue layers. Finally, stem cells located where gastric glands join the gastric pits quickly replace damaged epithelial mucosal cells, when the epithelial cells are shed. In fact, the surface epithelium of the stomach is completely replaced every 3 to 6 days.

Table 21.5.1: Hormones Secreted by the Stomach

Hormone	Production site	Production stimulus	Target organ	Action
Gastrin	Stomach mucosa, mainly G cells of the pyloric antrum	Presence of peptides and amino acids in stomach	Stomach	Increases secretion by gastric glands; promotes gastric emptying
Gastrin	Stomach mucosa, mainly G cells of the pyloric antrum	Presence of peptides and amino acids in stomach	Small intestine	Promotes intestinal muscle contraction
Gastrin	Stomach mucosa, mainly G cells of the pyloric antrum	Presence of peptides and amino acids in stomach	Ileocecal valve	Relaxes valve
Gastrin	Stomach mucosa, mainly G cells of the pyloric antrum	Presence of peptides and amino acids in stomach	Large intestine	Triggers mass movements
Ghrelin	Stomach mucosa, mainly fundus	Fasting state (levels increase just prior to meals)	Hypothalamus	Regulates food intake, primarily by stimulating hunger and satiety
Histamine	Stomach mucosa	Presence of food in the stomach	Stomach	Stimulates parietal cells to release HCl
Serotonin	Stomach mucosa	Presence of food in the stomach	Stomach	Contracts stomach muscle

Hormone	Production site	Production stimulus	Target organ	Action
Somatostatin	Mucosa of stomach, especially pyloric antrum; also duodenum	Presence of food in the stomach; sympathetic axon stimulation	Stomach	Restricts all gastric secretions, gastric motility, and emptying
Somatostatin	Mucosa of stomach, especially pyloric antrum; also duodenum	Presence of food in the stomach; sympathetic axon stimulation	Pancreas	Restricts pancreatic secretions
Somatostatin	Mucosa of stomach, especially pyloric antrum; also duodenum	Presence of food in the stomach; sympathetic axon stimulation	Small intestine	Reduces intestinal absorption by reducing blood flow

DISORDER OF THE...

Digestive System: Ulcers in Mucosal Barrier

As effective as the mucosal barrier is, it is not a “fail-safe” mechanism. Sometimes, gastric juice eats away at the superficial lining of the stomach mucosa, creating erosions, which mostly heal on their own. Deeper and larger erosions are called ulcers.

Why does the mucosal barrier break down? A number of factors can interfere with its ability to protect the stomach lining. The majority of all ulcers are caused by either excessive intake of non-steroidal anti-inflammatory drugs (NSAIDs), including aspirin, or Helicobacter pylori infection.

Antacids help relieve symptoms of ulcers such as “burning” pain and indigestion. When ulcers are caused by NSAID use, switching to other classes of pain relievers allows healing. When caused by H. pylori infection, antibiotics are effective.

A potential complication of ulcers is perforation: Perforated ulcers create a hole in the stomach wall, resulting in peritonitis (inflammation of the peritoneum). These ulcers must be repaired surgically.

Digestive Functions of the Stomach

The stomach participates in virtually all the digestive activities with the exception of ingestion and defecation. Although almost all absorption takes place in the small intestine, the stomach does absorb some nonpolar substances, such as alcohol and aspirin.

Mechanical Digestion

Within a few moments after food after enters your stomach, mixing waves begin to occur at intervals of approximately 20 seconds. A **mixing wave** is a unique type of peristalsis that mixes and softens the food with gastric juices to create chyme. The initial mixing waves are relatively gentle, but these are followed by more intense waves, starting at the body of the stomach and increasing in force as they reach the pylorus. It is fair to say that long before your sushi exits through the pyloric sphincter, it bears little resemblance to the sushi you ate.

The pylorus, which holds around 30 mL (1 fluid ounce) of chyme, acts as a filter, permitting only liquids and small food particles to pass through the mostly, but not fully, closed pyloric sphincter. In a process called **gastric emptying**, rhythmic mixing waves force about 3 mL of chyme at a time through the pyloric sphincter and into the duodenum. Release of a greater amount of chyme at one time would overwhelm the capacity of the small intestine to handle it. The rest of the chyme is pushed back into the body of the stomach, where it continues mixing. This process is repeated when the next mixing waves force more chyme into the duodenum.

Gastric emptying is regulated by both the stomach and the duodenum. The presence of chyme in the duodenum activates receptors that inhibit gastric secretion. This prevents additional chyme from being released by the stomach before the duodenum is ready to process it.

Chemical Digestion

The fundus plays an important role, because it stores both undigested food and gases that are released during the process of chemical digestion. Food may sit in the fundus of the stomach for a while before being mixed with the chyme. While the food is in the fundus, the digestive activities of salivary amylase continue until the food begins mixing with the acidic chyme. Ultimately, mixing waves incorporate this food with the chyme, the acidity of which inactivates salivary amylase and activates lingual lipase. Lingual lipase then begins chemical digestion of lipids, breaking down triglycerides into free fatty acids, and mono- and diglycerides.

The secretion of gastric juice is controlled by both nerves and hormones. Stimuli in the brain, stomach, and small intestine activate or inhibit gastric juice production. This is why the three phases of gastric secretion are called the cephalic, gastric, and intestinal phases. However, once gastric secretion begins, all three phases can occur simultaneously.

The breakdown of protein begins in the stomach through the actions of HCl and the enzyme pepsin. During infancy, gastric glands also produce rennin, an enzyme that helps digest milk protein.

Its numerous digestive functions notwithstanding, there is only one stomach function necessary to life: the production of intrinsic factor. The intestinal absorption of vitamin B_{12}, which is necessary for both the production of mature red blood cells and normal neurological functioning, cannot occur without intrinsic factor. People who undergo total gastrectomy (stomach removal)—for life-threatening stomach cancer, for example—can survive with minimal digestive dysfunction if they receive vitamin B_{12} injections.

The contents of the stomach are completely emptied into the duodenum within 2 to 4 hours after you eat a meal. Different types of food take different amounts of time to process. Foods heavy in carbohydrates empty fastest, followed by high-protein foods. Meals with a high triglyceride content remain in the stomach the longest. Since enzymes in the small intestine digest fats slowly, food can stay in the stomach for 6 hours or longer when the duodenum is processing fatty chyme. However, note that this is still a fraction of the 24 to 72 hours that full digestion typically takes from start to finish.

Concept Review

The stomach is a curved organ that connects the esophagus to the small intestine. It has a greater curvature and lesser curvature and can expand because of rugae. There are four main regions in the stomach: the cardia, fundus, body, and pylorus. The mucosa has gastric pits that lead to gastric glands that secrete gastric juices, comprised of mucus, acid, and different proteins to aid in digestion. The muscularis externa has an additional layer, the oblique smooth muscle layer to aid in churning of chyme. The stomach participates in all digestive activities except ingestion and defecation. The stomach begins the digestion of protein and continues the digestion of carbohydrates and fats. It stores food as chyme, and releases it gradually into the small intestine through the pyloric sphincter. It absorbs certain drugs, including aspirin and some alcohol.

Review Questions

Q. Which is not related to the stomach?

A. lesser omentum

B. greater curvature

C. stratified squamous cells

D. enteroendocrine cells

Answer

Answer: C

Q. Which is/are unique about the stomach?

A. Muscularis has 3 layers of muscles.

B. Rugae allow the stomach to expand.

C. It has pits leading to glands.

D. All of the above.

Answer

Answer: D

Q. During gastric emptying, chyme is released into the duodenum through the _____.

A. esophageal hiatus

B. pyloric antrum

C. pyloric canal

D. pyloric sphincter

Answer

Answer: D

Q. Parietal cells are located in the _____.

A. gastric pits

B. gastric glands

C. lamina propria

D. muscularis mucosa

Answer

Answer: B

Critical Thinking Questions

Q. Explain how the stomach is protected from self-digestion and why this is necessary.

Answer

A. The mucosal barrier protects the stomach from self-digestion. It includes a thick coating of bicarbonate-rich mucus; the mucus is physically protective, and bicarbonate neutralizes gastric acid. Epithelial cells meet at tight junctions, which block gastric juice from penetrating the underlying tissue layers, and stem cells quickly replace sloughed off epithelial mucosal cells.

Q. Describe unique anatomical features that enable the stomach to perform digestive functions.

Answer

A. The stomach has an additional inner oblique smooth muscle layer that helps the muscularis churn and mix food. The epithelium includes gastric glands that secrete gastric fluid. The gastric fluid consists mainly of mucous, HCl, and the enzyme pepsin released as pepsinogen.

Glossary

body
: mid-portion of the stomach

cardia
: (also, cardiac region) part of the stomach surrounding the cardiac orifice (esophageal hiatus)

cephalic phase
: (also, reflex phase) initial phase of gastric secretion that occurs before food enters the stomach

chief cell
: gastric gland cell that secretes pepsinogen

enteroendocrine cell
: gastric gland cell that releases hormones

fundus
: dome-shaped region of the stomach above and to the left of the cardia

G cell
: gastrin-secreting enteroendocrine cell

gastric emptying
: process by which mixing waves gradually cause the release of chyme into the duodenum

gastric gland
: gland in the stomach mucosal epithelium that produces gastric juice

gastric phase
: phase of gastric secretion that begins when food enters the stomach

gastric pit
: narrow channel formed by the epithelial lining of the stomach mucosa

gastrin
: peptide hormone that stimulates secretion of hydrochloric acid and gut motility

hydrochloric acid (HCl)
: digestive acid secreted by parietal cells in the stomach

intrinsic factor
: glycoprotein required for vitamin B_{12} absorption in the small intestine

intestinal phase
: phase of gastric secretion that begins when chyme enters the intestine

mixing wave
: unique type of peristalsis that occurs in the stomach

mucosal barrier
: protective barrier that prevents gastric juice from destroying the stomach itself

mucous neck cell
: gastric gland cell that secretes a uniquely acidic mucus

parietal cell
: gastric gland cell that secretes hydrochloric acid and intrinsic factor

pepsinogen
: inactive form of pepsin

pyloric antrum
: wider, more superior part of the pylorus

pyloric canal
: narrow, more inferior part of the pylorus

pyloric sphincter
: sphincter that controls stomach emptying

pylorus
: lower, funnel-shaped part of the stomach that is continuous with the duodenum

ruga
: fold of alimentary canal mucosa and submucosa in the empty stomach and other organs

stomach
: alimentary canal organ that contributes to chemical and mechanical digestion of food from the esophagus before releasing it, as chyme, to the small intestine

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21.6: Small and Large Intestines

By the end of the section, you will be able to:

- Compare and contrast the location and gross anatomy of the small and large intestines
- Identify three main adaptations of the small intestine wall that increase its absorptive capacity
- Describe the mechanical and chemical digestion of chyme upon its release into the small intestine
- List three features unique to the wall of the large intestine and identify their contributions to its function
- Identify the beneficial roles of the bacterial flora in digestive system functioning
- Trace the pathway of food waste from its point of entry into the large intestine through its exit from the body as feces

The word intestine is derived from a Latin root meaning “internal,” and indeed, the two organs together nearly fill the interior of the abdominal cavity. In addition, called the small and large bowel, or colloquially the “guts,” they constitute the greatest mass and length of the alimentary canal and, with the exception of ingestion, perform all digestive system functions.

Small Intestine

Chyme released from the stomach enters the **small intestine**, which is the primary digestive organ in the body. Not only is this where most digestion occurs, it is also where practically all absorption occurs. The longest part of the alimentary canal, the small intestine is about 3.05 meters (10 feet) long in a living person (but about twice as long in a cadaver due to the loss of muscle tone). Since this makes it about five times longer than the large intestine, you might wonder why it is called “small.” In fact, its name derives from its relatively smaller diameter of only about 2.54 cm (1 in), compared with 7.62 cm (3 in) for the large intestine. As we’ll see shortly, in addition to its length, the folds and projections of the lining of the small intestine work to give it an enormous surface area, which is approximately 200 m^2, more than 100 times the surface area of your skin. This large surface area is necessary for complex processes of digestion and absorption that occur within it.

Structure

The coiled tube of the small intestine is subdivided into three regions. From proximal (at the stomach) to distal, these are the duodenum, jejunum, and ileum (Figure 21.6.1). The shortest region is the 25.4-cm (10-in) **duodenum**, which begins at the pyloric sphincter. Just past the pyloric sphincter, it bends posteriorly behind the peritoneum, becoming retroperitoneal, and then makes a C-shaped curve around the head of the pancreas before ascending anteriorly again to return to the peritoneal cavity and join the jejunum. The duodenum can therefore be subdivided into four segments: the superior, descending, horizontal, and ascending duodenum.

Of particular interest is the **hepatopancreatic ampulla** (ampulla of Vater). Located in the duodenal wall, the ampulla marks the transition from the anterior portion of the alimentary canal to the mid-region, and is where the bile duct (through which bile passes from the liver) and the **main pancreatic duct** (through which pancreatic juice passes from the pancreas) join. This ampulla opens into the duodenum at a tiny volcano-shaped structure called the **major duodenal papilla**. The **hepatopancreatic sphincter** (sphincter of Oddi) regulates the flow of both bile and pancreatic juice from the ampulla into the duodenum.

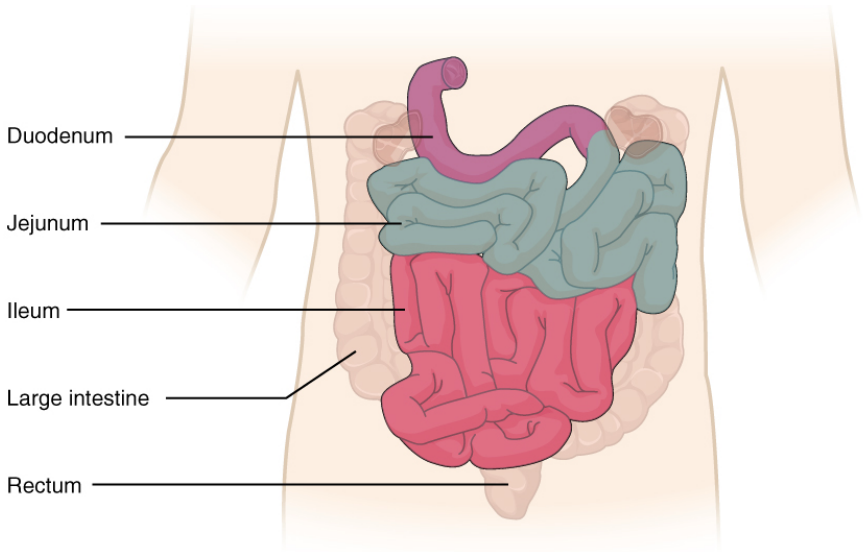

Figure 21.6.1: Small Intestine. The three regions of the small intestine are the duodenum, jejunum, and ileum. (Image credit: "Small Intestine" by OpenStax is licensed under CC BY 3.0)

The **jejunum** is about 0.9 meters (3 feet) long (in life) and runs from the duodenum to the ileum. Jejunum means "empty" in Latin and supposedly was so named by the ancient Greeks who noticed it was always empty at death. No clear demarcation exists between the jejunum and the final segment of the small intestine, the ileum.

The **ileum** is the longest part of the small intestine, measuring about 1.8 meters (6 feet) in length. It is thicker, more vascular, and has more developed mucosal folds than the jejunum. The ileum joins the cecum, the first portion of the large intestine, at the **ileocecal sphincter** (or valve). The jejunum and ileum are tethered to the posterior abdominal wall by the mesentery. The large intestine frames these three parts of the small intestine.

Parasympathetic nerve fibers from the vagus nerve and sympathetic nerve fibers from the thoracic splanchnic nerve provide extrinsic innervation to the small intestine. The superior mesenteric artery is its main arterial supply. Veins run parallel to the arteries and drain into the superior mesenteric vein. Nutrient-rich blood from the small intestine is then carried to the liver via the hepatic portal vein.

Histology

The wall of the small intestine is composed of the same four layers typically present in the alimentary system. However, three features of the mucosa and submucosa are unique. These features, which increase the absorptive surface area of the small intestine more than 600 times, include circular folds (**plicae circulares**), villi, and microvilli (Figure 21.6.2). These adaptations are most abundant in the proximal two-thirds of the small intestine, where the majority of absorption occurs.

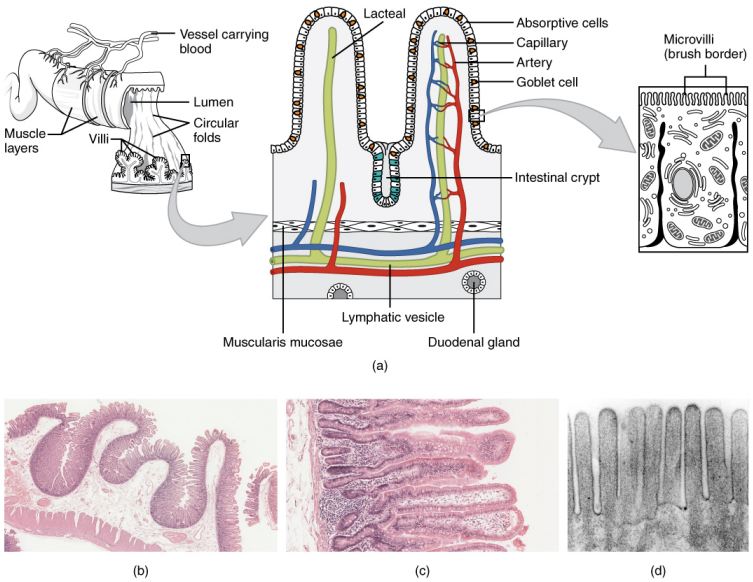

Figure 21.6.2: Histology of the Small Intestine. (a) The absorptive surface of the small intestine is vastly enlarged by the presence of circular folds, villi, and microvilli. (b) Micrograph of the circular folds. (c) Micrograph of the villi. (d) Electron micrograph of the microvilli. From left to right, LM x 56, LM x 508, EM x 196,000. (credit b-d: Micrograph provided by the Regents of University of Michigan Medical School © 2012; (Image credit: "Histology of Small Intestine" by OpenStax is licensed under CC BY 3.0)

Circular folds

Also called a plica circulare, a **circular fold** is a deep ridge in the mucosa and submucosa. These plicae circulares form transverse ridges that can be up to 1 cm in depth and are visible to the naked eye. Beginning near the proximal part of the duodenum and ending near the middle of the ileum, these folds facilitate absorption. In addition to increasing the surface area, their shape causes the chyme to spiral, rather than move in a straight line, through the small intestine. Spiraling slows the movement of chyme and provides the time needed for nutrients to be fully absorbed.

Villi

Within the circular folds are small (0.5–1 mm long) hairlike vascularized projections called **villi** (singular = villus) that give the mucosa a furry texture. There are about 20 to 40 villi per square millimeter, increasing the surface area of the epithelium tremendously. The mucosal simple columnar epithelium, primarily composed of absorptive cells, covers the villi. In addition to muscle and connective tissue to support its structure, each villus contains a capillary bed composed of one arteriole and one venule, as well as a lymphatic capillary called a **lacteal**. The breakdown products of carbohydrates and proteins (sugars and amino acids) can enter the bloodstream directly, but lipid breakdown products are absorbed by the lacteals and transported to the bloodstream via the lymphatic system.

Microvilli

As their name suggests, **microvilli** (singular = microvillus) are much smaller (1 μm) than villi. They are cylindrical apical surface extensions of the plasma membrane of the mucosa's epithelial cells, and are supported by microfilaments within those cells. Although their small size makes it difficult to see each microvillus, their combined microscopic appearance suggests a mass of bristles, which is termed the **brush border**. Fixed to the surface of the microvilli membranes are enzymes that finish digesting carbohydrates and proteins and in some cases transporter proteins to aid in digestion. There are an estimated 200 million microvilli per square millimeter of small intestine, greatly expanding the surface area of the plasma membrane and thus greatly enhancing absorption.

Intestinal Glands

In addition to the three specialized absorptive features just discussed, the mucosa between the villi is dotted with deep crevices that each lead into a tubular **intestinal gland** (crypt of Lieberkühn), which is formed by cells that line the crevices (Figure 21.6.2).

These produce **intestinal juice**, a slightly alkaline (pH 7.4 to 7.8) mixture of water and mucus. Each day, about 0.95 to 1.9 liters (1 to 2 quarts) are secreted in response to the distention of the small intestine or the irritating effects of chyme on the intestinal mucosa. In addition to the exocrine glands making intestinal juice, there are enteroendocrine cells to secrete many regulatory hormones that communicate with other digestive organs including the pancreas and gallbladder.

The submucosa of the duodenum is the only site of the complex mucus-secreting **duodenal glands** (Brunner's glands), which produce a bicarbonate-rich alkaline mucus that buffers the acidic chyme as it enters from the stomach.

The lamina propria of the small intestine mucosa is studded with quite a bit of mucosa associated lymphoid tissue (MALT). In addition to solitary lymphatic nodules, aggregations of intestinal MALT, which are typically referred to as Peyer's patches, are concentrated in the distal ileum, and serve to keep bacteria from entering the bloodstream. Peyer's patches are most prominent in young people and become less distinct as you age, which coincides with the general activity of our immune system.

Digestive Functions of the Small Intestine

Mechanical Digestion

The movement of intestinal smooth muscles includes both segmentation and a form of peristalsis called migrating motility complexes. The kind of peristaltic mixing waves seen in the stomach are not observed here.

If you could see into the small intestine when it was going through segmentation, it would look as if the contents were being shoved incrementally back and forth, as the rings of smooth muscle repeatedly contract and then relax. Segmentation in the small intestine does not force chyme through the tract. Instead, it combines the chyme with digestive juices and pushes food particles against the mucosa to be digested and absorbed. The duodenum is where the most rapid segmentation occurs, at a rate of about 12 times per minute. In the ileum, segmentations are only about eight times per minute (Figure 21.6.3). Figure 21.6.3 is a drawing of the small intestine undergoing segmentation with alternating constriction and relaxation of the smooth muscles to mix and move the contents inside.

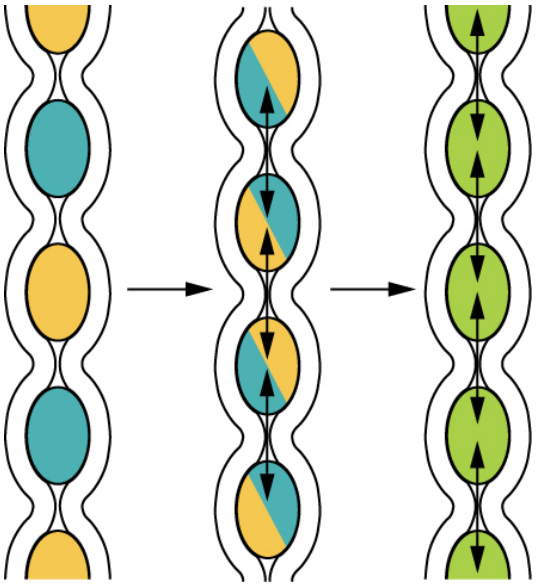

Figure 21.6.3: Segmentation. Segmentation separates chyme and then pushes it back together, mixing it and providing time for digestion and absorption. (Image credit: "Segmentation" by OpenStax is licensed under CC BY 3.0)

When most of the chyme has been absorbed, the small intestinal wall becomes less distended. At this point, the localized segmentation process is replaced by transport movements. The duodenal mucosa secretes the hormone **motilin**, which initiates peristalsis in the form of a **migrating motility complex**. These complexes, which begin in the duodenum, force chyme through a short section of the small intestine and then stop. The next contraction begins a little bit farther down than the first, forces chyme a bit farther through the small intestine, then stops. These complexes move slowly down the small intestine, forcing chyme on the way, taking around 90 to 120 minutes to finally reach the end of the ileum. At this point, the process is repeated, starting in the duodenum.

The ileocecal valve, a sphincter, is usually in a constricted state, but when motility in the ileum increases, this sphincter relaxes, allowing food residue to enter the first portion of the large intestine, the cecum. Relaxation of the ileocecal sphincter is controlled by both nerves and hormones. First, digestive activity in the stomach provokes the **gastroileal reflex**, which increases the force of ileal segmentation. Second, the stomach releases the hormone gastrin, which enhances ileal motility, thus relaxing the ileocecal sphincter. After chyme passes through, backward pressure helps close the sphincter, preventing backflow into the ileum. Because of this reflex, your lunch is completely emptied from your stomach and small intestine by the time you eat your dinner. It takes about 3 to 5 hours for all chyme to leave the small intestine.

Chemical Digestion

The digestion of proteins and carbohydrates, which partially occurs in the stomach, is completed in the small intestine with the aid of intestinal and pancreatic juices. Pancreatic and brush border enzymes continue and complete chemical digestion of carbohydrates and proteins. Lipids arrive in the intestine largely undigested, so much of the focus here is on lipid digestion, which is facilitated by bile and the enzyme pancreatic lipase.

Moreover, intestinal juice combines with pancreatic juice to provide a liquid medium that facilitates absorption. The intestine is also where most water is absorbed, via osmosis. The small intestine's absorptive cells also synthesize digestive enzymes and then place them in the plasma membranes of the microvilli. This distinguishes the small intestine from the stomach; that is, enzymatic digestion occurs not only in the lumen, but also on the luminal surfaces of the mucosal cells.

For optimal chemical digestion, chyme must be delivered from the stomach slowly and in small amounts. This is because chyme from the stomach is typically hypertonic (higher concentration than the content in small intestine), and if large quantities were forced all at once into the small intestine, the resulting osmotic water loss from the blood into the intestinal lumen, to dilute the chyme, would result in potentially life-threatening low blood volume. In addition, continued digestion requires an upward adjustment of the low pH of stomach chyme, along with rigorous mixing of the chyme with bile and pancreatic juices. Both processes take time, so the pumping action of the pylorus must be carefully controlled to prevent the duodenum from being overwhelmed with chyme.

DISORDERS OF THE...

Digestive System: Lactose Intolerance

Lactose intolerance is a condition characterized by indigestion caused by dairy products. It occurs when the absorptive cells of the small intestine do not produce enough lactase, the enzyme that digests the milk sugar lactose. In most mammals, lactose intolerance increases with age. In contrast, some human populations, most notably Caucasians, are able to maintain the ability to produce lactase as adults.

In people with lactose intolerance, the lactose in chyme is not digested. Bacteria in the large intestine ferment the undigested lactose, a process that produces gas. In addition to gas, symptoms include abdominal cramps, bloating, and diarrhea. Symptom severity ranges from mild discomfort to severe pain; however, symptoms resolve once the lactose is eliminated in feces.

The hydrogen breath test is used to help diagnose lactose intolerance. Lactose-tolerant people have very little hydrogen in their breath. Those with lactose intolerance exhale hydrogen, which is one of the gases produced by the bacterial fermentation of lactose in the colon. After the hydrogen is absorbed from the intestine, it is transported through blood vessels into the lungs. There are a number of lactose-free dairy products available in grocery stores. In addition, dietary supplements are available. Taken with food, they provide lactase to help digest lactose.

Large Intestine

The **large intestine** is the terminal part of the alimentary canal. The primary function of this organ is to finish absorption of nutrients and water, synthesize certain vitamins, form feces, and eliminate feces from the body.

Structure

The large intestine runs from the appendix to the anus. It frames the small intestine on three sides. Despite its being about one-half as long as the small intestine, it is called large because it has a diameter that is more than twice the diameter of the small intestine, about 3 inches. The large intestine is subdivided into four main regions: the cecum, the colon, the rectum, and the anus. The ileocecal valve, located at the opening between the ileum and the large intestine, controls the flow of chyme from the small intestine to the large intestine.

Cecum

The first part of the large intestine is the **cecum**, a sac-like structure that is suspended inferior to the ileocecal valve. It is about 6 cm (2.4 in) long, receives the contents of the ileum, and continues the absorption of water and salts. The **appendix** (or vermiform appendix) is a winding, dead-end tube that attaches to the cecum. Although the 7.6-cm (3-in) long appendix contains lymphoid tissue, suggesting an immunologic function, this organ is generally considered vestigial (a structure present in our ancestors that has over time lost its original function). However, at least one recent report postulates a survival advantage conferred by the appendix: In diarrheal illness, the appendix may serve as a bacterial reservoir to repopulate the enteric bacteria for those surviving the initial phases of the illness. Moreover, its twisted anatomy provides a haven for the accumulation and multiplication of enteric bacteria. The **mesoappendix**, the mesentery of the appendix, tethers it to the mesentery of the ileum.

Colon

The cecum blends seamlessly with the **colon**. The small intestine is faintly superimposed to show the location of both the large and small intestines. Upon entering the colon, the food residue first travels up the **ascending colon** on the right side of the abdomen. At the inferior surface of the liver, the colon bends to form the **right colic flexure** (hepatic flexure) and becomes the **transverse colon**. The region defined as hindgut begins with the last third of the transverse colon and continues on. Food residue passing through the transverse colon travels across to the left side of the abdomen, where the colon angles sharply immediately inferior to the spleen, at the **left colic flexure** (splenic flexure). From there, food residue passes through the **descending colon**, which runs down the left side of the posterior abdominal wall. After entering the pelvis inferiorly, it becomes the s-shaped **sigmoid colon**, which extends medially to the midline (Figure 21.6.4). The ascending and descending colon, and the rectum (discussed next) are located in the retroperitoneum. The transverse and sigmoid colon are tethered to the posterior abdominal wall by the mesocolon.

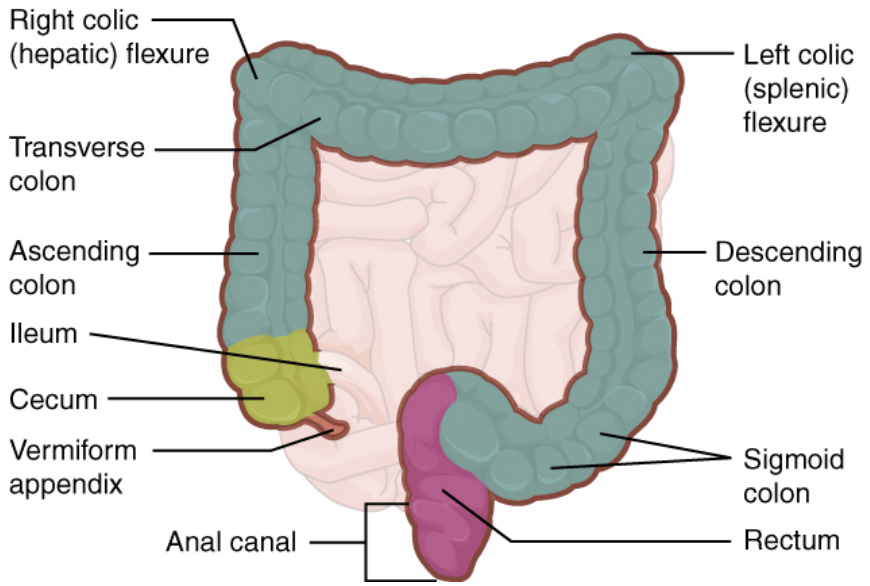

Figure 21.6.4: Large Intestine. The large intestine includes the cecum, colon, and rectum. (Image credit: "Large Intestine" by OpenStax is licensed under CC BY 3.0)

DISORDER OF THE...

Digestive System: Colorectal Cancer

Each year, approximately 140,000 Americans are diagnosed with colorectal cancer, and another 49,000 die from it, making it one of the most deadly malignancies. People with a family history of colorectal cancer are at increased risk. Smoking, excessive alcohol consumption, and a diet high in animal fat and protein also increase the risk. Despite popular opinion to the contrary, studies support the conclusion that dietary fiber and calcium do not reduce the risk of colorectal cancer.

Colorectal cancer may be signaled by constipation or diarrhea, cramping, abdominal pain, and rectal bleeding. Bleeding from the rectum may be either obvious or occult (hidden in feces). Since most colon cancers arise from benign mucosal growths called polyps, cancer prevention is focused on identifying these polyps. The colonoscopy is both diagnostic and therapeutic. Colonoscopy not only allows identification of precancerous polyps, the procedure also enables them to be removed before they become malignant. Screening for fecal occult blood tests and colonoscopy is recommended for those over 50 years of age.

Rectum

Food residue leaving the sigmoid colon enters the **rectum** in the pelvis, near the third sacral vertebra. The final 20.3 cm (8 in) of the alimentary canal, the rectum extends anterior to the sacrum and coccyx. Even though rectum is Latin for “straight,” this structure follows the curved contour of the sacrum and has three lateral bends that create a trio of internal transverse folds called the **rectal valves**. These valves help separate the feces from gas to prevent the simultaneous passage of feces and gas.

Anal Canal

Finally, food residue reaches the last part of the large intestine, the **anal canal**, which is located in the perineum, completely outside of the abdominopelvic cavity. This 3.8–5 cm (1.5–2 in) long structure opens to the exterior of the body at the anus. The anal canal includes two sphincters. The **internal anal sphincter** is made of smooth muscle, and its contractions are involuntary. The **external anal sphincter** is made of skeletal muscle, which is under voluntary control. Except when defecating, both usually remain closed.

Histology

There are several notable differences between the walls of the large and small intestines (Figure 21.6.5). For example, few enzyme-secreting cells are found in the wall of the large intestine, and there are no circular folds or villi. Other than in the anal canal, the mucosa of the colon is simple columnar epithelium made mostly of absorptive enterocytes with microvilli and goblet cells. In addition, the mucosa has far more intestinal glands, which contain a vast population of enterocytes and goblet cells. These goblet cells secrete mucus that eases the movement of feces and protects the intestine from the effects of the acids and gases produced by enteric bacteria. The enterocytes absorb water and salts as well as vitamins produced by your intestinal bacteria.

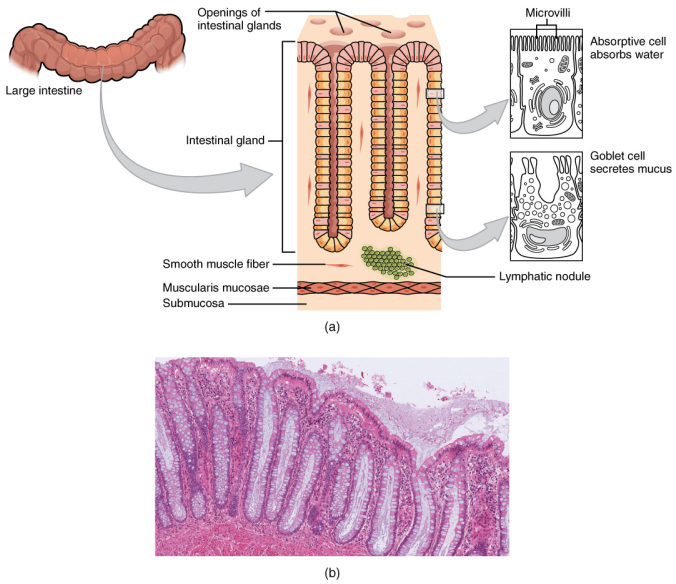

Figure 21.6.5: Histology of the large Intestine. (a) The histologies of the large intestine and small intestine (not shown) are adapted for the digestive functions of each organ. (b) This micrograph shows the colon's simple columnar epithelium and goblet cells. LM x 464. Micrograph provided by the Regents of University of Michigan Medical School © 2012. (Image credit: "Histology of Large Intestine" by OpenStax is licensed under CC BY 3.0)

Structural Features

The **teniae coli** are three bands of smooth muscle that make up the longitudinal muscle layer of the muscularis of the large intestine, except at its terminal end. Tonic contractions of the teniae coli bunch up the colon into a succession of pouches called **haustra** (singular = hostrum), which are responsible for the wrinkled appearance of the colon. Attached to the teniae coli are small, fat-filled sacs of visceral peritoneum called **epiploic appendages**. The purpose of these is unknown. Although the rectum and anal canal have neither teniae coli nor haustra, they do have well-developed layers of muscularis that create the strong contractions needed for defecation.

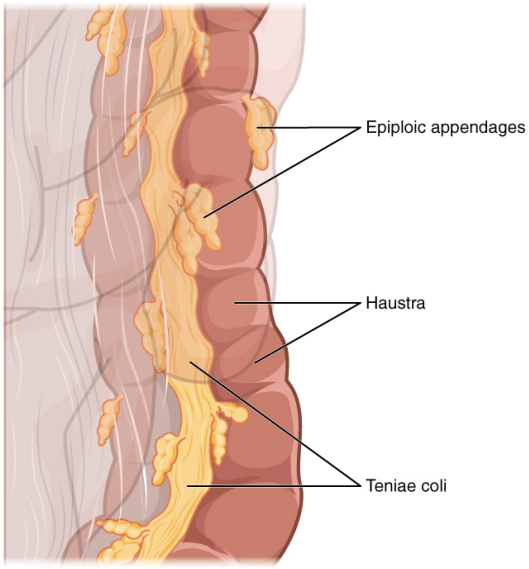

Figure 21.6.6: Teniae Coli, Haustra, and Epiploic Appendages. On the surface of the colon, there are fatty projections (epiploic appendages), bulges (haustra), and remnants of longitudinal smooth muscles (teniae coli). (Image credit: "Teniae Coli Haustra Epiploic Appendage" by OpenStax is licensed under CC BY 3.0)

The stratified squamous epithelial mucosa of the anal canal connects to the skin on the outside of the anus. This mucosa varies considerably from that of the rest of the colon to accommodate the high level of abrasion as feces pass through. The anal canal's

mucous membrane is organized into longitudinal folds, each called an **anal column**, which house a grid of arteries and veins. Two superficial venous plexuses are found in the anal canal: one within the anal columns and one at the anus.

Depressions between the anal columns, each called an **anal sinus**, secrete mucus that facilitates defecation. The **pectinate line** (or dentate line) is a horizontal, jagged band that runs circumferentially just below the level of the anal sinuses, and represents the junction between the hindgut and external skin. The mucosa above this line is fairly insensitive, whereas the area below is very sensitive. The resulting difference in pain threshold is due to the fact that the upper region is innervated by visceral sensory fibers, and the lower region is innervated by somatic sensory fibers.

Bacterial Flora

Most bacteria that enter the alimentary canal are killed by lysozyme, defensins, HCl, or protein-digesting enzymes. However, trillions of bacteria live within the large intestine and are referred to as the **bacterial flora**. Most of the more than 700 species of these bacteria are nonpathogenic commensal organisms that cause no harm as long as they stay in the gut lumen. In fact, many facilitate chemical digestion and absorption, and some synthesize certain vitamins, mainly biotin, pantothenic acid, and vitamin K. Some are linked to increased immune response. A refined system prevents these bacteria from crossing the mucosal barrier.

Digestive Functions of the Large Intestine

The residue of chyme that enters the large intestine contains few nutrients except water, which is reabsorbed as the residue lingers in the large intestine, typically for 12 to 24 hours. Thus, it may not surprise you that the large intestine can be completely removed without significantly affecting digestive functioning. For example, in severe cases of inflammatory bowel disease, the large intestine can be removed by a procedure known as a colectomy. Often, a new fecal pouch can be crafted from the small intestine and sutured to the anus, but if not, an ileostomy can be created by bringing the distal ileum through the abdominal wall, allowing the watery chyme to be collected in a bag-like adhesive appliance.

Mechanical Digestion

In the large intestine, mechanical digestion begins when chyme moves from the ileum into the cecum, an activity regulated by the ileocecal sphincter. Right after you eat, peristalsis in the ileum forces chyme into the cecum. When the cecum is distended with chyme, contractions of the ileocecal sphincter strengthen to prevent backflow. Once chyme enters the cecum, colon movements begin.

Mechanical digestion in the large intestine includes a combination of three types of movements. The presence of food residues in the colon stimulates a slow-moving **haustral contraction**. This type of movement involves sluggish segmentation, primarily in the transverse and descending colons. When a haustrum is distended with chyme, its muscle contracts, pushing the residue into the next haustrum. These contractions occur about every 30 minutes, and each last about 1 minute. These movements also mix the food residue, which helps the large intestine absorb water. The second type of movement is peristalsis, which, in the large intestine, is slower than in the more proximal portions of the alimentary canal. The third type is a **mass movement**. These strong waves start midway through the transverse colon and quickly force the contents toward the rectum. Mass movements usually occur three or four times per day, either while you eat or immediately afterward. Distension in the stomach and the breakdown products of digestion in the small intestine provoke the **gastrocolic reflex**, which increases motility, including mass movements, in the colon. Fiber in the diet both softens the stool and increases the power of colonic contractions, optimizing the activities of the colon.

Chemical Digestion

Although the glands of the large intestine secrete mucus, they do not secrete digestive enzymes. Therefore, chemical digestion in the large intestine occurs exclusively because of bacteria in the lumen of the colon. Through the process of **saccharolytic fermentation**, bacteria break down some of the remaining carbohydrates. This results in the discharge of hydrogen, carbon dioxide, and methane gases that create **flatus** (gas) in the colon; flatulence is excessive flatus. Each day, up to 1500 mL of flatus is produced in the colon. More is produced when you eat foods such as beans, which are rich in otherwise indigestible sugars and complex carbohydrates like soluble dietary fiber.

Absorption, Feces Formation, and Defecation

The small intestine absorbs about 90 percent of the water you ingest (either as liquid or within solid food). The large intestine absorbs most of the remaining water, a process that converts the liquid chyme residue into semisolid **feces** (“stool”). Feces is composed of undigested food residues, unabsorbed digested substances, millions of bacteria, old epithelial cells from the GI mucosa, inorganic salts, other waste products, and enough water to let it pass smoothly out of the body. Of every 500 mL (17 ounces) of food residue that enters the cecum each day, about 150 mL (5 ounces) become feces.

The process of defecation begins when mass movements force feces from the colon into the rectum, stretching the rectal wall and provoking the defecation reflex, which eliminates feces from the rectum. This parasympathetic reflex is mediated by the spinal cord. It contracts the sigmoid colon and rectum, relaxes the internal anal sphincter, and initially contracts the external anal sphincter. The presence of feces in the anal canal sends a signal to the brain, which gives you the choice of voluntarily opening the external anal sphincter (defecating) or keeping it temporarily closed. If you decide to delay defecation, it takes a few seconds for the reflex contractions to stop and the rectal walls to relax. The next mass movement will trigger additional defecation reflexes until you defecate.

If defecation is delayed for an extended time, additional water is absorbed, making the feces firmer and potentially leading to constipation. On the other hand, if the waste matter moves too quickly through the intestines, not enough water is absorbed, and diarrhea can result. This can be caused by the ingestion of foodborne pathogens. In general, diet, health, and stress determine the frequency of bowel movements. The number of bowel movements varies greatly between individuals, ranging from two or three per day to three or four per week.

Concept Review

The three main regions of the small intestine are the duodenum, the jejunum, and the ileum. The small intestine is where digestion is completed and virtually all absorption occurs. These two activities are facilitated by structural adaptations that increase the mucosal surface area by 600-fold, including circular folds, villi, and microvilli. There are around 200 million microvilli per square millimeter of small intestine, which contain brush border enzymes that complete the digestion of carbohydrates and proteins. Combined with pancreatic juice, intestinal juice provides the liquid medium needed to further digest and absorb substances from chyme. The small intestine is also the site of unique mechanical digestive movements. Segmentation moves the chyme back and forth, increasing mixing and opportunities for absorption. Migrating motility complexes propel the residual chyme toward the large intestine.

The main regions of the large intestine are the cecum, the colon, and the rectum. The large intestine absorbs water and forms feces, and is responsible for defecation. Bacterial flora break down additional carbohydrate residue, and synthesize certain vitamins. The mucosa of the large intestinal wall is generously endowed with goblet cells, which secrete mucus that eases the passage of feces. The entry of feces into the rectum activates the defecation reflex.

Review Questions

Q. Which part of the alimentary canal is retroperitoneal?

A. stomach

B. proximal small intestine

C. distal small intestine

D. transverse colon

Answer

B

Q. Which of these are found inside villi?

A. haustra

B. lacteals

C. bacterial flora

D. intestinal glands

Answer

B

Q. What section of the alimentary canal has the greatest amount of MALT?”

A. stomach

B. duodenum

C. cecum

D. ileum

Answer

D

Q. Which part of the large intestine attaches to the appendix?

A. cecum

B. ascending colon

C. transverse colon

D. descending colon

Answer

A

Critical Thinking Questions

Q. Why should there be capillaries inside villi?

Answer

A. Water soluble nutrients from the breakdown of carbohydrates and proteins are absorbed through a capillary bed in the villi of the small intestine. Lipid breakdown products are absorbed into a lacteal in the villi, and transported via the lymphatic system to the bloodstream.

Q. Should a person, with the colon removed, worry about becoming malnourished? Why or why not?

Answer

A. No, the colon absorbs very little nutrients; it does absorb water. Without the colon, the content leaving the small intestine will contain more fluid than normal feces.

Q. Describe some differences between the walls of the large and small intestines.

Answer

A. The mucosa of the small intestine includes circular folds, villi, and microvilli. The wall of the large intestine has a

thick mucosal layer, and deeper and more abundant mucus-secreting glands that facilitate the smooth passage of feces. There are three features that are unique to the large intestine: teniae coli, haustra, and epiploic appendages.

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Glossary

anal canal
final segment of the large intestine

anal column
long fold of mucosa in the anal canal

anal sinus
recess between anal columns

appendix
(vermiform appendix) coiled tube attached to the cecum

ascending colon
first region of the colon

bacterial flora
bacteria in the large intestine

brush border
fuzzy appearance of the small intestinal mucosa created by microvilli

cecum
pouch forming the beginning of the large intestine

circular fold
(also, plica circulare) deep fold in the mucosa and submucosa of the small intestine

colon
part of the large intestine between the cecum and the rectum

descending colon
part of the colon between the transverse colon and the sigmoid colon

duodenal gland
(also, Brunner's gland) mucous-secreting gland in the duodenal submucosa

duodenum
first part of the small intestine, which starts at the pyloric sphincter and ends at the jejunum

epiploic appendage
small sac of fat-filled visceral peritoneum attached to teniae coli

external anal sphincter
: voluntary skeletal muscle sphincter in the anal canal

feces
: semisolid waste product of digestion

flatus
: gas in the intestine

gastrocolic reflex
: propulsive movement in the colon activated by the presence of food in the stomach

gastroileal reflex
: long reflex that increases the strength of segmentation in the ileum

haustrum
: small pouch in the colon created by tonic contractions of teniae coli

haustral contraction
: slow segmentation in the large intestine

hepatopancreatic ampulla
: (also, ampulla of Vater) bulb-like point in the wall of the duodenum where the bile duct and main pancreatic duct unite

hepatopancreatic sphincter
: (also, sphincter of Oddi) sphincter regulating the flow of bile and pancreatic juice into the duodenum

ileocecal sphincter
: sphincter located where the small intestine joins with the large intestine

ileum
: end of the small intestine between the jejunum and the large intestine

internal anal sphincter
: involuntary smooth muscle sphincter in the anal canal

intestinal gland
: (also, crypt of Lieberkühn) gland in the small intestinal mucosa that secretes intestinal juice

intestinal juice
: mixture of water and mucus that helps absorb nutrients from chyme

jejunum
: middle part of the small intestine between the duodenum and the ileum

lacteal
: lymphatic capillary in the villi

large intestine
: terminal portion of the alimentary canal

left colic flexure
: (also, splenic flexure) point where the transverse colon curves below the inferior end of the spleen

main pancreatic duct
: (also, duct of Wirsung) duct through which pancreatic juice drains from the pancreas

major duodenal papilla
: point at which the hepatopancreatic ampulla opens into the duodenum

mass movement
long, slow, peristaltic wave in the large intestine

mesoappendix
mesentery of the appendix

microvillus
small projection of the plasma membrane of the absorptive cells of the small intestinal mucosa

migrating motility complex
form of peristalsis in the small intestine

motilin
hormone that initiates migrating motility complexes

pectinate line
horizontal line that runs like a ring, perpendicular to the inferior margins of the anal sinuses

rectal valve
one of three transverse folds in the rectum where feces is separated from flatus

rectum
part of the large intestine between the sigmoid colon and anal canal

right colic flexure
(also, hepatic flexure) point, at the inferior surface of the liver, where the ascending colon turns abruptly to the left

saccharolytic fermentation
anaerobic decomposition of carbohydrates

sigmoid colon
end portion of the colon, which terminates at the rectum

small intestine
section of the alimentary canal where most digestion and absorption occurs

tenia coli
one of three smooth muscle bands that make up the longitudinal muscle layer of the muscularis in all of the large intestine except the terminal end

transverse colon
part of the colon between the ascending colon and the descending colon

Valsalva's maneuver
voluntary contraction of the diaphragm and abdominal wall muscles and closing of the glottis, which increases intra-abdominal pressure and facilitates defecation

villus
projection of the mucosa of the small intestine

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21.7: Accessory Organs in Digestion- Liver, Pancreas, and Gallbladder

By the end of the section, you will be able to:

- State the main digestive roles of the liver, pancreas, and gallbladder
- Identify three main features of liver histology that are critical to its function
- Discuss the composition and function of bile
- Identify the major types of enzymes and buffers present in pancreatic juice

Chemical digestion in the small intestine relies on the activities of three accessory digestive organs: the liver, pancreas, and gallbladder (Figure 21.7.1). The digestive role of the liver is to produce bile and export it to the duodenum. The gallbladder primarily stores, concentrates, and releases bile. The pancreas produces pancreatic juice, which contains digestive enzymes and bicarbonate ions, and delivers it to the duodenum.

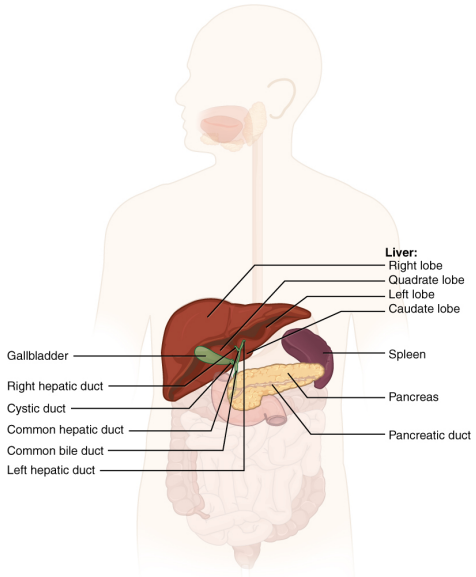

Figure 21.7.1: Accessory Organs. The liver, pancreas, and gallbladder are considered accessory digestive organs, but their roles in the digestive system are vital. (Image credit: "Accessory Organs" by OpenStax is licensed under CC BY 3.0)

Liver

The **liver** is the largest gland in the body, weighing about three pounds in an adult. It is also one of the most important organs. In addition to being an accessory digestive organ, it plays a number of roles in metabolism and regulation. The liver lies inferior to the diaphragm in the right upper quadrant of the abdominal cavity and receives protection from the surrounding ribs.

The liver is divided into two primary lobes: a large **right lobe** and a much smaller **left lobe**. In the right lobe, some anatomists also identify an inferior **quadrate lobe** and a posterior **caudate lobe**, which are defined by internal features. The liver is connected to the abdominal wall and diaphragm by five peritoneal folds referred to as ligaments. These are the **falciform ligament**, the **coronary ligament**, two **lateral ligaments**, and the **ligamentum teres hepatis**. The falciform ligament and ligamentum teres hepatis are actually remnants of the umbilical vein, and separate the right and left lobes anteriorly. The lesser omentum tethers the liver to the lesser curvature of the stomach.

The **porta hepatis** ("gate to the liver") is where the **hepatic artery** and **hepatic portal vein** enter the liver. These two vessels, along with the common hepatic duct, run behind the lateral border of the lesser omentum on the way to their destinations. As shown in Figure 21.7.2, the hepatic artery delivers oxygenated blood from the heart to the liver. The hepatic portal vein delivers

partially deoxygenated blood containing nutrients absorbed from the small intestine and actually supplies more oxygen to the liver than do the much smaller hepatic arteries. In addition to nutrients, drugs and toxins are also absorbed. After processing the bloodborne nutrients and toxins, the liver releases nutrients needed by other cells back into the blood, which drains into the central vein and then through the hepatic vein to the inferior vena cava. With this hepatic portal circulation, all blood from the alimentary canal passes through the liver. This largely explains why the liver is the most common site for the metastasis of cancers that originate in the alimentary canal.

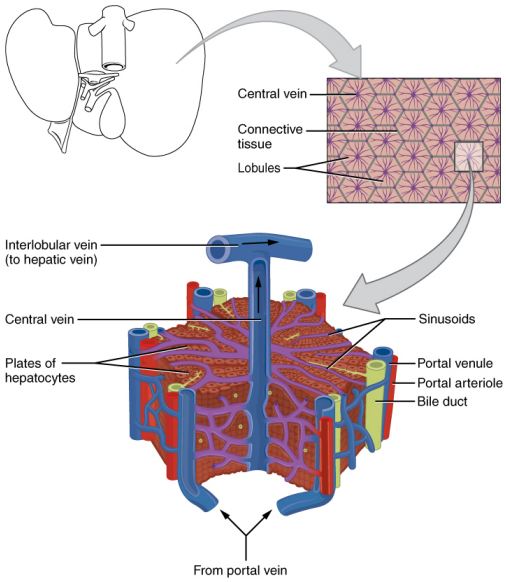

Figure 21.7.2: Microscopic Anatomy of the Liver. The liver receives oxygenated blood from the hepatic artery and nutrient-rich deoxygenated blood from the hepatic portal vein. (Image credit: "Microscopic Anatomy of Liver" by OpenStax is licensed under CC BY 3.0)

Histology

The liver has three main components: hepatocytes, bile canaliculi, and hepatic sinusoids. A **hepatocyte** is the liver's main cell type, accounting for around 80 percent of the liver's volume. These cells play a role in a wide variety of secretory, metabolic, and endocrine functions. Plates of hepatocytes called hepatic laminae radiate outward from the central vein in each **hepatic lobule**. The liver lobule is a hexagon shape with **portal triads** on each corner at the perimeter of the hexagon. The portal triad is a distinctive arrangement consisting of three basic structures: a bile duct, a small branch of the hepatic artery (portal arteriole) bringing in oxygenated blood and a branch of the hepatic portal vein (portal venule) delivering nutrient rich blood. The bile duct carries freshly made bile away from hepatocytes toward the gallbladder and duodenum.

Between adjacent hepatocytes, grooves in the cell membranes provide room for each **bile canaliculus** (plural = canaliculi). These small ducts accumulate the bile produced by hepatocytes. From the hepatocyes, bile flows first into bile ductules and then into bile ducts. The bile ducts unite to form the larger right and left hepatic ducts, which themselves merge and exit the liver as the **common hepatic duct** (Figure 21.7.4). This duct then joins with the cystic duct from the gallbladder, forming the **common bile duct** through which bile flows into the small intestine.

A **hepatic sinusoid** is an open, porous blood space formed by fenestrated capillaries from nutrient-rich hepatic portal veins and oxygen-rich hepatic arteries. Hepatocytes are tightly packed around the fenestrated endothelium of these spaces, giving them easy access to the blood. From their central position, hepatocytes process the nutrients, toxins, and waste materials carried by the blood. Materials such as bilirubin are processed and excreted into the bile canaliculi. Other materials including proteins, lipids, and carbohydrates are processed and secreted into the sinusoids or just stored in the cells until called upon. The hepatic sinusoids combine and send blood to a **central vein**. Blood then flows through a **hepatic vein** into the inferior vena cava. This means that blood and bile flow in opposite directions. The hepatic sinusoids also contain star-shaped **reticuloendothelial cells** (Kupffer cells), phagocytes that remove dead red and white blood cells, bacteria, and other foreign material that enter the sinusoids.

Bile

Recall that lipids are hydrophobic, that is, they do not dissolve in water. Thus, before they can be digested in the watery

environment of the small intestine, large lipid globules must be broken down into smaller lipid globules, a process called emulsification. **Bile** is a mixture secreted by the liver to accomplish the emulsification of lipids in the small intestine.

Hepatocytes secrete about one liter of bile each day. A yellow-brown or yellow-green alkaline solution (pH 7.6 to 8.6), bile is a mixture of water, bile salts, bile pigments (including bilirubin), phospholipids (such as lecithin), electrolytes, cholesterol, and triglycerides. Some molecules in bile have regions attracted to water molecules and regions attracted to lipids. This results in the large lipid globules being pulled apart into many tiny lipid fragments of about 1 μm in diameter. This change dramatically increases the surface area available for lipid-digesting enzyme activity. This is the same way dish soap works on fats mixed with water.

Bile salts act as emulsifying agents, explained above, so they are also important for the absorption of digested lipids. While most constituents of bile are eliminated in feces, bile salts are reclaimed by the **enterohepatic circulation**. Once bile salts reach the ileum, they are absorbed and returned to the liver in the hepatic portal blood. The hepatocytes then excrete the bile salts into newly formed bile. Thus, this precious resource is recycled.

Bilirubin, the main bile pigment, is a waste product produced when the spleen removes old or damaged red blood cells from the circulation. These breakdown products, including proteins, iron, and toxic bilirubin, are transported to the liver via the splenic vein of the hepatic portal system. In the liver, proteins and iron are recycled, whereas bilirubin is excreted in the bile. It accounts for the green color of bile. Bilirubin is eventually transformed by intestinal bacteria into stercobilin, a brown pigment that gives your stool its characteristic color! In some disease states, bile does not enter the intestine, resulting in white ('acholic') stool with a high fat content, since virtually no fats are broken down or absorbed.

Hepatocytes work non-stop, but bile production increases when fatty chyme enters the duodenum and stimulates the secretion of the gut hormone secretin. Between meals, bile is produced but conserved. The valve-like hepatopancreatic ampulla closes, allowing bile to divert to the gallbladder, where it is concentrated and stored until the next meal.

Pancreas

The soft, oblong, glandular **pancreas** lies transversely in the retroperitoneum behind the stomach. Its head is nestled into the "c-shaped" curvature of the duodenum with the body extending to the left about 15.2 cm (6 in) and ending as a tapering tail in the hilum of the spleen. It performs a curious mix of exocrine (secreting digestive enzymes) and endocrine (releasing hormones into the blood) functions (Figure 21.7.3). Histology of the pancreas reveals round clusters of acinar cells connected to the pancreatic duct and the bigger clusters of pancreatic islets.

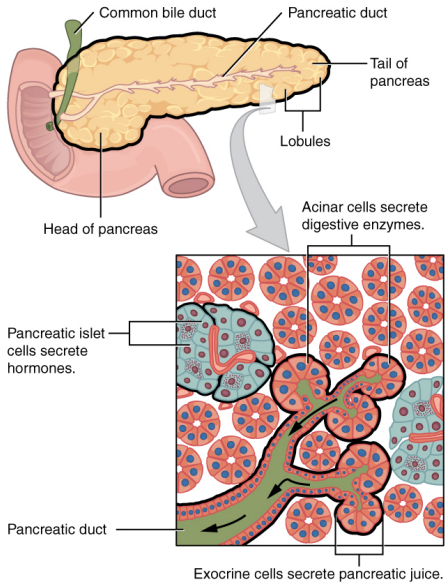

Figure 21.7.3: Exocrine and Endocrine Pancreas. The pancreas has a head, a body, and a tail. It delivers pancreatic juice to the duodenum through the pancreatic duct. (Image credit: "Exocrine and Endocrine Pancreas" by OpenStax is licensed under CC BY 3.0)

The exocrine part of the pancreas arises as little grape-like cell clusters, each called an **acinus** (plural = acini), located at the terminal ends of pancreatic ducts. These acinar cells secrete enzyme-rich **pancreatic juice** into tiny merging ducts that form two

dominant ducts. The larger duct fuses with the common bile duct (carrying bile from the liver and gallbladder) just before entering the duodenum via a common opening (the hepatopancreatic ampulla). The smooth muscle sphincter of the hepatopancreatic ampulla controls the release of pancreatic juice and bile into the small intestine. The second and smaller pancreatic duct, the **accessory duct** (duct of Santorini), present in approximately 30% of the population, runs from the pancreas directly into the duodenum, approximately 1 inch above the hepatopancreatic ampulla. When present, it is a persistent remnant of pancreatic development.

Scattered through the sea of exocrine acini are small islands of endocrine cells, the islets of Langerhans. These vital cells produce the hormones pancreatic polypeptide, insulin, glucagon, and somatostatin. These hormones play roles in regulating several metabolic functions.

Pancreatic Juice

The pancreas produces over a liter of pancreatic juice each day. Unlike bile, it is clear and composed mostly of water along with some salts, sodium bicarbonate, and several digestive enzymes. Sodium bicarbonate is responsible for the slight alkalinity of pancreatic juice (pH 7.1 to 8.2), which serves to buffer the acidic gastric juice in chyme, inactivate pepsin from the stomach, and create an optimal environment for the activity of pH-sensitive digestive enzymes in the small intestine. Pancreatic enzymes are active in the digestion of sugars, proteins, and fats.

The pancreas produces protein-digesting enzymes in their inactive forms. These enzymes are activated in the duodenum. If produced in an active form, they would digest the pancreas (which is exactly what occurs in the disease, pancreatitis). The intestinal brush border enzyme **enteropeptidase** stimulates the activation of an enzyme that starts the cascade of other enzymes to digest proteins.

The enzymes that digest starch (amylase), fat (lipase), and nucleic acids (nuclease) are secreted in their active forms, since they do not attack the pancreas as do the protein-digesting enzymes.

Pancreatic Secretion

Regulation of pancreatic secretion is the job of hormones and the parasympathetic nervous system. The entry of acidic chyme into the duodenum and the presence of proteins and fats in the duodenum stimulates the release of multiple hormones of digestion. Parasympathetic regulation occurs through the vagus nerve, cranial nerve X, mainly during the cephalic and gastric phases of gastric secretion. Usually, the pancreas secretes just enough bicarbonate to counterbalance the amount of HCl produced in the stomach.

Gallbladder

Figure 21.7.4 is a drawing showing the anterior view of the gallbladder, part of the liver superior to the gallbladder, and the duct connecting the liver to gallbladder, eventually becoming the common bile duct. The **gallbladder** is 8–10 cm (~3–4 in) long and is nested in a shallow area on the posterior aspect of the right lobe of the liver. This muscular sac stores, concentrates, and, when stimulated, propels the bile into the duodenum via the common bile duct. The gallblader can accumulate gall stones over time, resulting in removal of the gallbladder with the gall stones in some people. It is divided into three regions. The fundus is the widest portion and tapers medially into the body, which in turn narrows to become the neck. The neck angles slightly superiorly as it approaches the hepatic duct. The cystic duct is 1–2 cm (less than 1 in) long and turns inferiorly as it bridges the neck and hepatic duct.

The simple columnar epithelium of the gallbladder mucosa is organized in rugae, similar to those of the stomach. There is no submucosa in the gallbladder wall. The wall's middle, muscular coat is made of smooth muscle fibers. When these fibers contract, the gallbladder's contents are ejected through the **cystic duct** and into the bile duct (Figure 21.7.4). Visceral peritoneum reflected from the liver capsule holds the gallbladder against the liver and forms the outer coat of the gallbladder. The gallbladder's mucosa absorbs water and ions from bile, concentrating it by up to 10-fold.

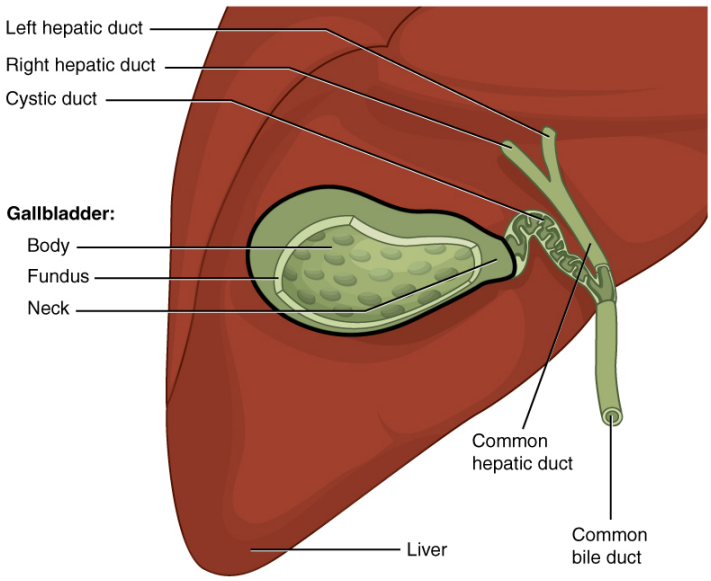

Figure 21.7.4: Gallbladder. The gallbladder stores and concentrates bile, and releases it into the two-way cystic duct when it is needed by the small intestine. (Image credit: "Gallbladder" by OpenStax is licensed under CC BY 3.0)

Concept Review

Chemical digestion in the small intestine cannot occur without the help of the liver and pancreas. The liver produces bile and delivers it to the common hepatic duct. Bile contains bile salts and phospholipids, which emulsify large lipid globules into tiny lipid droplets, a necessary step in lipid digestion and absorption. The gallbladder stores and concentrates bile, releasing it when it is needed by the small intestine.

The pancreas produces the enzyme- and bicarbonate-rich pancreatic juice and delivers it to the small intestine through ducts. Pancreatic juice buffers the acidic gastric juice in chyme, inactivates pepsin from the stomach, and enables the optimal functioning of digestive enzymes in the small intestine.

Review Questions

Q. Which of these statements about bile is true?

A. It is brown.

B. It is stored in the liver.

C. It is synthesized in the gallbladder.

D. Bile salts are recycled.

Answer

Answer: D

Q. Pancreas _____.

A. is anterior to the stomach.

B. has only a body and tail.

C. has a pancreatic duct to carry pancreatic juice to duodenum.

D. merges with the cystic duct.

Answer

Answer: C

Critical Thinking Questions

Q. When will gall stones be dangerous?

Answer

A. The pancreas secretes protein-digesting enzymes and empties them into the duodenum via the pancreatic duct. The pancreatic duct merges with the common bile duct prior to entering into the duodenum. A gall stone blocking this merging point can be dangerous because it leads to pancreatitis since the pancreatic enzymes are not emptied into the duodenum.

Q. Describe the location of hepatocytes in the liver and how this arrangement enhances their function.

Answer

A. The hepatocytes are the main cell type of the liver. They process, store, and release nutrients into the blood. Radiating out from the central vein, they are tightly packed around the hepatic sinusoids, allowing the hepatocytes easy access to the blood flowing through the sinusoids.

Glossary

accessory duct
(also, duct of Santorini) duct that runs from the pancreas into the duodenum

acinus
cluster of glandular epithelial cells in the pancreas that secretes pancreatic juice in the pancreas

bile
alkaline solution produced by the liver and important for the emulsification of lipids

bile canaliculus
small duct between hepatocytes that collects bile

bilirubin
main bile pigment, which is responsible for the brown color of feces

central vein
vein that receives blood from hepatic sinusoids

common bile duct
structure formed by the union of the common hepatic duct and the gallbladder's cystic duct

common hepatic duct
duct formed by the merger of the two hepatic ducts

cystic duct
duct through which bile drains and enters the gallbladder

enterohepatic circulation
recycling mechanism that conserves bile salts

enteropeptidase
intestinal brush-border enzyme that activates trypsinogen to trypsin

gallbladder
accessory digestive organ that stores and concentrates bile

hepatic artery
artery that supplies oxygenated blood to the liver

hepatic lobule
hexagonal-shaped structure composed of hepatocytes that radiate outward from a central vein

hepatic portal vein
vein that supplies deoxygenated nutrient-rich blood to the liver

hepatic sinusoid
blood capillaries between rows of hepatocytes that receive blood from the hepatic portal vein and the branches of the hepatic artery

hepatic vein
vein that drains into the inferior vena cava

hepatocytes
major functional cells of the liver

liver
largest gland in the body whose main digestive function is the production of bile

pancreas
accessory digestive organ that secretes pancreatic juice

pancreatic juice
secretion of the pancreas containing digestive enzymes and bicarbonate

porta hepatis
“gateway to the liver” where the hepatic artery and hepatic portal vein enter the liver

portal triad
bile duct, hepatic artery branch, and hepatic portal vein branch

reticuloendothelial cell
(also, Kupffer cell) phagocyte in hepatic sinusoids that filters out material from venous blood from the alimentary canal

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22: URINARY SYSTEM

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22.1: Introduction to the Urinary System

22.2: Overview of the Kidney

22.3: Microscopic Anatomy of the Kidney

22.4: Urinary Tract

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22.1: Introduction to the Urinary System

Chapter Learning Objectives

- Label structures of the urinary system
- Characterize the roles of each of the parts of the urinary system
- Illustrate the macroscopic and microscopic structures of the kidney
- Trace the flow of blood and urine through the kidney
- Trace the flow of urine through the urinary tract

This chapter will help you to understand the anatomy of the urinary system: kidneys, ureters, urinary bladder, and urethra. You will trace the blood flow through the kidney; think of the kidney as a regulator of plasma makeup rather than simply a urine producer. Knowing the anatomy will help you to understand how the urinary system maintains homeostasis and affects all the other systems of the body when you take physiology.

Interactive Link

QR Code representing a URL

Watch this video Kidney Function from the Howard Hughes Medical Institute for an introduction to the urinary system.

The Urinary or Renal System consists of two kidneys and the pathway, two ureters, urinary bladder, and one urethra, for urine to exit the body. The kidneys' primary function is to make urine by first filtering out many of the electrolytes, solutes, and water in the blood, forming the filtrate. As the filtrate passes through microscopic units called nephrons, certain solutes and water molecules are reabsorbed back to the blood because they are too precious to waste and other molecules are secreted because the body does not want them. As the filtrate becomes more concentrated, because water has been reabsorbed back to the blood, as it moves through the nephron, the end product is urine containing the waste products that the body can spare. Another perspective on the function of the kidneys is to monitor the level of certain solutes in the blood to maintain homeostasis. The kidneys' secondary function is to make hormones. Please review the Endocrine chapter for details.

The two ureters will carry urine from the kidneys down to the urinary bladder by peristalsis for storage. As the urinary bladder fills with urine, nerve endings will detect the stretched bladder to signal emptying. With sphincters relaxing, urine will flow out of the urinary bladder through the urethra to be expelled.

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22.2: Overview of the Kidney

By the end of the section, you will be able to:

- Describe the external structure of the kidney, including its location, support structures, and covering
- Identify the major internal divisions and structures of the kidney
- Identify the major blood vessels associated with the kidney and trace the path of blood through the kidney
- Name the structures in a nephron
- Trace the flow of fluid from blood through the kidney as urine

The kidneys lie on either side of the spine in the retroperitoneal space between the parietal peritoneum and the posterior abdominal wall, well protected by muscle, fat, and ribs. They are roughly the size of your fist, and the male kidney is typically a bit larger than the female kidney. The kidneys are well vascularized, receiving about 25 percent of the cardiac output at rest.

Interactive Link

QR Code representing a URL

There have never been sufficient kidney donations to provide a kidney to each person needing one. Watch this video Printing A Human Kidney to learn about the TED (Technology, Entertainment, Design) Conference held in March 2011. In this video, Dr. Anthony Atala discusses a cutting-edge technique in which a new kidney is “printed.” The successful utilization of this technology is still several years in the future, but imagine a time when you can print a replacement organ or tissue on demand.

External Anatomy

The left kidney is located at about the T12 to L3 vertebrae, whereas the right is lower due to slight displacement by the liver. Upper portions of the kidneys are somewhat protected by the eleventh and twelfth ribs (Figure 22.2.1). The two lowest ribs, which are also floating ribs, are hovering over the two kidneys. Each kidney weighs about 125–175 g in males and 115–155 g in females. They are about 11–14 cm in length, 6 cm wide, and 4 cm thick, and are directly covered by a **fibrous capsule** composed of dense, irregular connective tissue that helps to hold their shape and protect them. This capsule is covered by a shock-absorbing layer of adipose tissue called the **renal fat pad**, which in turn is encompassed by a tough **renal fascia**. The fascia and, to a lesser extent, the overlying peritoneum serve to firmly anchor the kidneys to the posterior abdominal wall in a retroperitoneal position.

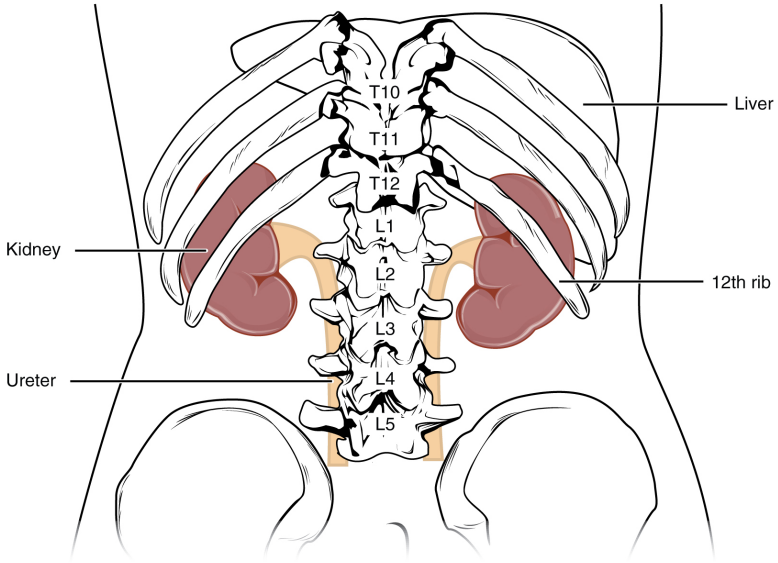

Figure 22.2.1: Kidneys. The kidneys are slightly protected by the ribs and are surrounded by fat for protection (Image credit: "Kidney Position in Abdomen" by OpenStax is licensed under CC BY 3.0).

On the superior aspect of each kidney is the adrenal gland. The adrenal cortex directly influences renal function through the production of the hormone aldosterone to stimulate sodium reabsorption.

Renal Hilum

The **renal hilum** is the entry and exit site for structures servicing the kidneys: vessels, nerves, lymphatics, and **ureters**. The medial-facing hila are tucked into the sweeping convex outline of the cortex. Emerging from the hilum is the **renal pelvis**, which is formed from the **major** and **minor calyces** (calyx singular) in the kidney. The smooth muscle in the renal pelvis funnels urine via peristalsis into the ureter. The **renal arteries** form directly from the descending aorta, whereas the **renal veins** return cleansed blood directly to the inferior vena cava. The artery, vein, and renal pelvis are arranged in an anterior-to-posterior order.

Internal Anatomy

A frontal section through the kidney reveals a thin outer region called the **renal cortex** and an inner region called the **medulla** (Figure 22.2.2). The **renal columns** are connective tissue extensions that radiate downward from the cortex through the medulla to separate the most characteristic features of the medulla: the **renal pyramids** and **renal papillae**. The papillae are bundles of collecting ducts that transport urine made by nephrons, explained further down, to the **minor calyces** then the **major calyces** of the kidney then to the renal pelvis for excretion. The renal columns also serve to divide the kidney into 6–8 lobes and provide a supportive framework for vessels that enter and exit the cortex. The pyramids and renal columns taken together constitute the kidney lobes.

Longitudinal cross-section of kidney showing the gross anatomical structures.

Figure 22.2.2: Left Kidney Cross section reveals outer cortex and inner medulla with blood vessels and ureter branching toward medulla. (Image credit: "Kidney Anatomy" by BruceBlaus is licensed under CC BY 3.0)

Blood Vessels

The renal artery enters the kidney medially, first divides into **segmental arteries** moving toward the medulla, followed by further branching to form **interlobar arteries** that pass through the renal columns to reach the cortex (Figure 22.2.3). The interlobar arteries, in turn, branch into **arcuate arteries** lying between the renal cortex and renal medulla. Arcuate arteries will branch further to form **interlobular** or **cortical radiate arteries** that extends into the cortex, and then branch into **afferent arterioles**. The afferent arterioles service about 1.3 million nephrons in each kidney. Afferent arterioles lead blood to the beginning of the nephron.

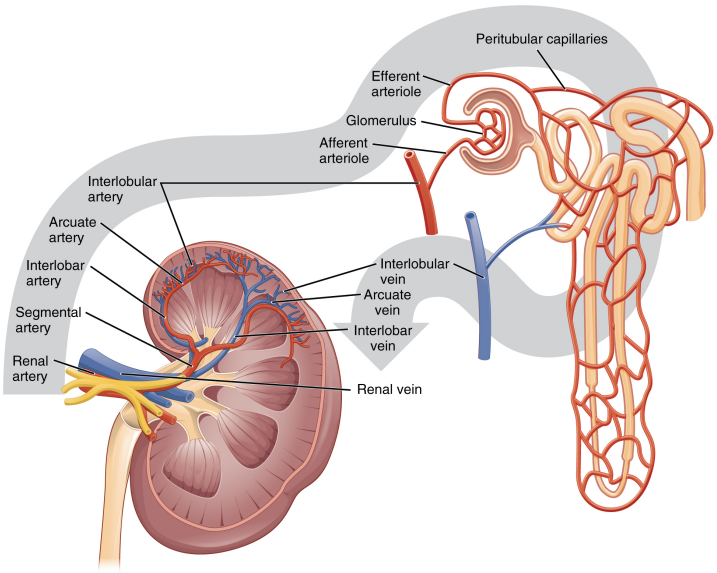

Figure 22.2.3: Blood Flow in the Kidney . Image traces the blood from renal artery to capillary and back to renal vein. (Image credit: "Blood Flow in the Kidney" by OpenStax is licensed under CC BY 3.0)

Nephrons are the "functional units" of the kidney; they cleanse the blood and balance the constituents of the circulation. (Figures 22.2.5 and 22.2.6) The afferent arterioles form a tuft of high-pressure capillaries about 200 µm in diameter, called the **glomerulus**. The rest of the nephron consists of a continuous sophisticated tubule whose proximal end surrounds the glomerulus in an intimate embrace—this is **Bowman's capsule** (glomerular capsule). The glomerulus and Bowman's capsule together form the **renal corpuscle**. These glomerular capillaries filter the blood based on particle size. After passing through the renal corpuscle, the capillaries form a second arteriole, the **efferent arteriole**. These will next form a capillary network around the more distal portions of the nephron tubule, the **peritubular capillaries** (around the tubules) and **vasa recta** (straight vessels) that will run around the nephron loop, before returning to the venous system. Blood from the capillaries then empty into venules. These merge to form **interlobular veins**, which then merge to form **arcuate veins**. These then merge to form **interlobar veins** which merge to become the **renal vein**. (Figure 22.2.3) There is no segmental vein. As the glomerular filtrate progresses through the nephron, these capillary networks recover most of the solutes and water, and return them to the circulation.

Since a capillary bed (the glomerulus) drains into a vessel that in turn forms a second capillary bed, the definition of a portal system is met. This is the only portal system in which an arteriole is found between the first and second capillary beds. (Portal systems also link the hypothalamus to the anterior pituitary, and the blood vessels of the digestive viscera to the liver.)

Nephrons

Nephrons are microscopic structures to make urine, thus they are the "functional" units in the kidneys. Figures 22.2.4 shows one nephron and the blood vessels running around it. Each nephron starts with the **renal corpuscle**, which has the Bowman's capsule surrounding the glomerulus (capillary). The renal corpuscle continues as the **proximal convoluted tubule (PCT)** which straightens out as the **descending limb** and makes a U-turn to become the **ascending limb** of the nephron loop. **Nephron loop** is also called the **loop of Henle**. The loop will become the **distal convoluted tubule (DCT)** and this is the end of the nephron. The content inside, soon to be urine, will continue from the DCT to the collecting duct.

In a dissected kidney, it is easy to identify the cortex; it appears lighter in color compared to the rest of the kidney. Different parts of the nephrons are found in the cortex. All of the renal corpuscles as well as both the proximal convoluted tubules (PCTs) and distal convoluted tubules are found here. Some nephrons have a short loop of Henle that does not dip beyond the cortex. These nephrons are called **cortical nephrons**. About 15 percent of nephrons have long loops of Henle that extend deep into the medulla and are called **juxtamedullary nephrons**. Figure 22.2.5 shows two types of nephrons, cortical and juxtamedullary nephrons, named according to their locations. Details of nephrons will be discussed in the next section, Section 22.3.

Blood vessels are entering the nephron at the Bowman's capsule and capillaries are intertwined with tubules.

Figure 22.2.4: Nephron Anatomy. The capillaries are intertwined with the nephron. (Image credit: "Nephron Anatomy" by BruceBlaus is licensed under CC BY 3.0)

Juxtamedullary nephron is on the left and cortical nephron is on the right.

Figure 22.2.5: Two Types of Nephron. The cortex is in the upper region, lightly colored; the medulla is in the lower area, darkly colored. Juxtamedullary nephron is on the left with the loop of Henle dippin further in the medulla while the cortical nephron is on the right with the loop of Henle barely dipping into the medulla. (Image credit: "Kidney Nephrons" by Holly Fischer is licensed under CC BY 4.0)

Concept Review

As noted previously, the structure of the kidney is divided into two principle regions—the peripheral rim of cortex and the central medulla. The two kidneys receive about 25 percent of cardiac output. They are protected in the retroperitoneal space by the renal fat pad and overlying ribs and muscle. Ureters, blood vessels, lymph vessels, and nerves enter and leave at the renal hilum. The renal arteries arise directly from the aorta, and the renal veins drain directly into the inferior vena cava. Kidney function is derived from the actions of about 1.3 million nephrons per kidney; these are the "functional units." A capillary bed, the glomerulus, filters blood and the filtrate is captured by Bowman's capsule. A portal system is formed when the blood flows through a second capillary bed surrounding the proximal and distal convoluted tubules and the loop of Henle. Most water and solutes are recovered by this second capillary bed. This filtrate is processed and finally gathered by collecting ducts that drain into the minor calyces, which merge to form major calyces; the filtrate then proceeds to the renal pelvis and finally the ureters.

Review Questions

Q. The renal pyramids are separated from each other by extensions of the renal cortex called _____.

A. renal medulla

B. minor calyces

C. medullary cortices

D. renal columns

Answer

Answer: D

Q. The primary structure found within the medulla is the _____.

A. loop of Henle

B. minor calyces

C. portal system

D. ureter

Answer

Answer: A

Q. The right kidney is slightly lower because _____.

A. it is displaced by the liver

B. it is displace by the heart

C. it is slightly smaller

D. it needs protection of the lower ribs

Answer

Answer: A

Q. What are the names of the capillaries following the efferent arteriole?

A. arcuate and medullary

B. interlobar and interlobular

C. peritubular and vasa recta

D. peritubular and medullary

Answer

Answer: C

Critical Thinking Questions

Q. What anatomical structures provide protection to the kidney?

Answer

A. Retroperitoneal anchoring, renal fat pads, and ribs provide protection to the kidney.

Q. How does the renal portal system differ from the hypothalamo–hypophyseal and digestive portal systems?

Answer

A. The renal portal system has an artery between the first and second capillary bed. The others have a vein.

Glossary

Bowman's capsule
cup-shaped sack lined by a simple squamous epithelium (parietal surface) and specialized cells called podocytes (visceral surface) that participate in the filtration process; receives the filtrate which then passes on to the PCTs

calyces
cup-like structures receiving urine from the collecting ducts where it passes on to the renal pelvis and ureter

cortical nephrons
nephrons with loops of Henle that do not extend into the renal medulla

distal convoluted tubules
portions of the nephron distal to the loop of Henle that receive hyposmotic filtrate from the loop of Henle and empty into collecting ducts

efferent arteriole
arteriole carrying blood from the glomerulus to the capillary beds around the convoluted tubules and loop of Henle; portion of the portal system

glomerulus
tuft of capillaries surrounded by Bowman's capsule; filters the blood based on size

juxtamedullary nephrons
nephrons adjacent to the border of the cortex and medulla with loops of Henle that extend into the renal medulla

loop of Henle
descending and ascending portions between the proximal and distal convoluted tubules; those of cortical nephrons

do not extend into the medulla, whereas those of juxtamedullary nephrons do extend into the medulla

nephrons
functional units of the kidney that carry out all filtration and modification to produce urine; consist of renal corpuscles, proximal and distal convoluted tubules, and descending and ascending loops of Henle; drain into collecting ducts

medulla
inner region of kidney containing the renal pyramids

peritubular capillaries
second capillary bed of the renal portal system; surround the proximal and distal convoluted tubules; associated with the vasa recta

proximal convoluted tubules (PCTs)
tortuous tubules receiving filtrate from Bowman's capsule; most active part of the nephron in reabsorption and secretion

renal columns
extensions of the renal cortex into the renal medulla; separates the renal pyramids; contains blood vessels and connective tissues

renal corpuscle
consists of the glomerulus and Bowman's capsule

renal cortex
outer part of kidney containing all of the nephrons; some nephrons have loops of Henle extending into the medulla

renal fat pad
adipose tissue between the renal fascia and the renal capsule that provides protective cushioning to the kidney

renal hilum
recessed medial area of the kidney through which the renal artery, renal vein, ureters, lymphatics, and nerves pass

renal papillae
medullary area of the renal pyramids where collecting ducts empty urine into the minor calyces

renal pyramids
six to eight cone-shaped tissues in the medulla of the kidney containing collecting ducts and the loops of Henle of juxtamedullary nephrons

vasa recta
branches of the efferent arterioles that parallel the course of the loops of Henle and are continuous with the peritubular capillaries; with the glomerulus, form a portal system

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22.3: Microscopic Anatomy of the Kidney

By the end of the section, you will be able to:

- Describe the structure of the filtration membrane
- Identify the major structures and subdivisions of the renal corpuscles and renal tubules
- Identify the location of the juxtaglomerular apparatus and describe the cells that line it
- Describe the histology of the proximal convoluted tubule, loop of Henle, distal convoluted tubule, and collecting ducts

The renal structures that conduct the essential work of the kidney cannot be seen by the naked eye. Only a light or electron microscope can reveal these structures. Even then, serial sections and computer reconstruction are necessary to give us a comprehensive view of the functional anatomy of the nephron and its associated blood vessels.

Nephrons: The Functional Unit

Nephrons take a simple filtrate of the blood and modify it into urine. Many changes take place in the different parts of the nephron before urine is created for disposal. The term **forming urine** will be used hereafter to describe the filtrate as it is modified into true urine. The principle task of the nephron population is to balance the plasma to homeostatic set points and excrete potential toxins in the urine. They do this by accomplishing three principle functions—filtration, reabsorption, and secretion. They also have additional secondary functions that exert control in three areas: blood pressure (via production of **renin**), red blood cell production (via the hormone EPO), and calcium absorption (via conversion of calcidiol into calcitriol, the active form of vitamin D).

Renal Corpuscle

As discussed earlier, the renal corpuscle consists of a tuft of capillaries called the glomerulus that is largely surrounded by Bowman's (glomerular) capsule. The glomerulus is a high-pressure capillary bed between afferent and efferent arterioles. Bowman's capsule surrounds the glomerulus to form a lumen, and captures and directs this filtrate to the PCT. The outermost part of Bowman's capsule, the parietal layer, is a simple squamous epithelium. It transitions onto the glomerular capillaries in an intimate embrace to form the visceral layer of the capsule. Here, the cells are not squamous, but uniquely shaped cells (**podocytes**) extending finger-like arms (**pedicels**) to cover the glomerular capillaries (Figure 22.3.1 and 22.3.2). These projections interdigitate to form **filtration slits**, leaving small gaps between the digits to form a sieve. As blood passes through the glomerulus, 10 to 20 percent of the plasma filters between these sieve-like fingers to be captured by Bowman's capsule and funneled to the PCT. Where the fenestrae (windows) in the glomerular capillaries match the spaces between the podocyte "fingers," the only thing separating the capillary lumen and the lumen of Bowman's capsule is their shared basement membrane (Figure 22.3.3). These three features, fenestrated endothelium, basement membrane, and pedicels comprise what is known as the **filtration membrane**. This membrane permits very rapid movement of filtrate from capillary to capsule though pores that are only 70 nm in diameter.

Figure 22.3.1: Glomerulum. Glomerulus of mouse kidney in Scanning Electron Microscope, magnification 1,000x. (Image credit: "Glomerulus" by SecretDisc is licensed under CC BY 3.0)

Figure 22.3.2: Glomerulum, Cross-Section. Glomerulus of mouse kidney with broken capillary in Scanning Electron Microscope, magnification 10,000x. (Image credit: "Broken Capillary Glomerulum" by SecretDisc is licensed under CC BY 3.0)

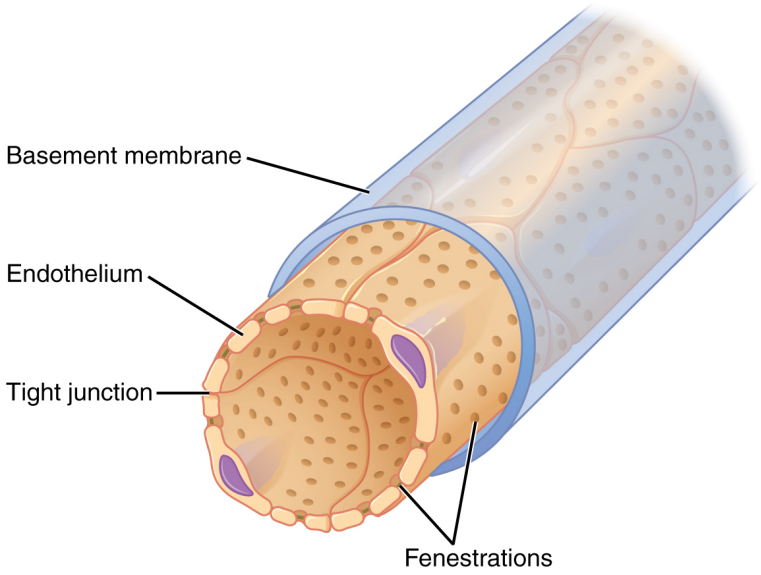

Figure 22.3.3: Fenestrated Capillary. Fenestrations allow many substances to diffuse from the blood based primarily on size. (Image credit: "Fenestrated Capillary" by OpenStax is licensed under CC BY 3.0).

The **fenestrations** prevent filtration of blood cells or large proteins, but allow most other constituents through. These substances cross readily if they are less than 4 nm in size and most pass freely up to 8 nm in size. An additional factor affecting the ability of substances to cross this barrier is their electric charge. The proteins associated with these pores are negatively charged, so they tend to repel negatively charged substances and allow positively charged substances to pass more readily. The basement membrane prevents filtration of medium-to-large proteins such as globulins. There are also **mesangial** cells in the filtration membrane that can contract to help regulate the rate of filtration of the glomerulus. Overall, filtration is regulated by fenestrations in capillary endothelial cells, podocytes with filtration slits, membrane charge, and the basement membrane between capillary cells. The result is the creation of a filtrate that does not contain cells or large proteins, and has a slight predominance of positively charged substances.

Lying just outside Bowman's capsule and the glomerulus is the **juxtaglomerular apparatus (JGA).** At the juncture where the afferent and efferent arterioles enter and leave Bowman's capsule, the initial part of the distal convoluted tubule (DCT) comes into direct contact with the arterioles. The wall of the DCT at that point forms a part of the JGA known as the **macula densa**. This cluster of cuboidal epithelial cells monitors the fluid composition of fluid flowing through the DCT (Figure 22.3.4).

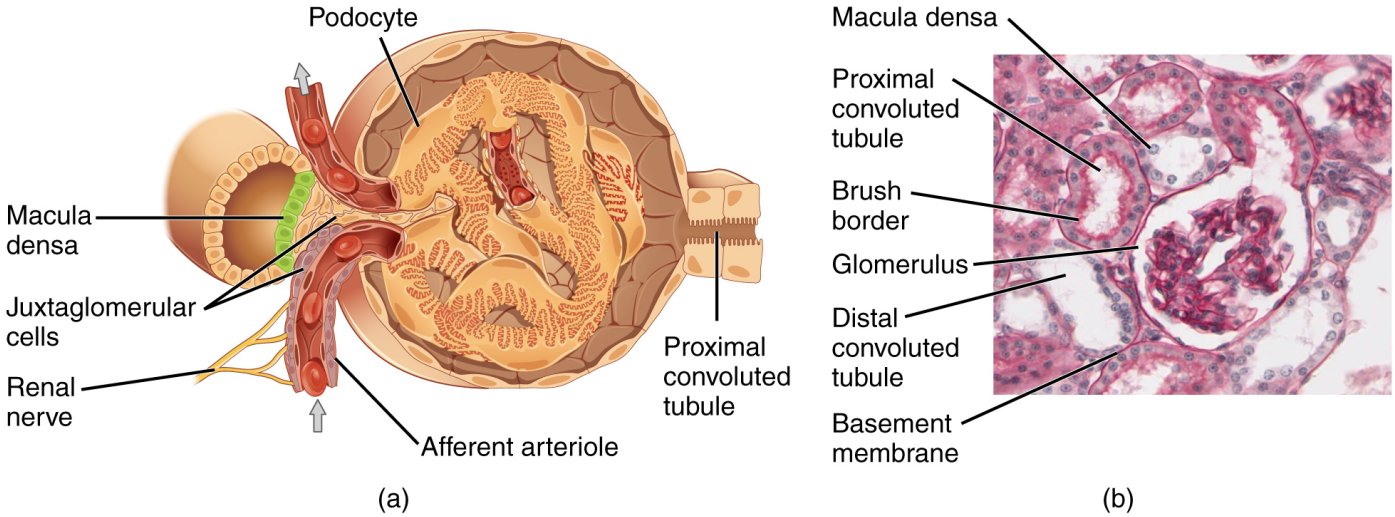

Figure 22.3.4:: Juxtaglomerular Apparatus and Glomerulus. (a) The JGA allows specialized cells to monitor the composition of the fluid in the DCT and adjust the glomerular filtration rate. (b) This micrograph shows the glomerulus and surrounding structures. LM × 1540; Micrograph provided by the Regents of University of Michigan Medical School © 2012. (Image credit: "Juxtaglomerular Apparatus and Glomerulus" by OpenStax is licensed under CC BY 3.0)

A second cell type in this apparatus is the **juxtaglomerular cell**. This is a modified, smooth muscle cell lining the afferent arteriole that can contract or relax in response to ATP or adenosine released by the macula densa. Such contraction and relaxation regulate blood flow to the glomerulus. A second function of the macula densa cells is to regulate **renin** release from the juxtaglomerular cells of the afferent arteriole. Renin, other proteins, such as **angiotensin I** and **angiotensin II**, and hormones, such as **antidiuretic hormone (ADH)** and **aldosterone**, regulate blood pressure by adjusting the amount of water retained by the kidneys.

Proximal Convoluted Tubule (PCT)

Filtered fluid collected by Bowman's capsule enters into the PCT. It is called convoluted due to its tortuous path. Simple cuboidal cells form this tubule with prominent microvilli on the luminal surface, forming a **brush border**. These microvilli create a large surface area to maximize the absorption and secretion of solutes (Na^+, Cl^-, glucose, etc.), the most essential function of this portion of the nephron. These cells actively transport ions across their membranes, so they possess a high concentration of mitochondria in order to produce sufficient ATP.

Loop of Henle

The descending and ascending portions of the loop of Henle (sometimes referred to as the nephron loop) are, of course, just continuations of the same tubule. They run adjacent and parallel to each other after having made a hairpin turn at the deepest point of their descent. The descending loop of Henle consists of an initial short, thick portion and long, thin portion, whereas the ascending loop consists of an initial short, thin portion followed by a long, thick portion. The descending thick portion consists of simple cuboidal epithelium similar to that of the PCT. The descending and ascending thin portions consists of simple squamous epithelium. These are important differences, since different portions of the loop have different permeabilities for solutes and water. The ascending thick portion consists of simple cuboidal epithelium similar to the DCT.

Distal Convoluted Tubule (DCT)

The DCT, like the PCT, is very tortuous and formed by simple cuboidal epithelium, but it is shorter than the PCT. These cells are not as active as those in the PCT; thus, there are fewer microvilli on the apical surface. However, these cells must also pump ions against their concentration gradient, so you will find of large numbers of mitochondria, although fewer than in the PCT.

Collecting Ducts

The collecting ducts are continuous with the nephron but not technically part of it. In fact, each duct collects filtrate from several nephrons for final modification. Collecting ducts merge as they descend deeper in the medulla to form about 30 terminal ducts, which empty at a papilla. They are lined with simple squamous epithelium with receptors for ADH. When stimulated by ADH, these cells will insert **aquaporin** channel proteins into their membranes, which as their name suggests, allow water to pass from the duct lumen through the cells and into the interstitial spaces to be recovered by the vasa recta (Figure 22.3.5). This process allows for the recovery of large amounts of water from the filtrate back into the blood. In the absence of ADH, these channels are not inserted, resulting in the excretion of water in the form of dilute urine. Most, if not all, cells of the body contain aquaporin molecules, whose channels are so small that only water can pass. At least 10 types of aquaporins are known in humans, and six of those are found in the kidney. The function of all aquaporins is to allow the movement of water across the lipid-rich, hydrophobic cell membrane. Figure 22.3.5 is a drawing of one aquaporin, water channel, as a large protein inserted in the phospholipid bilayer cell membrane and multiple water molecules passing through the channel.

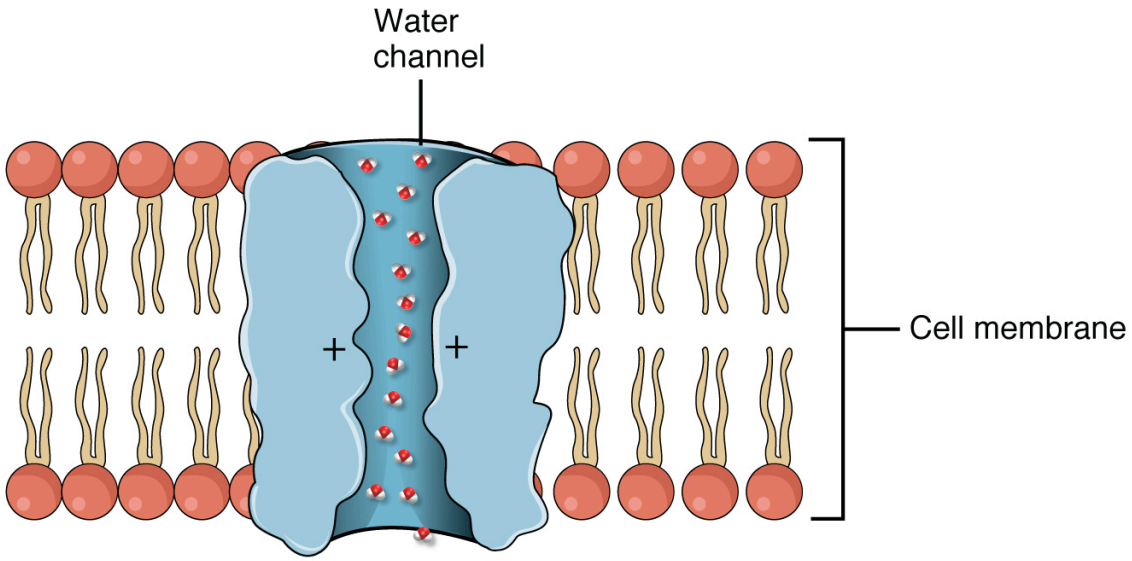

Figure 22.3.5:: Aquaporin Water Channel. Positive charges inside the channel prevent the leakage of electrolytes across the cell membrane, while allowing water to move due to osmosis. (Image credit: "Aquaporin Water Channel" by OpenStax is licensed under CC BY 3.0).

Concept Review

The functional unit of the kidney, the nephron, consists of the renal corpuscle, PCT, loop of Henle, and DCT. The glomerulus is a capillary bed that filters blood principally based on particle size. The filtrate is captured by Bowman's capsule and directed to the PCT. A filtration membrane is formed by the fused basement membranes of the podocytes and the capillary endothelial cells that they embrace. Contractile mesangial cells further perform a role in regulating the rate at which the blood is filtered. Specialized cells in the JGA produce paracrine signals to regulate blood flow and filtration rates of the glomerulus. Other JGA cells produce the enzyme renin, which plays a central role in blood pressure regulation. The filtrate enters the PCT where absorption and secretion of several substances occur. The descending and ascending limbs of the loop of Henle consist of thick and thin segments. Absorption and secretion continue in the DCT but to a lesser extent than in the PCT. Each collecting duct collects forming urine from several nephrons and responds to the posterior pituitary hormone ADH by inserting aquaporin water channels into the cell membrane to fine tune water recovery.

Review Questions

Q. Blood filtrate is captured in the lumen of the _____.

A. glomerulus

B. Bowman's capsule

C. calyces

D. renal papillae

Answer

Answer: B

Q. Which is least associated with the renal corpuscle?

A. podocyte

B. fenestration

C. cuboidal epithelium

D. pedicels

Answer

Answer: C

Q. Which is least associated with the juxtaglomerular apparatus?

A. afferent arteriole

B. distal convoluted tubule

C. proximal convoluted tubule

D. macula densa

Answer

Answer: C

Critical Thinking Questions

Q. Why is it abnormal to have blood in urine if the woman is not menstruating?

Answer

A. Red blood cells are too big to pass through the fenestrations from the glomerulus into the Bowman's capsule.

Q. What are the major structures comprising the filtration membrane?

Answer

A. The major structures comprising the filtration membrane are fenestrations and podocyte fenestra, fused basement membrane, and filtration slits.

Glossary

angiotensin-converting enzyme (ACE)
enzyme produced by the lungs that catalyzes the reaction of inactive angiotensin I into active angiotensin II

angiotensin I
protein produced by the enzymatic action of renin on angiotensinogen; inactive precursor of angiotensin II

angiotensin II
protein produced by the enzymatic action of ACE on inactive angiotensin I; actively causes vasoconstriction and stimulates aldosterone release by the adrenal cortex

angiotensinogen
inactive protein in the circulation produced by the liver; precursor of angiotensin I; must be modified by the enzymes renin and ACE to be activated

aquaporin
protein-forming water channels through the lipid bilayer of the cell; allows water to cross; activation in the collecting ducts is under the control of ADH

brush border
formed by microvilli on the surface of certain cuboidal cells; in the kidney it is found in the PCT; increases surface area for absorption in the kidney

fenestrations
small windows through a cell, allowing rapid filtration based on size; formed in such a way as to allow substances to cross through a cell without mixing with cell contents

filtration slits
formed by pedicels of podocytes; substances filter between the pedicels based on size

forming urine
filtrate undergoing modifications through secretion and reabsorption before true urine is produced

juxtaglomerular apparatus (JGA)
located at the juncture of the DCT and the afferent and efferent arterioles of the glomerulus; plays a role in the regulation of renal blood flow and GFR

juxtaglomerular cell
modified smooth muscle cells of the afferent arteriole; secretes renin in response to a drop in blood pressure

macula densa
cells found in the part of the DCT forming the JGA; sense Na^+ concentration in the forming urine

mesangial
contractile cells found in the glomerulus; can contract or relax to regulate filtration rate

pedicels
finger-like projections of podocytes surrounding glomerular capillaries; interdigitate to form a filtration membrane

podocytes
cells forming finger-like processes; form the visceral layer of Bowman's capsule; pedicels of the podocytes interdigitate to form a filtration membrane

renin
enzyme produced by juxtaglomerular cells in response to decreased blood pressure or sympathetic nervous activity; catalyzes the conversion of angiotensinogen into angiotensin I

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22.4: Urinary Tract

By the end of the section, you will be able to:

- Identify the ureters, urinary bladder, and urethra, as well as their location, structure, histology, and function
- Compare and contrast male and female urethras
- Describe the micturition reflex

Like the Digestive System with the digestive tract, the Urinary System also has a **urinary tract,** which includes the **ureters, urinary bladder**, and **urethra**. This section will start with urine excretion, tracing the flow of urine from the renal pelvis to ureter, urinary bladder, and urethra. Urine is a fluid of variable composition that requires specialized structures to remove it from the body safely and efficiently. Blood is filtered, and the filtrate is transformed into urine at a relatively constant rate throughout the day. This processed liquid is stored until a convenient time for excretion. All structures involved in the transport and storage of the urine are large enough to be visible to the naked eye. This transport and storage system not only stores the waste, but it protects the tissues from damage, prevents infection by foreign organisms, and for the male, provides reproductive functions.

Ureters

The kidneys and ureters are completely retroperitoneal, and the bladder has a peritoneal covering only over the dome. As urine is formed, it drains into the calyces of the kidney, which merge to form the funnel-shaped renal pelvis in the hilum of each kidney. The hilum narrows to become the ureter of each kidney. As urine passes through the ureter, it does not passively drain into the bladder but rather is propelled by waves of peristalsis. As the ureters enter the pelvis, they sweep laterally, hugging the pelvic walls. As they approach the bladder, they turn medially and pierce the bladder wall obliquely. This is important because it creates an one-way valve (a **physiological sphincter** rather than an **anatomical sphincter**) that allows urine into the bladder but prevents reflux of urine from the bladder back into the ureter. Children born lacking this oblique course of the ureter through the bladder wall are susceptible to “vesicoureteral reflux,” which dramatically increases their risk of serious UTI. Pregnancy also increases the likelihood of reflux and UTI.

The ureters are approximately 30 cm long (Figure 22.4.1). The inner mucosa is lined with transitional epithelium and scattered goblet cells that secrete protective mucus. The muscular layer of the ureter consists of longitudinal and circular smooth muscles that create the peristaltic contractions to move the urine into the bladder without the aid of gravity. Finally, a loose adventitial layer composed of collagen and fat anchors the ureters between the parietal peritoneum and the posterior abdominal wall.

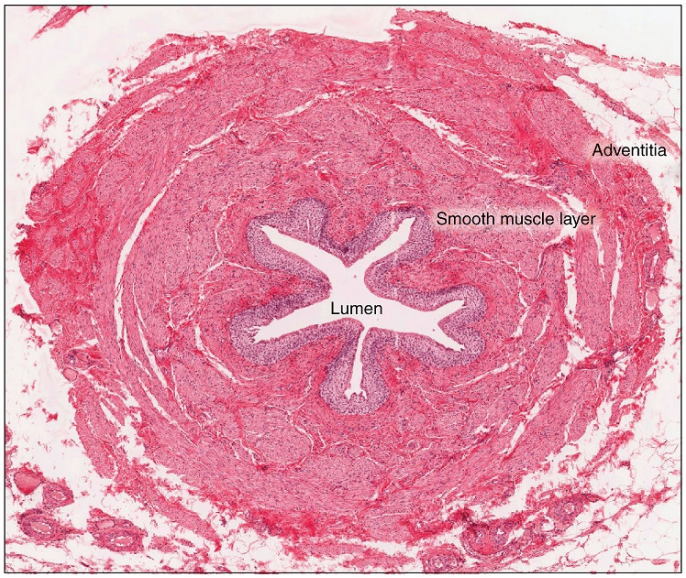

Figure 22.4.1: Ureter. Peristaltic contractions help to move urine through the lumen with contributions from fluid pressure and gravity. LM × 128; Micrograph provided by the Regents of the University of Michigan Medical School © 2012. (Image credit: "Ureter" by OpenStax is licensed under CC BY 3.0)

Urinary Bladder

The urinary bladder collects urine from both ureters (Figure 22.4.2). The bladder lies anterior to the uterus in females, posterior to the pubic bone and anterior to the rectum. During late pregnancy, its capacity is reduced due to compression by the enlarging uterus, resulting in increased frequency of urination. In males, the anatomy is similar, minus the uterus, and with the addition of the prostate inferior to the bladder. The bladder is partially **retroperitoneal** (outside the peritoneal cavity) with its peritoneal-covered "dome" projecting into the abdomen when the bladder is distended with urine.

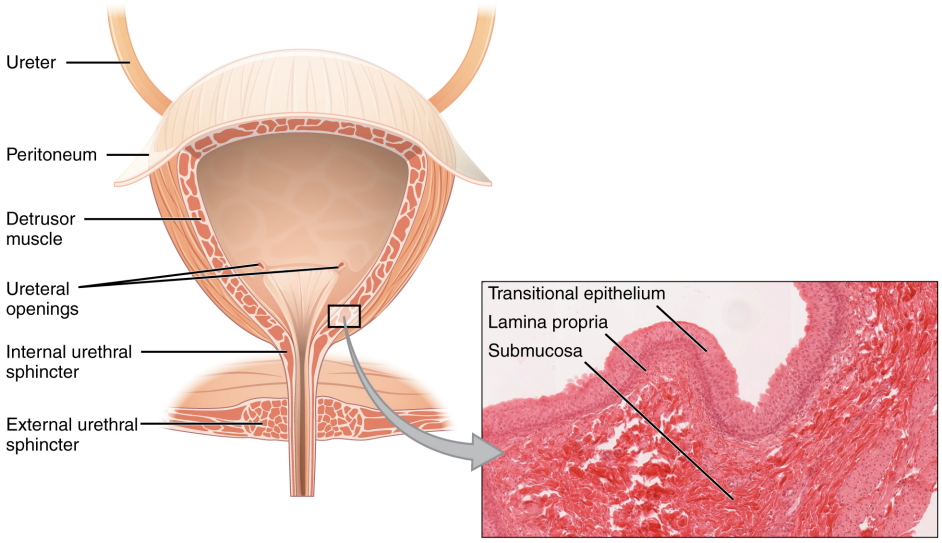

Figure 22.4.2: Bladder. (a) Anterior cross section of the bladder. (b) The detrusor muscle of the bladder (source: monkey tissue) LM × 448; Micrograph provided by the Regents of the University of Michigan Medical School © 2012. (Image credit: "Bladder" by OpenStax is licensed under CC BY 3.0)

The bladder is a highly distensible organ because the middle layer is comprised of irregular crisscrossing bands of smooth muscle collectively called the **detrusor muscle**. The interior surface is made of transitional cellular epithelium that is structurally

suited for the large volume fluctuations of the bladder. When empty, it resembles columnar epithelia, but when stretched, it "transitions" (hence the name) to a squamous appearance (see Figure 22.4.2). Volumes in adults can range from nearly zero to 500–600 mL. The detrusor muscle contracts with significant force in the young. The bladder's strength diminishes with age, but voluntary contractions of abdominal skeletal muscles can increase intra-abdominal pressure to promote more forceful bladder emptying. Such voluntary contraction is also used in forceful defecation and childbirth.

Urethra

The **urethra** transports urine from the bladder to the outside of the body for disposal. The urethra is the only urologic organ that shows any significant anatomic difference between males and females; all other urine transport structures are identical (Figure 22.4.3) The reproductive organs will be discussed in the next chapter for both male and female. The urinary structures are discussed in this chapter with more details to in the following paragraphs.

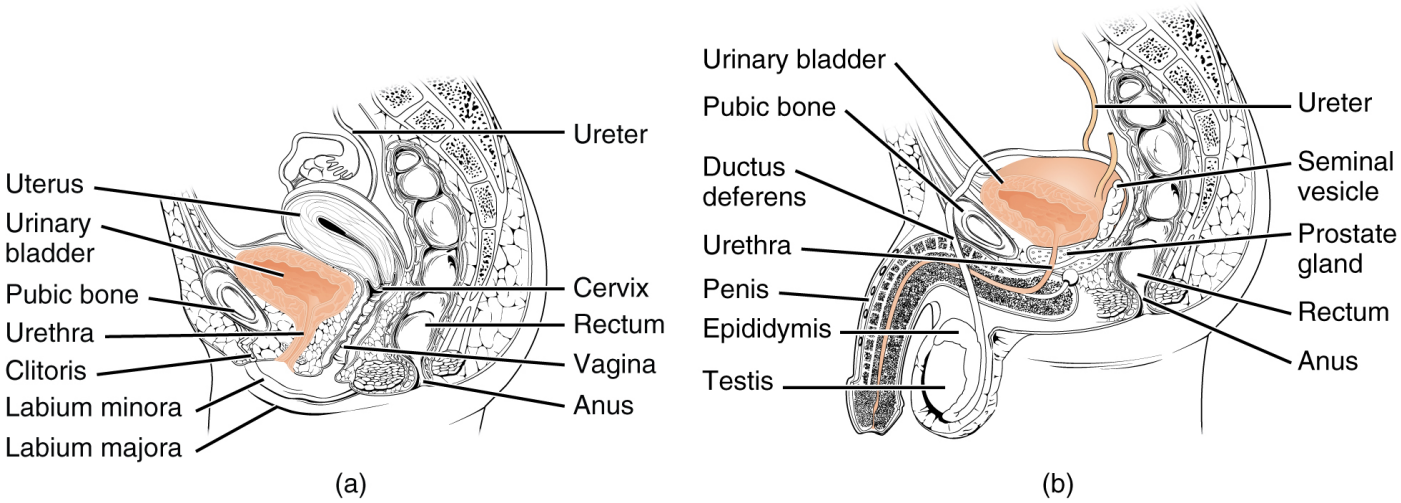

Figure 22.4.3: Female and Male Urethras. Urethra transports urine from the bladder to the outside of the body. This image shows (a) a female urethra and (b) a male urethra. (Image credit: "Female and Male Urethras" by OpenStax is licensed under CC BY 3.0)

The urethra in both males and females begins inferior and central to the two ureteral openings forming the three points of a triangular-shaped area at the base of the bladder called the **trigone** (Greek tri- = "triangle" and the root of the word "trigonometry"). The urethra tracks posterior and inferior to the pubic symphysis (see Figure 22.4.3). In both males and females, the proximal urethra is lined by transitional epithelium, whereas the terminal portion is a nonkeratinized, stratified squamous epithelium. In the male, pseudostratified columnar epithelium lines the urethra between these two cell types. Voiding is regulated by an involuntary autonomic nervous system-controlled **internal urinary sphincter**, consisting of smooth muscle and voluntary skeletal muscle that forms the **external urinary sphincter** below it.

Female Urethra

The external urethral orifice is embedded in the anterior vaginal wall inferior to the clitoris, superior to the vaginal opening (introitus), and medial to the labia minora. Its short length, about 4 cm, is less of a barrier to fecal bacteria than the longer male urethra and the best explanation for the greater incidence of UTI in women. Voluntary control of the external urethral sphincter is a function of the pudendal nerve. It arises in the sacral region of the spinal cord, traveling via the S2–S4 nerves of the sacral plexus.

Male Urethra

The male urethra passes through the prostate gland immediately inferior to the bladder before passing below the pubic symphysis (see Figure 22.4.3b). The length of the male urethra varies between men but averages 20 cm in length. It is divided into four regions: the **preprostatic urethra**, the **prostatic urethra**, the **membranous urethra**, and the **spongy** or **penile urethra**. The preprostatic urethra is very short and incorporated into the bladder wall. The prostatic urethra passes through the prostate gland. During sexual intercourse, it receives sperm via the ejaculatory ducts and secretions from the seminal vesicles. Paired Cowper's glands (bulbourethral glands) produce and secrete mucus into the urethra to buffer urethral pH during sexual stimulation. The

mucus neutralizes the usually acidic environment and lubricates the urethra, decreasing the resistance to ejaculation. The membranous urethra passes through the deep muscles of the perineum, where it is invested by the overlying urethral sphincters. The spongy urethra exits at the tip (external urethral orifice) of the penis after passing through the corpus spongiosum. Mucous glands are found along much of the length of the urethra and protect the urethra from extremes of urine pH. Innervation is the same in both males and females.

Micturition Reflex

Micturition is a less-often used, but proper term for urination or voiding. It results from an interplay of involuntary and voluntary actions by the internal and external urethral sphincters. When bladder volume reaches about 150 mL, an urge to void is sensed but is easily overridden. Voluntary control of urination relies on consciously preventing relaxation of the external urethral sphincter to maintain urinary continence. As the bladder fills, subsequent urges become harder to ignore. Ultimately, voluntary constraint fails with resulting **incontinence**, which will occur as bladder volume approaches 300 to 400 mL.

Nerves involved in the control of urination include the hypogastric, pelvic, and pudendal. Normal micturition is a result of stretch receptors in the bladder wall that transmit nerve impulses to the sacral region of the spinal cord to generate a spinal reflex. The resulting parasympathetic neural outflow causes contraction of the detrusor muscle and relaxation of the involuntary internal urethral sphincter. At the same time, the spinal cord inhibits somatic motor neurons, resulting in the relaxation of the skeletal muscle of the external urethral sphincter. The micturition reflex is active in infants but with maturity, children learn to override the reflex by asserting external sphincter control, thereby delaying voiding (potty training). This reflex may be preserved even in the face of spinal cord injury that results in paraplegia or quadriplegia. However, relaxation of the external sphincter may not be possible in all cases, and therefore, periodic catheterization may be necessary for bladder emptying.

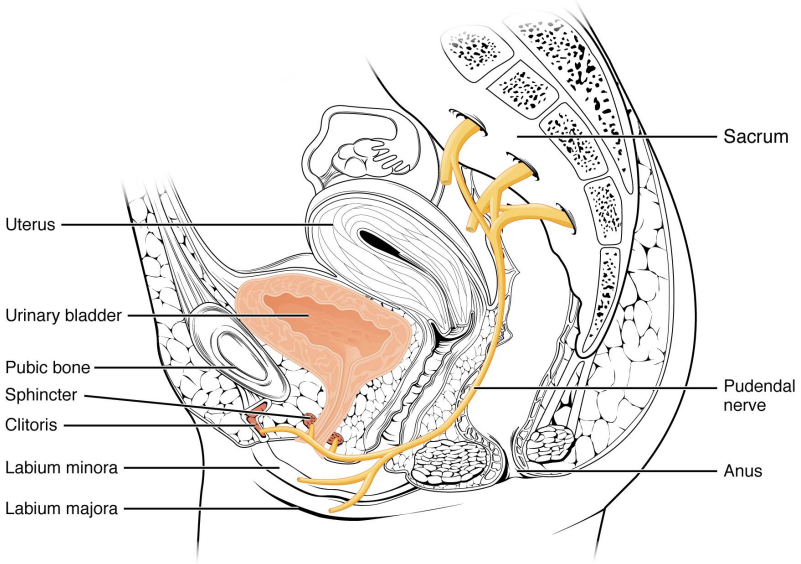

Figure 22.4.4: Female Pelvis with Nerves: Pudendal nerve is one nerve that innvervates this region. (Image credit: “Nerves Innervating the Urinary System” by OpenStax is licensed under CC BY 3.0).

Concept Review

The ureters are retroperitoneal and lead from the renal pelvis of the kidney to the trigone area at the base of the bladder. A thick muscular wall consisting of longitudinal and circular smooth muscle helps move urine toward the bladder by way of peristaltic contractions.The bladder is largely retroperitoneal and can hold up to 500–600 mL urine. The urethra is the only urinary structure that differs significantly between males and females. This is due to the dual role of the male urethra in transporting both urine and semen. The urethra arises from the trigone area at the base of the bladder. Urination is controlled by an involuntary internal sphincter of smooth muscle and a voluntary external sphincter of skeletal muscle. The shorter female urethra contributes to the higher incidence of bladder infections in females. The male urethra receives secretions from the prostate gland, Cowper’s gland, and seminal vesicles as well as sperm. Micturition is the process of voiding the urine and involves both involuntary and voluntary actions. Voluntary control of micturition requires a mature and intact sacral micturition center. It also requires an intact spinal cord. Loss of control of micturition is called incontinence and results in voiding when the bladder contains about 250 mL urine.

Review Questions

Q. Peristaltic contractions occur in the _____.

A. urethra

B. bladder

C. ureters

D. urethra, bladder, and ureters

Answer

Answer: C

Q. What is the epithelium of the urinary bladder?

A. stratified squamous

B. transitional

C. stratified cuboidal

D. simple columnar

Answer

Answer: B

Q. Which part of the urinary system is *not* completely retroperitoneal?

A. kidneys

B. ureters

C. bladder

D. nephrons

Answer

Answer: C

Critical Thinking Questions

Q. Why are females more likely to contract bladder infections than males?

Answer

A. The longer urethra of males means bacteria must travel farther to the bladder to cause an infection.

Q. How can the bladder fill with urine while we sleep? Gravity is not helping this process.

Answer

A. Peristalsis will move the urine to the bladder, without the effect of gravity. The one-way valve allows the urine to enter the bladder but prevents reflux back into the ureter. Thus, the bladder fills up with urine over night.

Glossary

anatomical sphincter
: smooth or skeletal muscle surrounding the lumen of a vessel or hollow organ that can restrict flow when contracted

detrusor muscle
: smooth muscle in the bladder wall; fibers run in all directions to reduce the size of the organ when emptying it of urine

external urinary sphincter
: skeletal muscle; must be relaxed consciously to void urine

internal urinary sphincter
: smooth muscle at the juncture of the bladder and urethra; relaxes as the bladder fills to allow urine into the urethra

incontinence
: loss of ability to control micturition

micturition
: also called urination or voiding

physiological sphincter
: sphincter consisting of circular smooth muscle indistinguishable from adjacent muscle but possessing differential innervations, permitting its function as a sphincter; structurally weak

retroperitoneal
: outside the peritoneal cavity; in the case of the kidney and ureters, between the parietal peritoneum and the abdominal wall

sacral micturition center
: group of neurons in the sacral region of the spinal cord that controls urination; acts reflexively unless its action is modified by higher brain centers to allow voluntary urination

trigone
: area at the base of the bladder marked by the two ureters in the posterior–lateral aspect and the urethral orifice in the anterior aspect oriented like points on a triangle

urethra
: transports urine from the bladder to the outside environment

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23: REPRODUCTIVE SYSTEM

Thumbnail Image Credit: Movements at Gestational Age of 9 Weeks by Mikael Häggström is licensed under CC BY 1.0

Note

This chapter is focused on the anatomy of the reproductive systems. A person with two X chromosomes (XX) will typically have ovaries for gonads and is genotypically classified as female. A person with one X chromosome and one Y chromosome (XY) will typically have testes for gonads and is genotypically classified as male. The differences seen in reproductive anatomy are due entirely to hormones, one of which is coded for on the Y chromosome. Gender genotype and anatomy is not linked to gender identity (phenotype) or sexuality. There is biology involved in both genotype and phenotype and it is a complex topic.

In this chapter, we will use the phrases "male", "XY", and "an individual with testes" to refer to the anatomy of an individual with testes that may make sperm and we will use the phrases "female", "XX", and "an individual with ovaries" to refer to the anatomy of an individual with ovaries that may make ova (eggs).

23.1: Introduction to the Reproductive System
23.2: Anatomy of the Male Reproductive System
23.3: Anatomy of the Female Reproductive System
23.4: Development of the Male and Female Reproductive Systems

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23.1: Introduction to the Reproductive System

Chapter Learning Objectives:

- Describe the anatomy of the male and female reproductive systems, including their accessory structures
- Explain the role of hypothalamic and pituitary hormones in male and female reproductive function
- Trace the path of a sperm cell from its initial production through fertilization of an oocyte
- Explain the events in the ovary prior to ovulation
- Describe the development and maturation of the sex organs and the emergence of secondary sex characteristics during puberty

Small, uncoordinated, and slick with amniotic fluid, a newborn encounters the world outside of her mother's womb. We do not often consider that a child's birth is proof of the healthy functioning of both her mother's and father's reproductive systems. Moreover, her parents' endocrine systems had to secrete the appropriate regulating hormones to induce the production and release of unique male and female gametes, reproductive cells containing the parents' genetic material (one set of 23 chromosomes). Her parent's reproductive behavior had to facilitate the transfer of male gametes—the sperm—to the female reproductive tract at just the right time to encounter the female gamete, an oocyte (egg). Finally, combination of the gametes (fertilization) had to occur, followed by implantation and development. In this chapter, you will explore the male and female reproductive systems, whose healthy functioning can culminate in the powerful sound of a newborn's first cry.

Figure 23.1.1: Ovulation. This is a color photograph of the surface of an ovary. The round bulge is a follicle that will rupture soon. The rupturing of the follicle is ovulation, and will result in the egg being released. Following a surge of luteinizing hormone (LH), an oocyte (immature egg cell) will be released into the uterine tube, where it will then be available to be fertilized by a male's sperm. Ovulation marks the end of the follicular phase of the ovarian cycle and the start of the luteal phase. (Image credit: "Ovulation" by OpenStax is licensed under CC BY 3.0)

Brief Overview

Before diving into the details, let's cover some basic common terms. Unique for its role in human reproduction, a **gamete** is a specialized sex cell carrying 23 chromosomes—one half the number in body cells. **Gonads** are the organs that make the gametes. Once the gametes are made, they travel in tubular structures. These structures are often the site for permanent sterilization procedures because if the gametes of the opposite sex cannot meet, then fertilization will not be possible. (Table 23.1.1) Comparing the midsagittal view of the female and male pelvis, we see multiple differences (Figure 23.1.2). Discussions on the female reproductive anatomy will be covered in section 23.3. Discussions on the male reproductive anatomy will be covered in section 23.2.

Table 23.1.1 Male and Female Reproductive Systems

Term	Male	Female
Gonads	Testes	Ovaries
Gametes	Sperms	Ova (ovum, singular, also known as eggs)
Tubes/Pathways	Vas deferens or Ductus deferens	Oviducts or Fallopian tubes
Permanent Sterilization Procedure	Vasectomy	Tubal ligation

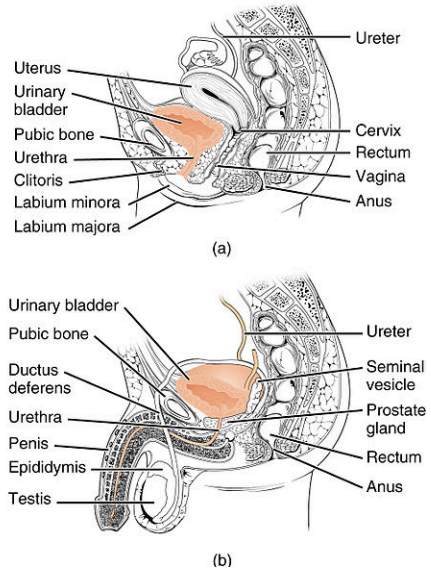

Figure 23.1.2: Reproductive Anatomy. Comparing female and male reproductive strutures. (Image credit: "Female and Male Reproductive Systems" by OpenStax is licensed under CC BY 3.0)

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23.2: Anatomy of the Male Reproductive System

By the end of the section, you will be able to:

- Describe the structure and function of the organs of the male reproductive system
- Describe the structure and function of the sperm cell
- Explain the events during spermatogenesis that produce haploid sperm from diploid cells
- Identify the importance of testosterone in male reproductive function

Unique for its role in human reproduction, a **gamete** is a specialized sex cell carrying 23 chromosomes—one half the number in body cells. At fertilization, the chromosomes in one male gamete, called a **sperm** (or spermatozoon), combine with the chromosomes in one female gamete, called an oocyte. The function of the male reproductive system is to produce sperm and transfer them to the female reproductive tract. The structures of the male reproductive system include the testes, the epididymides, the penis, and the ducts and glands that produce and carry semen (Figure 23.2.1). Sperm exit the scrotum through the ductus deferens, which is bundled in the spermatic cord. The spermatic cord is comprised of the ductus deferens, testicular artery, autonomic nerve, lymphatic vessel, and plexus of testicular veins. The seminal vesicles and prostate gland add fluids to the sperm to create semen. The paired testes are a crucial component in this process, as they produce both sperm and androgens, the hormones that support male reproductive physiology. In humans, the most important male androgen is testosterone. Several accessory organs and ducts aid the process of sperm maturation and transport the sperm and other seminal components to the penis, which delivers sperm to the female reproductive tract. In this section, we examine each of these different structures, and discuss the process of sperm production and transport. Details about these male anatomical structures will be discussed below.

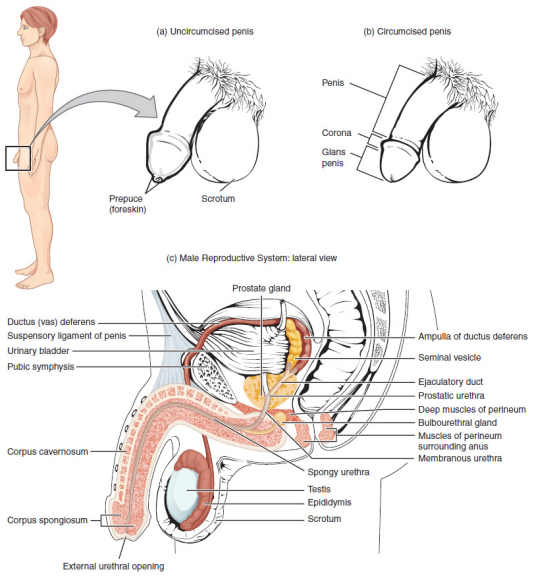

Figure 23.2.1: Male Reproductive System. (A) Lateral view of the uncircumcised (foreskin is still present) penis and the scrotum. (B) Lateral view of a circumcised (foreskin removed) penis with the glans penis and corona exposed. (C) Sagittal view of the male pelvis with reproductive and urinary organs labeled. (Image credit: "Male Reproductive System" by OpenStax is licensed under CC BY 3.0)

Scrotum

The testes are located in a skin-covered, highly pigmented, muscular sack called the **scrotum** that extends from the body behind the penis (see Figure 23.2.1). This location is important in sperm production, which occurs within the testes, and proceeds more efficiently when the testes are kept 2 to 4°C below core body temperature.

The **dartos muscle** makes up the subcutaneous muscle layer of the scrotum (Figure 23.2.2). It continues internally to make up the scrotal septum, a wall that divides the scrotum into two compartments, each housing one testis. Descending from the internal oblique muscle of the abdominal wall are the two **cremaster muscles**, which cover each testis like a muscular net. By contracting

simultaneously, the dartos and cremaster muscles can elevate the testes in cold weather (or water), moving the testes closer to the body and decreasing the surface area of the scrotum to retain heat. Alternatively, as the environmental temperature increases, the scrotum relaxes, moving the testes farther from the body core and increasing scrotal surface area, which promotes heat loss. Externally, the scrotum has a raised medial thickening on the surface called the **raphe.**

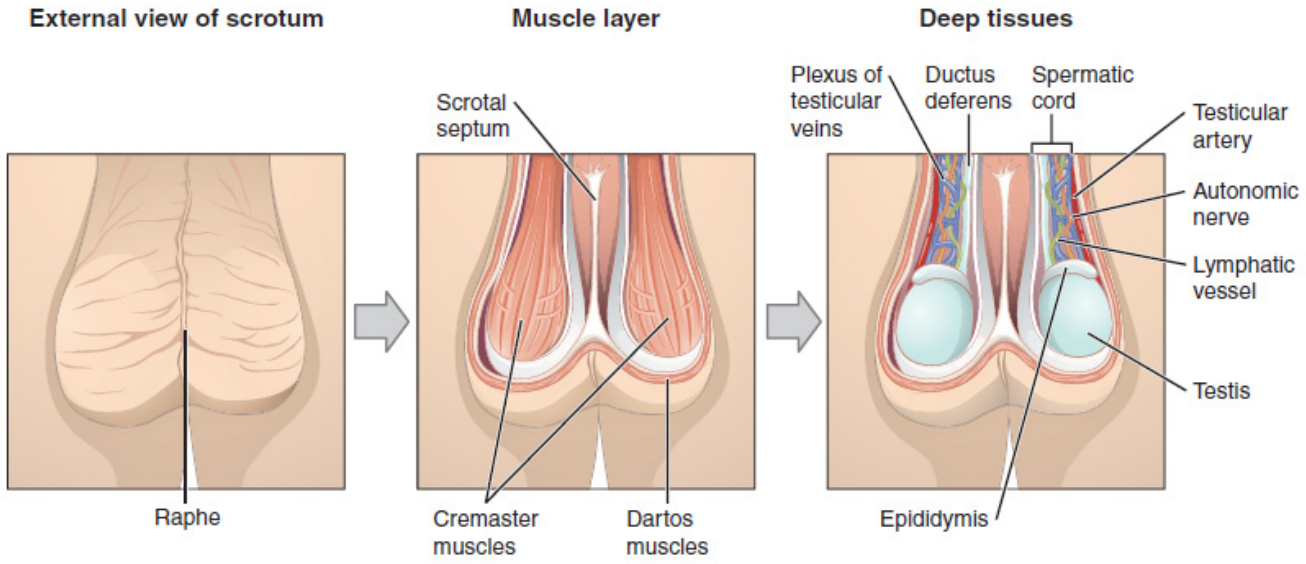

Figure 23.2.2: The Scrotum and Testes. This anterior view shows the different layers surrounding the scrotum and testes. (Image credit: "Scrotum and Internal Structures" by OpenStax is licensed under CC BY 3.0)

Testes

The **testes** (singular = testis) are the male gonads—that is, the male reproductive organs. They produce both sperm and androgens, such as testosterone, and are active throughout the reproductive lifespan of the male.

Paired ovals, the testes are each approximately 4 to 5 cm in length and are housed within the scrotum (see Figure 23.2.2). They are surrounded by two distinct layers of protective connective tissue. Immediately deep to the cremaster muscle is the tunica vaginalis. The outer **tunica vaginalis** is a serous membrane that has both a parietal and a thin visceral layer. Beneath the tunica vaginalis is the **tunica albuginea**, a tough, white, dense connective tissue layer covering the testis itself. Not only does the tunica albuginea cover the outside of the testis, it also invaginates to form septa that divide the testis into 300 to 400 structures called **lobules**. Within the lobules, sperm develop in structures called **seminiferous tubules** (Figure 23.2.3). During the seventh month of the developmental period of a male fetus, each testis moves through the abdominal musculature to descend into the scrotal cavity. This is called the "descent of the testis." Cryptorchidism is the clinical term used when one or both of the testes fail to descend into the scrotum prior to birth.

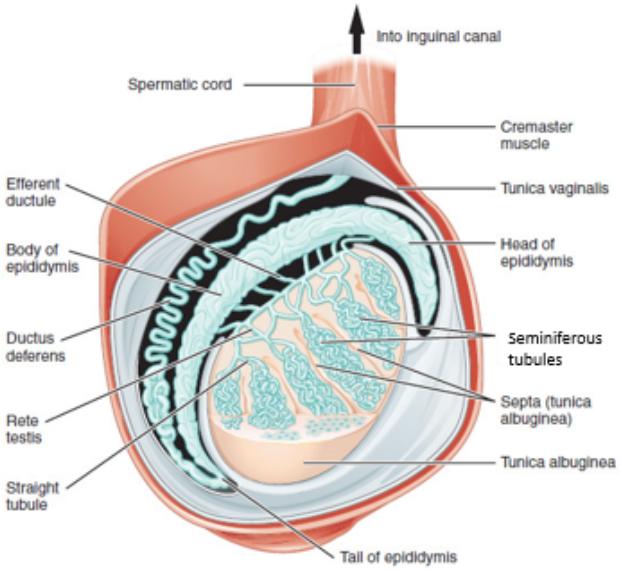

Figure 23.2.3: Testis. Inside the scrotum is a network of small tubes, all connected from the testis to the epididymis to the ductus deferens. (Image credit: "Testis" by KL Nguyen is licensed under CC BY 4.0 / A derivative from the original work)

The tightly coiled seminiferous tubules form the bulk of each testis. They are composed of developing sperm cells surrounding a lumen, the hollow center of the tubule, where formed sperm are released into the duct system of the testis. Specifically, from the lumens of the seminiferous tubules, sperm move into the **straight tubules** (or tubuli recti), and from there into a fine meshwork of tubules called the **rete testes**. Sperm leave the rete testes, and the testis itself, through the 15 to 20 **efferent ductules** that cross the tunica albuginea.

Interstitial cells (also known as **Leydig cells**) produce testosterone and are located in between the seminiferous tubules (Figure 23.2.4) Inside the seminiferous tubules are six different cell types. These include supporting cells called **sustentacular cells**, as well as five types of developing sperm cells called **germ cells**. Germ cell development progresses from the basement membrane—at the perimeter of the tubule—toward the lumen. Let's look more closely at these cell types.

Sertoli Cells

Surrounding all stages of the developing sperm cells are elongate, branching **Sertoli cells** (Figure 23.2.4). Sertoli cells are a type of supporting cell called sustentacular cells, or sustenocyte, that are typically found in epithelial tissue. Sertoli cells secrete signaling molecules that promote sperm production and can control whether germ cells live or die. Sertoli cells (also known as nurse cells) produce androgen- binding protein. This is needed for testosterone to actually have effects on the developing sperm. These cells also produce inhibin - this feeds back to the anterior pituitary gland to regulate sperm production. They extend physically around the germ cells from the peripheral basement membrane of the seminiferous tubules to the lumen. Tight junctions between these sustentacular cells create the **blood–testis barrier**, which keeps bloodborne substances from reaching the germ cells and, at the same time, keeps surface antigens on developing germ cells from escaping into the bloodstream and prompting an autoimmune response.

Germ Cells

The least mature cells, the **spermatogonia** (singular = spermatogonium), line the basement membrane inside the tubule. Spermatogonia are the stem cells of the testis, which means that they are still able to differentiate into a variety of different cell types throughout adulthood. Spermatogonia divide to produce **primary** and **secondary spermatocytes**, then **spermatids**, which finally produce formed sperm. The process that begins with spermatogonia and concludes with the production of sperm is called **spermatogenesis**.

Spermatogenesis

As just noted, spermatogenesis occurs in the seminiferous tubules that form the bulk of each testis (Figure 23.2.3). The process begins at puberty, after which time sperm are produced constantly throughout a man's life. One production cycle, from

spermatogonia through formed sperm, takes approximately 64 days. A new cycle starts approximately every 16 days, although this timing is not synchronous across the seminiferous tubules. Sperm counts—the total number of sperm a man produces—slowly decline after age 35, and some studies suggest that smoking can lower sperm counts irrespective of age.

The process of spermatogenesis begins with mitosis of the diploid spermatogonia in which one spermatogonium becomes two primary spermatocytes. Because these cells are diploid (2*n*), they each have a complete copy of the father's genetic material, or 46 chromosomes. After mitosis, the primary spermatocytes begin the two rounds of meiosis, i.e. meiosis I resulting in secondary spermatocytes, and meiosis II, resulting in spermatids. Mature gametes are haploid (1*n*), containing 23 chromosomes—meaning that daughter cells of spermatogonia must undergo a second cellular division through the process of meiosis Figure 23.2.4). These spermatids will continue with spermiogenesis to become spermatozoa, also known as sperm. A cross section of a seminiferous tubule will show the early cells of spermatogenesis at the outer edge and the more mature cells migrating toward the lumen in the center.

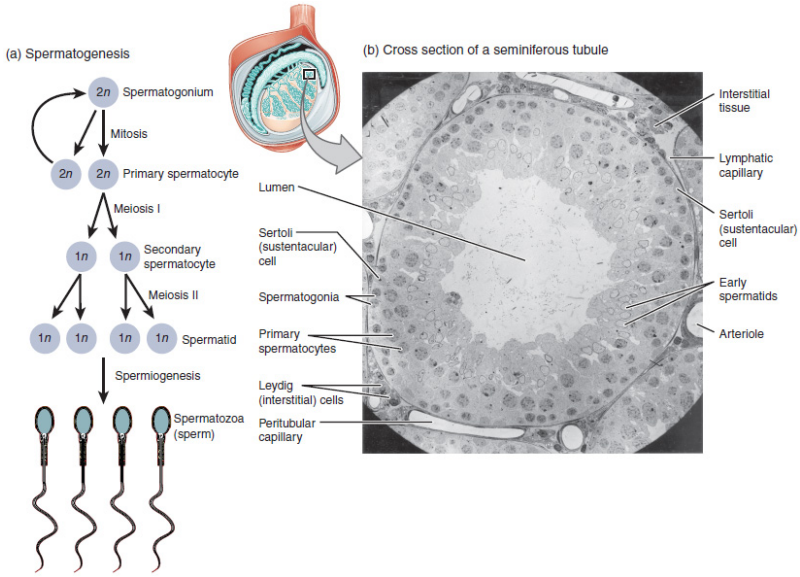

Figure 23.2.4: Spermatogenesis. (a) Mitosis of a spermatogonial stem cell involves a single cell division that results in two identical, diploid daughter cells (spermatogonia to primary spermatocyte). Meiosis has two rounds of cell division: primary spermatocyte to secondary spermatocyte, and then secondary spermatocyte to spermatid. This produces four haploid daughter cells (spermatids). (b) In this electron micrograph of a cross-section of a seminiferous tubule from a rat, the lumen is the light-shaded area in the center of the image. The location of the primary spermatocytes is near the basement membrane, and the early spermatids are approaching the lumen (tissue source: rat). EM × 900; Micrograph provided by the Regents of University of Michigan Medical School © 2012. (Image credit: "Spermatogenesis and Spermiogenesis" by OpenStax is licensed under CC BY 3.0)

Two identical diploid cells result from spermatogonia mitosis. One of these cells remains a spermatogonium, and the other becomes a **primary spermatocyte**, the next stage in the process of spermatogenesis. As in mitosis, DNA is replicated in a primary spermatocyte, and the cell undergoes cell division to produce two cells with identical chromosomes. Each of these is a **secondary spermatocyte**. Now a second round of cell division occurs in both of the secondary spermatocytes, separating the chromosome pairs. This second meiotic division results in a total of four cells with only half of the number of chromosomes. Each of these new cells is a **spermatid**. Although haploid, early spermatids look very similar to cells in the earlier stages of spermatogenesis, with a round shape, central nucleus, and large amount of cytoplasm. A process called **spermiogenesis** transforms these early spermatids, reducing the cytoplasm, and beginning the formation of the parts of a true sperm. The fifth stage of germ cell formation—**spermatozoa**, or formed sperm—is the end result of this process, which occurs in the portion of the tubule nearest the lumen. Eventually, the sperm are released into the lumen and are moved along a series of ducts in the testis toward a structure called the **epididymis** for the next step of sperm maturation.

Structure of Formed Sperm

Sperm are smaller than most cells in the body; in fact, the volume of a sperm cell is 85,000 times less than that of the female gamete. Approximately 100 to 300 million sperm are produced each day, whereas women typically ovulate only one oocyte per month as is true for most cells in the body, the structure of sperm cells speaks to their function. The **head** of the sperm contains the extremely compact haploid nucleus with very little cytoplasm (Figure 23.2.5). These qualities contribute to the overall

small size of the sperm (the head is only 5 μm long). A structure called the **acrosome** covers most of the head of the sperm cell as a "cap" that is filled with lysosomal enzymes important for preparing sperm to participate in fertilization. Tightly packed mitochondria fill the **mid-piece** of the sperm. ATP produced by these mitochondria will power the flagellum, which extends from the neck and the mid-piece through the **tail** of the sperm, enabling it to move the entire sperm cell. The central strand of the flagellum, the axial filament, is formed from one centriole inside the maturing sperm cell during the final stages of spermatogenesis.

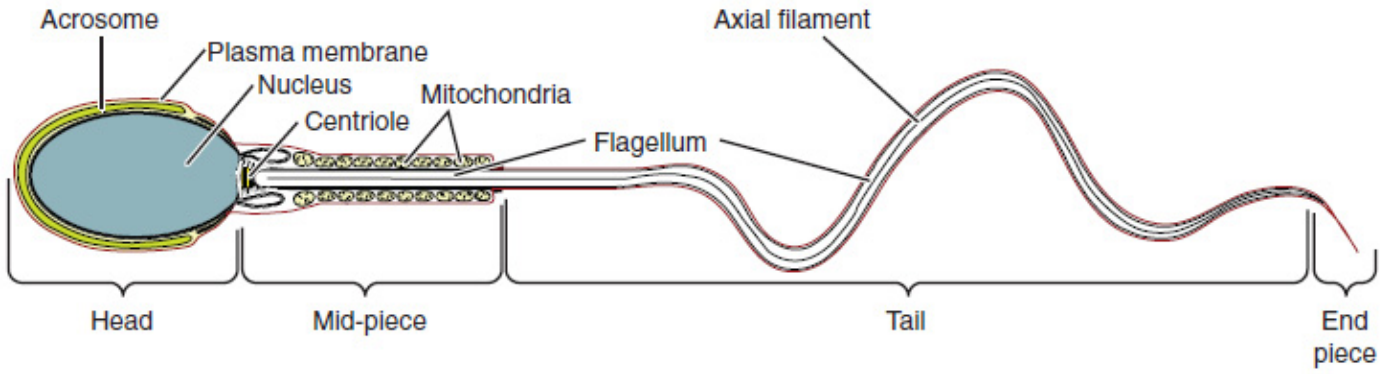

Figure 23.2.5: Structure of Sperm. Sperm cells are divided into a head, containing DNA; a mid-piece, containing mitochondria; and a tail, providing motility. The acrosome is oval and somewhat flattened. (Image credit: "Sperm" by OpenStax is licensed under CC BY 3.0)

Sperm Transport

To fertilize an egg, sperm must be moved from the seminiferous tubules in the testes, through the epididymis, and—later during ejaculation—along the length of the penis and out into the female reproductive tract.

Role of the Epididymis

From the lumen of the seminiferous tubules, the immotile sperm are surrounded by testicular fluid and moved to the **epididymis** (plural = epididymides), a coiled tube attached to the testis where newly formed sperm continue to mature (see Figure 23.2.3). Though the epididymis does not take up much room in its tightly coiled state, it would be approximately 6 m (20 feet) long if straightened. It takes an average of 12 days for sperm to move through the coils of the epididymis, with the shortest recorded transit time in humans being one day. Sperm enter the head of the epididymis and are moved along predominantly by the contraction of smooth muscles lining the epididymal tubes. The more mature sperm are then stored in the tail of the epididymis (the final section) until ejaculation occurs.

Duct System

During ejaculation, sperm exit the tail of the epididymis and are pushed by smooth muscle contraction to the **ductus deferens** (also called the vas deferens). The ductus deferens is a thick, muscular tube that is bundled together inside the scrotum with connective tissue, blood vessels, and nerves into a structure called the **spermatic cord** (see Figure 23.2.1 and Figure 23.2.2). Because the ductus deferens is physically accessible within the scrotum, surgical sterilization to interrupt sperm delivery can be performed by cutting and sealing a small section of the ductus (vas) deferens. This procedure is called a **vasectomy**, and it is an effective form of male birth control. Although it may be possible to reverse a vasectomy, clinicians consider the procedure permanent, and advise men to undergo it only if they are certain they no longer wish to father children.

Interactive Element

Watch this video Vasectomy to learn about a procedure in which a small section of the ductus (vas) deferens is removed from the scrotum. This interrupts the path taken by sperm through the ductus deferens. If sperm do not exit through the vas, either because the man has had a vasectomy or has not ejaculated, in what region of the testis do they remain?

Answer

Answer available at the end of this section.

From each epididymis, each ductus deferens extends superiorly into the abdominal cavity through the **inguinal canal** in the abdominal wall. From here, the ductus deferens continues posteriorly to the pelvic cavity, ending posterior to the bladder where it dilates in a region called the ampulla (meaning “flask”).

Sperm make up only 5 percent of the final volume of **semen**, the thick, milky fluid that the male ejaculates. The bulk of semen is produced by three critical accessory glands of the male reproductive system: the seminal vesicles, the prostate, and the bulbourethral glands (Figure 23.2.6).

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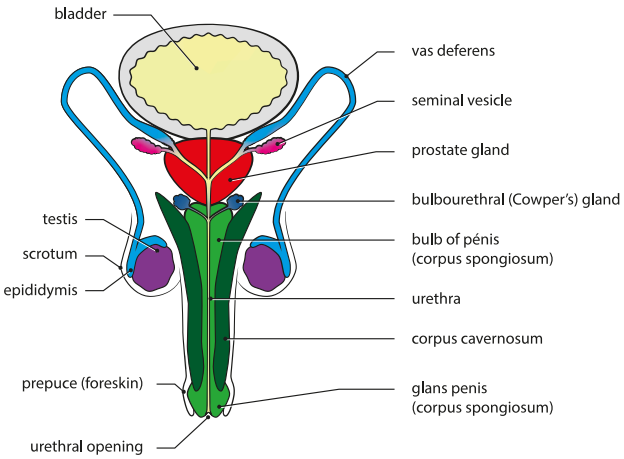

Figure 23.2.6: Front View of Male Reproductive System. The structures of the male reproductive system include the testes, the epididymis, the penis, and the ducts and glands that produce and carry semen. Sperm exit the scrotum through the vas deferens. The seminal vesicles, bulborethral gland, and prostate gland add fluids to the sperm to create semen. (Image credit: "Male Genital System Front View" by Bioscope, HUG, DIP and Odile Fillod is licensed under CC BY SA 4.0)

Seminal Vesicles

As sperm pass through the ampulla of the ductus deferens at ejaculation, they mix with fluid from the associated **seminal vesicle** (see Figure 23.2.6). The paired seminal vesicles are glands that contribute approximately 60 percent of the semen volume. Seminal vesicle fluid contains large amounts of fructose, which is used by the sperm mitochondria to generate ATP to allow movement through the female reproductive tract. Sperm are immobile until mixed with secretions of the seminal glands.

The fluid, now containing both sperm and seminal vesicle secretions, next moves into the associated **ejaculatory duct**, a short structure formed from the ampulla of the ductus deferens and the duct of the seminal vesicle. The paired ejaculatory ducts transport the seminal fluid into the next structure, the prostate gland.

Prostate Gland

As shown in Figure 23.2.6, the centrally located **prostate gland** sits anterior to the rectum at the base of the bladder surrounding the prostatic urethra (the portion of the urethra that runs within the prostate). About the size of a walnut, the prostate is formed of both muscular and glandular tissues. It excretes an alkaline, milky fluid to the passing seminal fluid—now called semen—that is critical to first coagulate and then decoagulate the semen following ejaculation. The temporary thickening of semen helps retain it within the female reproductive tract, providing time for sperm to utilize the fructose provided by seminal vesicle secretions. When the semen regains its fluid state, sperm can then pass farther into the female reproductive tract.

The prostate normally doubles in size during puberty. At approximately age 25, it gradually begins to enlarge again. This enlargement does not usually cause problems; however, abnormal growth of the prostate, or benign prostatic hyperplasia (BPH), can cause constriction of the urethra as it passes through the middle of the prostate gland, leading to a number of lower urinary tract symptoms, such as a frequent and intense urge to urinate, a weak stream, and a sensation that the bladder has not emptied completely. By age 60, approximately 40 percent of men have some degree of BPH. By age 80, the number of affected individuals has jumped to as many as 80 percent. Treatments for BPH attempt to relieve the pressure on the urethra so that urine can flow more normally. Mild to moderate symptoms are treated with medication, whereas severe enlargement of the prostate is treated by surgery in which a portion of the prostate tissue is removed.

Another common disorder involving the prostate is prostate cancer. According to the Centers for Disease Control and Prevention (CDC), prostate cancer is the second most common cancer in men. However, some forms of prostate cancer grow very slowly and thus may not ever require treatment. Aggressive forms of prostate cancer, in contrast, involve metastasis to vulnerable organs like the lungs and brain. There is no link between BPH and prostate cancer, but the symptoms are similar. Prostate cancer is detected by a medical history, a blood test, and a rectal exam that allows physicians to palpate the prostate and check for unusual masses. If a mass is detected, the cancer diagnosis is confirmed by biopsy of the cells.

Bulbourethral Glands

The final addition to semen is made by two **bulbourethral glands** (or Cowper's glands) that release a thick, salty fluid that lubricates the end of the urethra and the vagina, and helps to clean urine residues from the penile urethra. The fluid from these accessory glands is released after the male becomes sexually aroused, and shortly before the release of the semen. It is therefore sometimes called pre-ejaculate. It is important to note that, in addition to the lubricating proteins, it is possible for bulbourethral fluid to pick up sperm already present in the urethra, and therefore it may be able to cause pregnancy. Once inside the female reproductive tract, sperm will move toward the unfertilized egg and will undergo chemical changes called **capacitation** in order to fertilize the egg. Capacitation involves destabilization of the acrosomal membrane of the sperm head and greater mobility in the sperm's tail to permit fertilization.

Interactive Element

Watch this video Male Anatomy to explore the structures of the male reproductive system and the path of sperm, which starts in the testes and ends as sperm leave the penis through the urethra. Where are sperm deposited after they leave the ejaculatory duct?

Answer

Answer available at the end of this section.

Penis

The **penis** is the male organ of copulation (sexual intercourse). It is flaccid for non-sexual actions, such as urination, and turgid and rod-like with sexual arousal. When erect, the stiffness of the organ allows it to penetrate into the vagina and deposit semen into the female reproductive tract (Figure 23.2.7).

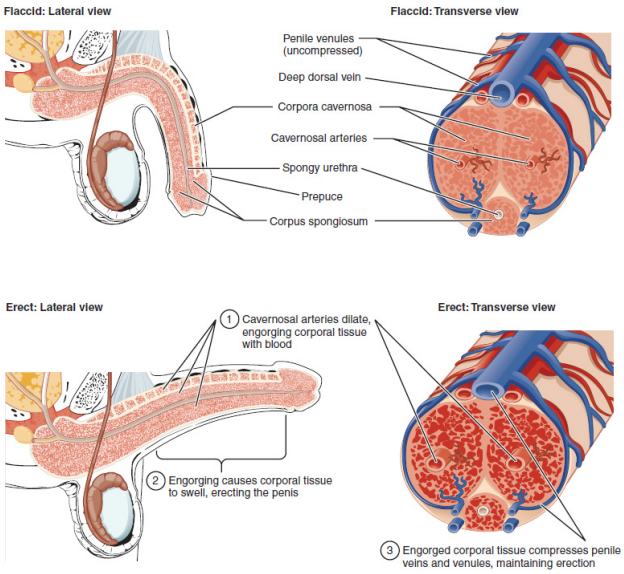

Figure 23.2.7 Cross-Sectional Anatomy of the Penis, Flaccid and Erect. Three columns of erectile tissue make up most of the volume of the penis. (Image credit: "Penis" by OpenStax is licensed under CC BY 3.0)

The shaft of the penis surrounds the urethra (Figure 23.2.7). The shaft is composed of three column-like chambers of erectile tissue that span the length of the shaft. Each of the two larger lateral chambers is called a **corpus cavernosum** (plural = corpora cavernosa). Together, these make up the bulk of the penis. The **corpus spongiosum**, which can be felt as a raised ridge on the erect penis, is a smaller chamber that surrounds the spongy, or penile, urethra. The end of the penis, called the **glans penis**, has a high concentration of nerve endings, resulting in very sensitive skin that influences the likelihood of ejaculation (see Figure 23.2.7). The skin from the shaft extends down over the glans and forms a collar called the **prepuce** (or foreskin). The foreskin also contains a dense concentration of nerve endings, and both lubricate and protect the sensitive skin of the glans penis. A surgical procedure called circumcision, often performed for religious or social reasons, removes the prepuce, typically within days of birth.

Both sexual arousal and REM sleep (during which dreaming occurs) can induce an erection. Penile erections are the result of vasocongestion, or engorgement of the tissues because of more arterial blood flowing into the penis than is leaving in the veins. During sexual arousal, nitric oxide (NO) is released from nerve endings near blood vessels within the corpora cavernosa and spongiosum. Release of NO activates a signaling pathway that results in relaxation of the smooth muscles that surround the penile arteries, causing them to dilate. This dilation increases the amount of blood that can enter the penis and induces the endothelial cells in the penile arterial walls to also secrete NO and perpetuate the vasodilation. The rapid increase in blood volume fills the erectile chambers, and the increased pressure of the filled chambers compresses the thin-walled penile venules, preventing venous drainage of the penis. The result of this increased blood flow to the penis and reduced blood return from the penis is erection. Depending on the flaccid dimensions of a penis, it can increase in size slightly or greatly during erection, with the average length of an erect penis measuring approximately 15 cm.

DISORDERS OF THE...

Male Reproductive System

Erectile dysfunction (ED) is a condition in which a man has difficulty either initiating or maintaining an erection. The combined prevalence of minimal, moderate, and complete ED is approximately 40 percent in men at age 40, and reaches nearly 70 percent by 70 years of age. In addition to aging, ED is associated with diabetes, vascular disease, psychiatric disorders, prostate disorders, the use of some drugs such as certain antidepressants, and problems with the testes resulting in low testosterone concentrations. These physical and emotional conditions can lead to interruptions in the vasodilation pathway and result in an inability to achieve an erection.

Recall that the release of NO induces relaxation of the smooth muscles that surround the penile arteries, leading to the vasodilation necessary to achieve an erection. To reverse the process of vasodilation, an enzyme called phosphodiesterase (PDE) degrades a key component of the NO signaling pathway called cGMP. There are several different forms of this enzyme, and PDE type 5 is the type of PDE found in the tissues of the penis. Scientists discovered that inhibiting PDE5 increases blood flow, and allows vasodilation of the penis to occur.

PDEs and the vasodilation signaling pathway are found in the vasculature in other parts of the body. In the 1990s, clinical trials of a PDE5 inhibitor called sildenafil were initiated to treat hypertension and angina pectoris (chest pain caused by poor blood flow through the heart). The trial showed that the drug was not effective at treating heart conditions, but many men experienced erection and priapism (erection lasting longer than 4 hours). Because of this, a clinical trial was started to investigate the ability of sildenafil to promote erections in men suffering from ED. In 1998, the FDA approved the drug, marketed as Viagra®. Since approval of the drug, sildenafil and similar PDE inhibitors now generate over a billion dollars a year in sales, and are reported to be effective in treating approximately 70 to 85 percent of cases of ED. Importantly, men with health problems—especially those with cardiac disease taking nitrates—should avoid Viagra or talk to their physician to find out if they are a candidate for the use of this drug, as deaths have been reported for at-risk users.

Testosterone

Testosterone, an androgen, is a steroid hormone produced by **Leydig cells**. The alternate term for Leydig cells, interstitial cells, reflects their location between the seminiferous tubules in the testes. In male embryos, testosterone is secreted by Leydig cells by the seventh week of development, with peak concentrations reached in the second trimester. This early release of testosterone results in the anatomical differentiation of the male sexual organs. In childhood, testosterone concentrations are low. They increase during puberty, activating characteristic physical changes and initiating spermatogenesis.

Functions of Testosterone

The continued presence of testosterone is necessary to keep the male reproductive system working properly, and Leydig cells produce approximately 6 to 7 mg of testosterone per day. Testicular steroidogenesis (the manufacture of androgens, including testosterone) results in testosterone concentrations that are 100 times higher in the testes than in the circulation. Maintaining these normal concentrations of testosterone promotes spermatogenesis, whereas low levels of testosterone can lead to infertility. In addition to intratesticular secretion, testosterone is also released into the systemic circulation and plays an important role in muscle development, bone growth, the development of secondary sex characteristics, and maintaining libido (sex drive) in both males and females. In females, the ovaries secrete small amounts of testosterone, although most is converted to estradiol. A small amount of testosterone is also secreted by the adrenal glands in both sexes.

Control of Testosterone

The regulation of testosterone concentrations throughout the body is critical for male reproductive function. The regulation of Leydig cell production of testosterone begins outside of the testes. The hypothalamus and the pituitary gland in the brain integrate external and internal signals to control testosterone synthesis and secretion. The regulation begins in the **hypothalamus**. Pulsatile release of a hormone called **gonadotropin-releasing hormone (GnRH)** from the hypothalamus stimulates the endocrine release of hormones from the pituitary gland. Binding of GnRH to its receptors on the **anterior pituitary** gland stimulates release of the two gonadotropins: **luteinizing hormone (LH)** and **follicle-stimulating hormone (FSH)**. These two hormones are critical for reproductive function in both men and women. In men, FSH binds predominantly to the Sertoli cells within the seminiferous tubules to promote spermatogenesis. FSH also stimulates the Sertoli cells to produce hormones called inhibins, which function to inhibit FSH release from the pituitary, thus reducing testosterone secretion. These polypeptide hormones correlate directly with Sertoli cell function and sperm number; inhibin can be used as a marker of spermatogenic activity. In men, LH binds to receptors on Leydig cells in the testes and upregulates the production of testosterone. Please refer to the Endocrine System, Sections 15.3 and 15.8 for additional details.

AGING AND THE...

Male Reproductive System

Declines in Leydig cell activity can occur in men beginning at 40 to 50 years of age. The resulting reduction in circulating testosterone concentrations can lead to symptoms of andropause, also known as male menopause. While the reduction in sex steroids in men is akin to female menopause, there is no clear sign—such as a lack of a menstrual period—to denote the initiation of andropause. Instead, men report feelings of fatigue, reduced muscle mass, depression, anxiety, irritability, loss of libido, and insomnia. A reduction in spermatogenesis resulting in lowered fertility is also reported, and sexual dysfunction can also be associated with andropausal symptoms.

Whereas some researchers believe that certain aspects of andropause are difficult to tease apart from aging in general, testosterone replacement is sometimes prescribed to alleviate some symptoms. Recent studies have shown a benefit from androgen replacement therapy on the new onset of depression in elderly men; however, other studies caution against testosterone replacement for long-term treatment of andropause symptoms, showing that high doses can sharply increase the risk of both heart disease and prostate cancer.

Concept Review

Gametes are the reproductive cells that combine to form offspring. Organs called gonads produce the gametes, along with the hormones that regulate human reproduction. The male gametes are called sperm. Spermatogenesis, the production of sperm, occurs within the seminiferous tubules that make up most of the testis. The scrotum is the muscular sac that holds the testes outside of the body cavity.

Spermatogenesis begins with mitotic division of spermatogonia (stem cells) to produce primary spermatocytes that undergo the two divisions of meiosis to become secondary spermatocytes, then the haploid spermatids. During spermiogenesis, spermatids are transformed into spermatozoa (formed sperm). Upon release from the seminiferous tubules, sperm are moved to the epididymis where they continue to mature. During ejaculation, sperm exit the epididymis through the ductus deferens, a duct in the spermatic cord that leaves the scrotum. The ampulla of the ductus deferens meets the seminal vesicle, a gland that contributes fructose and proteins, at the ejaculatory duct. The fluid continues through the prostatic urethra, where secretions from the prostate are added to form semen. These secretions help sperm to travel through the urethra and into the female reproductive tract. Secretions from the bulbourethral glands protect sperm and cleanse and lubricate the penile (spongy) urethra.

The penis is the male organ of copulation. Columns of erectile tissue called the corpora cavernosa and corpus spongiosum fill with blood when sexual arousal activates vasodilatation in the blood vessels of the penis. Testosterone regulates and maintains the sex organs and sex drive, and induces the physical changes of puberty. Interplay between the testes and the endocrine system precisely control the production of testosterone.

Review Questions

Q. What are male gametes called?

A. ova

B. sperm

C. testes

D. testosterone

Answer

Answer: B

Q. Leydig cells _____.

A. are found in between seminiferous tubules

B. activate the sperm flagellum

C. are spermatogonia

D. secrete seminal fluid

Answer

Answer: A

Q. Which structure is affected in a vasectomy?

A. testis

B. ductus deferens

C. prostate gland

D. epididymis

Answer

Answer: B

Q. Where is the epididymis?

A. in the scrotum

B. in the testes

C. posterior to the bladder

D. inside the pelvis

Answer

Answer: A

Q. Which muscle(s) surround(s) the testes?

A. cremaster

B. dartos

C. A & B

D. smooth muscle

Answer

Answer: C

Critical Thinking Questions

Q. Briefly explain why mature gametes carry only one set of chromosomes.

Answer

A. Humans have 46 chromosomes. Meiosis is cell division that produces sperm (gametes) with only 23 chromosomes. A single gamete must combine with a gamete from an individual of the opposite sex to produce a fertilized egg, which has a complete set of chromosomes (46) and is the first cell of a new individual.

Q. What special features are evident in sperm cells but not in somatic cells, and how do these specializations function?

Answer

A. Unlike somatic cells, sperm are haploid with 23 chromosomes. They also have very little cytoplasm. They have a head with a compact nucleus covered by an acrosome filled with enzymes, and a mid-piece filled with mitochondria that power their movement. They are motile because of their tail, a structure containing a flagellum, which is specialized for movement to find the egg for fertilization.

Q. Name three male accessory glands and explain how each contributes to the semen.

Answer

A. The three accessory glands make the following contributions to semen: the seminal vesicle contributes about 60 percent of the semen volume, with fluid that contains large amounts of fructose to power the movement of sperm; the prostate gland contributes substances critical to sperm maturation; and the bulbourethral glands contribute a thick fluid that lubricates the ends of the urethra and the vagina and helps to clean urine residues from the urethra.

Q. Describe how penile erection occurs.

Answer

A. During sexual arousal, nitric oxide (NO) is released from nerve endings near blood vessels within the corpora cavernosa and corpus spongiosum. The release of NO activates a signaling pathway that results in relaxation of the smooth muscles that surround the penile arteries, causing them to dilate. This dilation increases the amount of blood that can enter the penis, and induces the endothelial cells in the penile arterial walls to secrete NO, perpetuating the vasodilation. The rapid increase in blood volume fills the erectile chambers, and the increased pressure of the filled chambers compresses the thin-walled penile venules, preventing venous drainage of the penis. An erection is the result of this increased blood flow to the penis and reduced blood return from the penis.

Glossary

blood–testis barrier
tight junctions between Sertoli cells that prevent bloodborne pathogens from gaining access to later stages of spermatogenesis and prevent the potential for an autoimmune reaction to haploid sperm

bulbourethral glands
(also, Cowper's glands) glands that secrete a lubricating mucus that cleans and lubricates the urethra prior to and during ejaculation

corpus cavernosum
either of two columns of erectile tissue in the penis that fill with blood during an erection

corpus spongiosum
(plural = corpora cavernosa) column of erectile tissue in the penis that fills with blood during an erection and surrounds the penile urethra on the ventral portion of the penis

ductus deferens
(also, vas deferens) duct that transports sperm from the epididymis through the spermatic cord and into the ejaculatory duct; also referred as the vas deferens

ejaculatory duct
duct that connects the ampulla of the ductus deferens with the duct of the seminal vesicle at the prostatic urethra

epididymis
(plural = epididymides) coiled tubular structure in which sperm start to mature and are stored until ejaculation

gamete
haploid reproductive cell that contributes genetic material to form an offspring

glans penis
bulbous end of the penis that contains a large number of nerve endings

gonadotropin-releasing hormone (GnRH)
hormone released by the hypothalamus that regulates the production of follicle-stimulating hormone and luteinizing hormone from the pituitary gland

gonads
reproductive organs (testes in men and ovaries in women) that produce gametes and reproductive hormones

inguinal canal
opening in abdominal wall that connects the testes to the abdominal cavity

Leydig cells
cells between the seminiferous tubules of the testes that produce testosterone; a type of interstitial cell

penis
male organ of copulation

prepuce
(also, foreskin) flap of skin that forms a collar around, and thus protects and lubricates, the glans penis; also referred as the foreskin

prostate gland
doughnut-shaped gland at the base of the bladder surrounding the urethra and contributing fluid to semen during ejaculation

scrotum
external pouch of skin and muscle that houses the testes

semen
ejaculatory fluid composed of sperm and secretions from the seminal vesicles, prostate, and bulbourethral glands

seminal vesicle
gland that produces seminal fluid, which contributes to semen

seminiferous tubules
tube structures within the testes where spermatogenesis occurs

Sertoli cells
cells that support germ cells through the process of spermatogenesis; a type of sustentacular cell

sperm
(also, spermatozoon) male gamete

spermatic cord
bundle of nerves and blood vessels that supplies the testes; contains ductus deferens

spermatid
immature sperm cells produced by meiosis II of secondary spermatocytes

spermatocyte
cell that results from the division of spermatogonium and undergoes meiosis I and meiosis II to form spermatids

spermatogenesis
formation of new sperm, occurs in the seminiferous tubules of the testes

spermatogonia
(singular = spermatogonium) diploid precursor cells that become sperm

spermiogenesis
transformation of spermatids to spermatozoa during spermatogenesis

testes
(singular = testis) male gonads

Contributors and Attributions

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Answers

Interactive Element

Answer: Sperm remain in the epididymis until they degenerate

Interactive Element

Answer: Sperm enter the prostate.

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23.3: Anatomy of the Female Reproductive System

By the end of the section, you will be able to:

- Describe the structure and function of the organs of the female reproductive system
- List the steps of oogenesis
- Describe the changes that occur during the ovarian and menstrual cycles
- Trace the path of an oocyte from ovary to fertilization

The female reproductive system functions to produce gametes and reproductive hormones, just like the male reproductive system; however, it also has the additional task of supporting the developing fetus and delivering it to the outside world. Unlike its male counterpart, the female reproductive system is located primarily inside the pelvic cavity. Recall that the **ovaries** are the female gonads. The gamete they produce is called an **oocyte**. We'll discuss the production of oocytes in detail shortly. First, let's look at some of the structures of the female reproductive system (Figure 23.3.1).

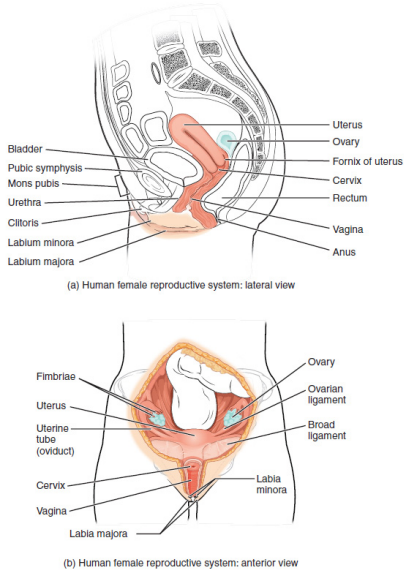

Figure 23.3.1: Female Reproductive System. The major organs of the female reproductive system are located inside the pelvic cavity. (Image credit: "Female Reproductive System" by OpenStax is licensed under CC BY 3.0)

External Female Genitals

The external female reproductive structures are referred to collectively as the vulva (Figure 23.3.2) The **mons pubis** is a pad of fat that is located at the anterior, over the pubic bone. After puberty, it becomes covered in pubic hair. The **labia majora** (labia = "lips"; majora = "larger") are folds of hair-covered skin that begin just posterior to the mons pubis. The thinner and more pigmented **labia minora** (labia = "lips"; minora = "smaller") extend medial to the labia majora. Although they naturally vary in shape and size from woman to woman, the labia minora serve to protect the female urethra and the entrance to the female reproductive tract.

The superior, anterior portions of the labia minora come together to encircle the **clitoris** (or glans clitoris), an organ that originates from the same cells as the glans penis and has abundant nerves that make it important in sexual sensation and orgasm. The **hymen** is a thin membrane that sometimes partially covers the entrance to the vagina. An intact hymen cannot be used as an indication of "virginity"; even at birth, this is only a partial membrane, as menstrual fluid and other secretions must be able to exit the body, regardless of penile–vaginal intercourse. The vaginal opening is located between the opening of the urethra and the anus. It is flanked by outlets to the **Bartholin's glands** (or greater vestibular glands) which secrete mucoid secretions to aid in vaginal and vulvar lubrication; they are the equivalent of Cowper's glands in the men. Skene's glands (or lesser vestibular glands) flank the urethral opening and lubricate opening to the urethra; their secretions have an antimicrobial quality. Similar to male

anatomy, women also have corpus cavernosum.

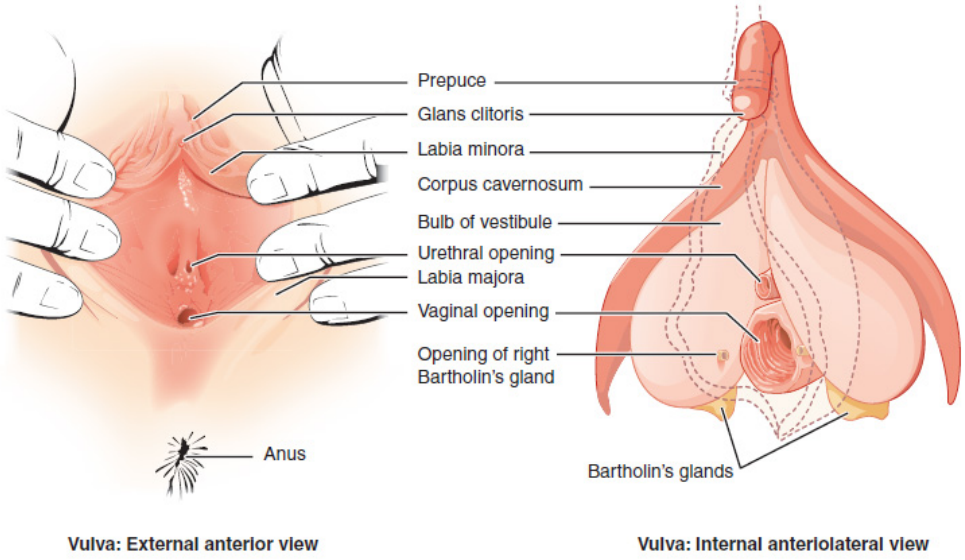

Figure 23.3.2: The Vulva. The external female genitalia are referred to collectively as the vulva. Just deep to the skin are glands and structures similar to those found in male anatomy. (Image credit: "Vulva" by OpenStax is licensed under CC BY 3.0)

Vagina

The **vagina**, shown at the bottom of Figure 23.3.1 and Figure 23.3.2, is a muscular canal (approximately 10 cm long) that serves as the entrance to the reproductive tract. It also serves as the exit from the uterus during menses and childbirth. The outer walls of the anterior and posterior vagina are formed into longitudinal columns, or ridges, and the superior portion of the vagina—called the fornix—meets the protruding uterine cervix. The walls of the vagina are lined with an outer, fibrous adventitia; a middle layer of smooth muscle; and an inner mucous membrane with transverse folds called **rugae**. Together, the middle and inner layers allow the expansion of the vagina to accommodate intercourse and childbirth. The thin, perforated hymen can partially surround the opening to the vaginal orifice. The hymen can be ruptured with strenuous physical exercise, penile–vaginal intercourse, and childbirth. The Bartholin's glands and the lesser vestibular glands (located near the clitoris) secrete mucus, which keeps the vestibular area moist.

The vagina is home to a normal population of microorganisms that help to protect against infection by pathogenic bacteria, yeast, or other organisms that can enter the vagina. In a healthy woman, the most predominant type of vaginal bacteria is from the genus *Lactobacillus*. This family of beneficial bacterial flora secretes lactic acid, and thus protects the vagina by maintaining an acidic pH (below 4.5). Potential pathogens are less likely to survive in these acidic conditions. Lactic acid, in combination with other vaginal secretions, makes the vagina a self-cleansing organ. However, douching—or washing out the vagina with fluid—can disrupt the normal balance of healthy microorganisms, and actually increase a woman's risk for infections and irritation. Indeed, the American College of Obstetricians and Gynecologists recommend that women do not douche, and that they allow the vagina to maintain its normal healthy population of protective microbial flora.

Ovaries

The **ovaries** are the female gonads. Paired ovals, they are each about 2 to 3 cm in length, about the size of an almond (Figure 23.3.3). The ovaries are located within the pelvic cavity, and are supported by the **mesovarium**, an extension of the peritoneum that connects the ovaries to the **broad ligament**. Extending from the mesovarium itself is the **suspensory ligament** that contains the ovarian blood and lymph vessels. Finally, the ovary itself is attached to the uterus via the **ovarian ligament**.

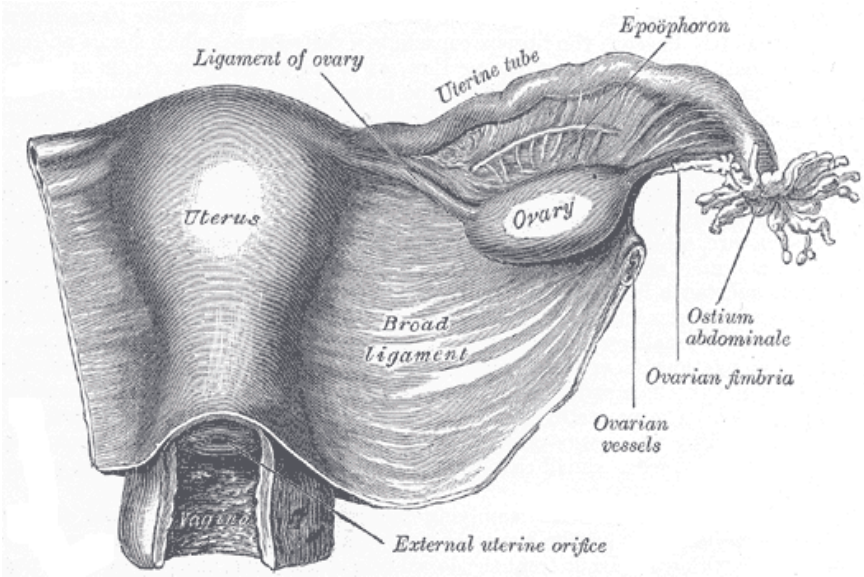

Figure 23.3.3: Uterus and right broad ligament, seen from behind. The broad ligament has been spread out and the ovary drawn downward. The ligament of ovary is labeled at the center top. The suspensory ligament of the ovary (not labeled), which may be confused with ligament of ovary, is shown incompletely and in section; it surrounds the ovarian vessels (labeled). (Image credit: "Uterus and Ligaments" by Henry Gray is in the Public Domain CC0)

The ovary comprises an outer covering of cuboidal epithelium called the ovarian surface epithelium that is superficial to a dense connective tissue covering called the tunica albuginea. Beneath the tunica albuginea is the cortex, or outer portion, of the organ. The cortex is composed of a tissue framework called the ovarian stroma that forms the bulk of the adult ovary. Oocytes develop within the outer layer of this stroma, each surrounded by supporting cells. This grouping of an oocyte and its supporting cells is called a **follicle**. The growth and development of ovarian follicles will be described shortly. Beneath the cortex lies the inner ovarian medulla, the site of blood vessels, lymph vessels, and the nerves of the ovary.

Ovarian Cycle

The **ovarian cycle** is a set of predictable changes in a female's oocytes and ovarian follicles. During a woman's reproductive years, it is a roughly 28-day cycle that can be correlated with, but is not the same as, the menstrual cycle (discussed shortly). The cycle includes two interrelated processes: **oogenesis** (the production of female gametes) and **folliculogenesis** (the growth and development of ovarian follicles).

Oogenesis

Oogenesis is the process of forming an egg or oocyte (Figure 23.3.4). The process begins with the ovarian stem cells, or **oogonia** (singular is oogonium). Oogonia are formed during fetal development, and divide via mitosis, much like spermatogonia in the testis. Unlike spermatogonia, however, oogonia form **primary oocytes** in the fetal ovary prior to birth. These primary oocytes are then arrested in this stage of meiosis I, only to resume it years later, beginning at puberty and continuing until the woman is near menopause (the cessation of a woman's reproductive functions). The number of primary oocytes present in the ovaries declines from one to two million in an infant, to approximately 400,000 at puberty, to zero by the end of menopause.

The initiation of **ovulation**—the release of an oocyte from the ovary—marks the transition from puberty into reproductive maturity for women. From then on, throughout a woman's reproductive years, ovulation occurs approximately once every 28 days. Just prior to ovulation, a surge of luteinizing hormone triggers the resumption of meiosis in a primary oocyte. This initiates the transition from primary to secondary oocyte. However, as you can see in Figure 23.3.4, this cell division does not result in two identical cells. Instead, the cytoplasm is divided unequally, and one daughter cell is much larger than the other. This larger cell, the secondary oocyte, eventually leaves the ovary during ovulation. The smaller cell, called the first **polar body**, may or may not complete meiosis and produce second polar bodies; in either case, it eventually disintegrates. Therefore, even though oogenesis produces up to four cells, only one survives.

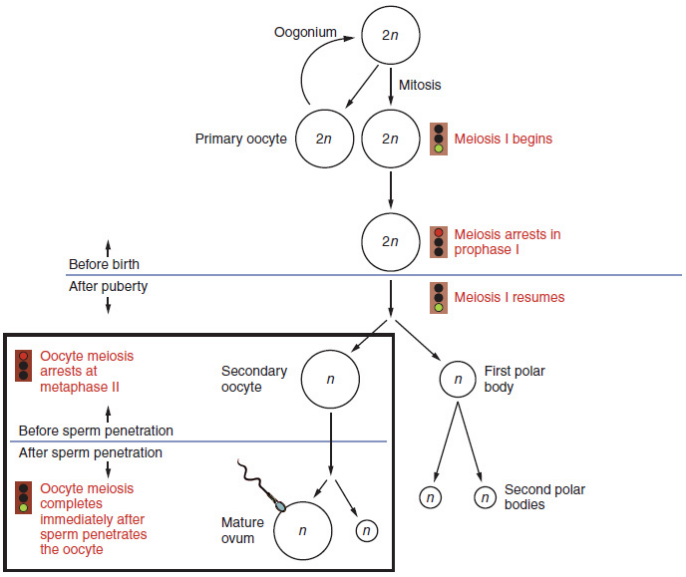

Figure 23.3.4: Oogenesis. The unequal cell division of oogenesis produces one to three polar bodies that later degrade, as well as a single haploid ovum, which is produced only if there is penetration of the secondary oocyte by a sperm cell. (Image credit: "Oogenesis" by OpenStax is licensed under CC BY 3.0)

How does the diploid secondary oocyte become an **ovum**—the haploid female gamete? Meiosis of a secondary oocyte is completed only if a sperm succeeds in penetrating its barriers, which must occur within 24 hours of ovulation. Meiosis II then resumes, producing one haploid ovum that, at the instant of fertilization by a (haploid) sperm, becomes the first diploid cell of the new offspring (a **zygote**). Thus, the ovum can be thought of as a brief, transitional, haploid stage between the diploid oocyte and diploid zygote. If sperm does not penetrate, then the secondary oocyte will break down after 24 hrs.

The larger amount of cytoplasm contained in the female gamete is used to supply the developing zygote with nutrients during the period between fertilization and implantation into the uterus. Interestingly, sperm contribute only DNA at fertilization —not cytoplasm. Therefore, the cytoplasm and all of the cytoplasmic organelles in the developing embryo are of maternal origin. This includes mitochondria, which contain their own DNA. Scientific research in the 1980s determined that mitochondrial DNA was maternally inherited, meaning that you can trace your mitochondrial DNA directly to your mother, her mother, and so on back through your female ancestors.

EVERYDAY CONNECTIONS FEATURE: Mapping Human History with Mitochondrial DNA

When we talk about human DNA, we're usually referring to nuclear DNA; that is, the DNA coiled into chromosomal bundles in the nucleus of our cells. We inherit half of our nuclear DNA from our father, and half from our mother. However, mitochondrial DNA (mtDNA) comes only from the mitochondria in the cytoplasm of the fat ovum we inherit from our mother. She received her mtDNA from her mother, who got it from her mother, and so on. Each of our cells contains approximately 1700 mitochondria, with each mitochondrion packed with mtDNA containing approximately 37 genes.

Mutations (changes) in mtDNA occur spontaneously in a somewhat organized pattern at regular intervals in human history. By analyzing these mutational relationships, researchers have been able to determine that we can all trace our ancestry back to one female population who lived in Africa about 200,000 years ago. Scientists have given these women the biblical name Eve, although they are not, of course, the first Homo sapiens females. More precisely, they are our most recent common ancestor through matrilineal descent.

This doesn't mean that everyone's mtDNA today looks exactly like that of our ancestral Eve. Because of the spontaneous mutations in mtDNA that have occurred over the centuries, researchers can map different "branches" off of the "main trunk" of our mtDNA family tree. Your mtDNA might have a pattern of mutations that aligns more closely with one branch, and your neighbor's may align with another branch. Still, all branches eventually lead back to Eve.

> But what happened to the mtDNA of all of the other Homo sapiens females who were living at the time of Eve? Researchers explain that, over the centuries, their female descendants died childless or with only male children, and thus, their maternal line—and its mtDNA—ended.

Folliculogenesis

Again, ovarian follicles are oocytes and their supporting cells. They grow and develop in a process called **folliculogenesis**, which typically leads to ovulation of one follicle approximately every 28 days, along with death to multiple other follicles (Figure 23.3.5). The death of ovarian follicles is called atresia, and can occur at any point during follicular development. Recall that, a female infant at birth will have one to two million oocytes within her ovarian follicles, and that this number declines throughout life until menopause, when no follicles remain. As you'll see next, follicles progress from primordial, to primary, to secondary and tertiary stages prior to ovulation—with the oocyte inside the follicle remaining as a primary oocyte until right before ovulation.

Folliculogenesis begins with follicles in a resting state. These small **primordial follicles** are present in newborn females and are the prevailing follicle type in the adult ovary . Primordial follicles have only a single flat layer of support cells, called **granulosa cells**, that surround the oocyte, and they can stay in this resting state for years—some until right before menopause.

After puberty, a few primordial follicles will respond to a recruitment signal each day, and will join a pool of immature growing follicles called **primary follicles**. Primary follicles start with a single layer of granulosa cells, but the granulosa cells then become active and transition from a flat or squamous shape to a rounded, cuboidal shape as they increase in size and proliferate. As the granulosa cells divide, the follicles—now called **secondary follicles** (see Figure 23.3.5)—increase in diameter, adding a new outer layer of connective tissue, blood vessels, and **theca cells**—cells that work with the granulosa cells to produce estrogens.

Within the growing secondary follicle, the primary oocyte now secretes a thin acellular membrane called the zona pellucida that will play a critical role in fertilization. A thick fluid, called follicular fluid, that has formed between the granulosa cells also begins to collect into one large pool, or **antrum**. Follicles in which the antrum has become large and fully formed are considered **tertiary follicles** (or antral follicles). Several follicles reach the tertiary stage at the same time, and most of these will undergo atresia. The one that does not die will continue to grow and develop until ovulation, when it will expel its secondary oocyte surrounded by several layers of granulosa cells from the ovary. Keep in mind that most follicles don't make it to this point. In fact, roughly 99 percent of the follicles in the ovary will undergo atresia, which can occur at any stage of folliculogenesis.

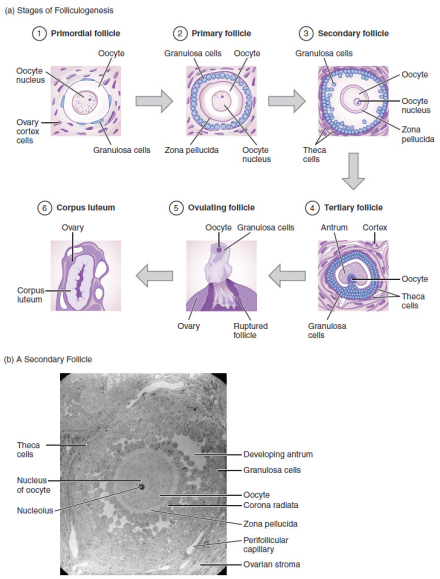

Figure 23.3.5: Folliculogenesis. (a) The maturation of a follicle is shown in a clockwise direction proceeding from the primordial follicles. FSH stimulates the growth of a tertiary follicle, and LH stimulates the production of estrogen by granulosa and theca cells. Once the follicle is mature, it ruptures and releases the oocyte. Cells remaining in the follicle then develop into the corpus luteum. (b) In this electron micrograph of a secondary follicle, the oocyte, theca cells (thecae folliculi), and developing antrum are clearly visible. EM × 1100; Micrograph provided by the Regents of University of Michigan Medical School © 2012. (Image credit: "Folliculogenesis" by OpenStax is licensed under CC BY 3.0)

Hormonal Control of the Ovarian Cycle

The process of development that we have just described, from primordial follicle to early tertiary follicle, takes approximately two months in humans. The final stages of development of a small cohort of tertiary follicles, ending with ovulation of a secondary oocyte, occur over a course of approximately 28 days. These changes are regulated by many of the same hormones that regulate the male reproductive system, including GnRH, LH, and FSH (Figure 23.3.6).

As in men, the hypothalamus produces GnRH, a hormone that signals the anterior pituitary gland to produce the gonadotropins FSH and LH. These gonadotropins leave the pituitary and travel through the bloodstream to the ovaries, where they bind to receptors on the granulosa and theca cells of the follicles. FSH stimulates the follicles to grow (hence its name of follicle-stimulating hormone), and the five or six tertiary follicles expand in diameter. The release of LH also stimulates the granulosa and theca cells of the follicles to produce the sex steroid hormone estradiol, a type of estrogen. This phase of the ovarian cycle, when the tertiary follicles are growing and secreting estrogen, is known as the follicular phase.

The more granulosa and theca cells a follicle has (that is, the larger and more developed it is), the more estrogen it will produce in response to LH stimulation. As a result of these large follicles producing large amounts of estrogen, systemic plasma estrogen concentrations increase. Following a classic negative feedback loop, the high concentrations of estrogen will stimulate the hypothalamus and pituitary to reduce the production of GnRH, LH, and FSH. Because the large tertiary follicles require FSH to grow and survive at this point, this decline in FSH caused by negative feedback leads most of them to die (atresia). Typically only one follicle, now called the dominant follicle, will survive this reduction in FSH, and this follicle will be the one that releases an oocyte. Scientists have studied many factors that lead to a particular follicle becoming dominant: size, the number of granulosa cells, and the number of FSH receptors on those granulosa cells all contribute to a follicle becoming the one surviving dominant follicle.

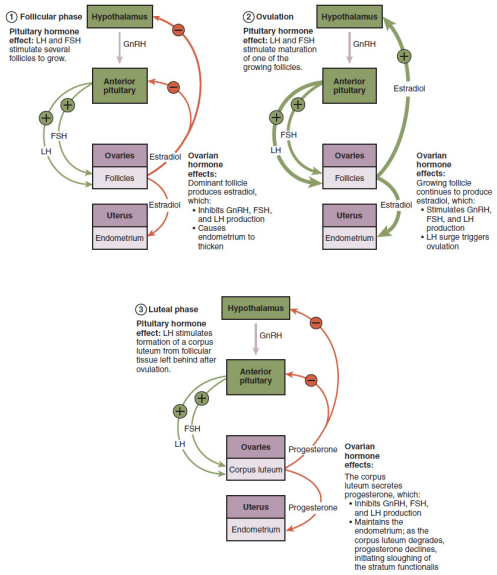

Figure 23.3.6: Hormonal Regulation of Ovulation. The hypothalamus and pituitary gland regulate the ovarian cycle and ovulation. GnRH activates the anterior pituitary to produce LH and FSH, which stimulate the production of estrogen and progesterone by the ovaries. (Image credit: "Hormonal Control of the Ovarian Cycle" by OpenStax is licensed under CC BY 3.0)

When only the one dominant follicle remains in the ovary, it again begins to secrete estrogen. It produces more estrogen than all of the developing follicles did together before the negative feedback occurred. It produces so much estrogen that the normal negative feedback doesn't occur. Instead, these extremely high concentrations of systemic plasma estrogen trigger a regulatory switch in the anterior pituitary that responds by secreting large amounts of LH and FSH into the bloodstream (see Figure 23.3.6). The positive feedback loop by which more estrogen triggers release of more LH and FSH only occurs at this point in the cycle.

It is this large burst of LH (called the LH surge) that leads to ovulation of the dominant follicle. The LH surge induces many changes in the dominant follicle, including stimulating the resumption of meiosis of the primary oocyte to a secondary oocyte. As noted earlier, the polar body that results from unequal cell division simply degrades. The LH surge also triggers proteases (enzymes that cleave proteins) to break down structural proteins in the ovary wall on the surface of the bulging dominant follicle. This degradation of the wall, combined with pressure from the large, fluid-filled antrum, results in the expulsion of the oocyte surrounded by granulosa cells into the peritoneal cavity. This release is ovulation.

In the next section, you will follow the ovulated oocyte as it travels toward the uterus, but there is one more important event that occurs in the ovarian cycle. The surge of LH also stimulates a change in the granulosa and theca cells that remain in the follicle after the oocyte has been ovulated. This change is called luteinization (recall that the full name of LH is luteinizing hormone), and it transforms the collapsed follicle into a new endocrine structure called the **corpus luteum**, a term meaning "yellowish body" (see Figure 23.3.5). In addition to estrogen, the luteinized granulosa and theca cells of the corpus luteum begin to produce large amounts of the sex steroid hormone progesterone, a hormone that is critical for the establishment and maintenance of pregnancy. Progesterone triggers negative feedback at the hypothalamus and pituitary, which keeps GnRH, LH, and FSH secretions low, so no new dominant follicles develop at this time.

The post-ovulatory phase of progesterone secretion is known as the luteal phase of the ovarian cycle. If pregnancy does not occur within 10 to 12 days, the corpus luteum will stop secreting progesterone and degrade into the **corpus albicans**, a nonfunctional "whitish body" that will disintegrate in the ovary over a period of several months. During this time of reduced progesterone secretion, FSH and LH are once again stimulated, and the follicular phase begins again with a new cohort of early tertiary follicles beginning to grow and secrete estrogen.

Uterine Tubes

The **uterine tubes** (also called fallopian tubes or oviducts) serve as the conduit of the oocyte from the ovary to the uterus (Figure 23.3.7). Each of the two uterine tubes is close to, but not directly connected to, the ovary. It is divided into sections. The **isthmus** is the narrow medial end of each uterine tube that is connected to the uterus. The wide distal **infundibulum** flares out with slender, finger-like projections called **fimbriae**. The middle region of the tube, called the **ampulla**, is where fertilization often occurs. The uterine tubes also have three layers: an outer serosa, a middle smooth muscle layer, and an inner mucosal layer. In addition to its mucus-secreting cells, the inner mucosa contains ciliated cells that beat in the direction of the uterus, producing a current that will be critical to move the oocyte.

Following ovulation, the secondary oocyte surrounded by a few granulosa cells is released into the peritoneal cavity. The nearby uterine tube, either left or right, receives the oocyte. Unlike sperm, oocytes lack flagella, and therefore cannot move on their own. So how do they travel into the uterine tube and toward the uterus? High concentrations of estrogen that occur around the time of ovulation induce contractions of the smooth muscle along the length of the uterine tube. These contractions occur every 4 to 8 seconds, and the result is a coordinated movement that sweeps the surface of the ovary and the pelvic cavity. Current flowing toward the uterus is generated by coordinated beating of the cilia that line the outside and lumen of the length of the uterine tube. These cilia beat more strongly in response to the high estrogen concentrations that occur around the time of ovulation. As a result of these mechanisms, the oocyte–granulosa cell complex is pulled into the interior of the tube. Once inside, the muscular contractions and beating cilia move the oocyte slowly toward the uterus. When fertilization does occur, sperm typically meets the egg while it is still moving through the ampulla.

Interactive Link

Watch this video Ovulation to observe ovulation and its initiation in response to the release of FSH and LH from the pituitary gland. What specialized structures help guide the oocyte from the ovary into the uterine tube?

Answer

Answer available at the end of this section.

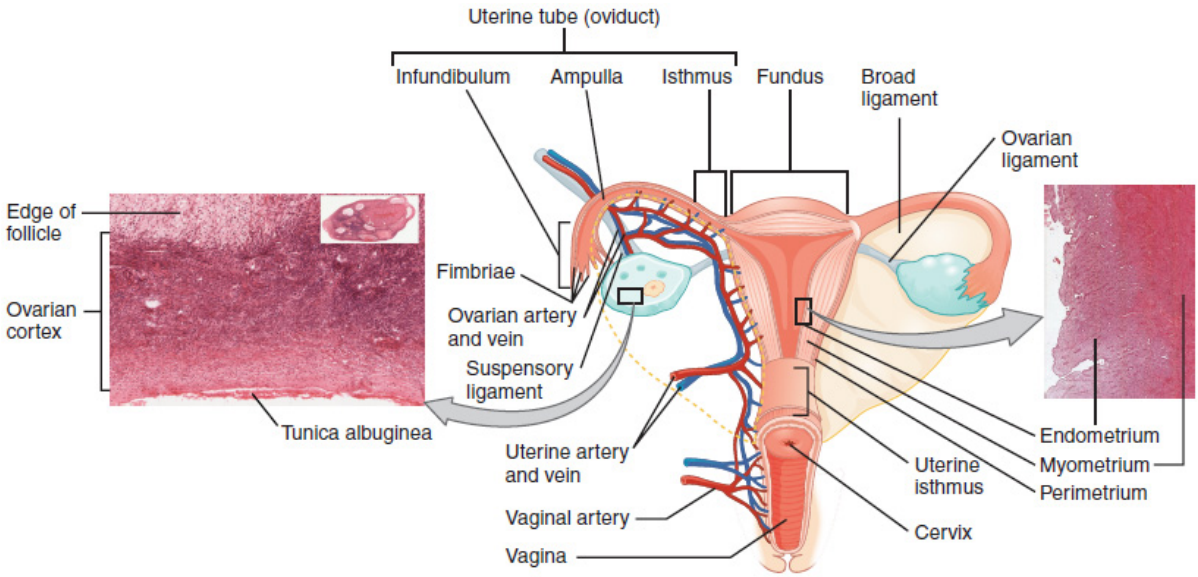

Figure 23.3.7: Ovaries, Uterine Tubes, and Uterus. This anterior view shows the relationship of the ovaries, uterine tubes (oviducts), and uterus. Sperm enter through the vagina, and fertilization of an ovulated oocyte usually occurs in the distal uterine tube. From left to right, LM × 400, LM × 20; Micrographs provided by the Regents of University of Michigan Medical School © 2012. (Image credit: "Uterus & Nearby Organs" by OpenStax is licensed under CC BY 3.0)

The open-ended structure of the uterine tubes can have significant health consequences if bacteria or other contagions enter through the vagina and move through the uterus, into the tubes, and then into the pelvic cavity. If this is left unchecked, a bacterial infection (sepsis) could quickly become life-threatening. The spread of an infection in this manner is of special concern when unskilled practitioners perform abortions in non-sterile conditions. Sepsis is also associated with sexually transmitted bacterial infections, especially gonorrhea and chlamydia. These increase a woman's risk for pelvic inflammatory disease (PID), infection of the uterine tubes or other reproductive organs. Even when resolved, PID can leave scar tissue in the tubes, leading to infertility.

If the oocyte is successfully fertilized, the resulting zygote will begin to divide into two cells, then four, and so on, as it makes its way through the uterine tube and into the uterus. There, it will implant and continue to grow. If the egg is not fertilized, it will simply degrade—either in the uterine tube or in the uterus, where it may be shed with the next menstrual period.

Uterus and Cervix

The **uterus** is the muscular organ that nourishes and supports the growing embryo (Figure 23.3.7). Its average size is approximately 5 cm wide by 7 cm long (approximately 2 in by 3 in) when a female is not pregnant. It has three sections. The portion of the uterus superior to the opening of the uterine tubes is called the **fundus**. The middle section of the uterus is called the **body of uterus** (or corpus). The **cervix** is the narrow inferior portion of the uterus that projects into the vagina. The cervix produces mucus secretions that become thin and stringy under the influence of high systemic plasma estrogen concentrations, and these secretions can facilitate sperm movement through the reproductive tract.

Several ligaments maintain the position of the uterus within the abdominopelvic cavity. The broad ligament is a fold of peritoneum that serves as a primary support for the uterus, extending laterally from both sides of the uterus and attaching it to the pelvic wall (Figure 23.3.3). The **round ligament** attaches to the uterus near the uterine tubes, and extends to the labia majora. Finally, the **uterosacral ligament** stabilizes the uterus posteriorly by its connection from the cervix to the pelvic wall.

The wall of the uterus is made up of three layers. The most superficial layer is the serous membrane, or **perimetrium**, which consists of epithelial tissue that covers the exterior portion of the uterus. The middle layer, or **myometrium**, is a thick layer of smooth muscle responsible for uterine contractions. Most of the uterus is myometrial tissue, and the muscle fibers run horizontally, vertically, and diagonally, allowing the powerful contractions that occur during labor and the less powerful contractions (or cramps) that help to expel menstrual blood during a woman's period. Anteriorly directed myometrial contractions also occur near the time of ovulation, and are thought to possibly facilitate the transport of sperm through the female reproductive tract.

The innermost layer of the uterus is called the **endometrium**. The endometrium contains a connective tissue lining, the lamina

propria, which is covered by epithelial tissue that lines the lumen. Structurally, the endometrium consists of two layers: the **stratum basalis** and the **stratum functionalis** (the basal and functional layers). The stratum basalis layer is part of the lamina propria and is adjacent to the myometrium; this layer does not shed during menses. In contrast, the thicker stratum functionalis layer contains the glandular portion of the lamina propria and the endothelial tissue that lines the uterine lumen. It is the stratum functionalis that grows and thickens in response to increased levels of estrogen and progesterone. In the luteal phase of the menstrual cycle, special branches off of the uterine artery called spiral arteries supply the thickened stratum functionalis. This inner functional layer provides the proper site of implantation for the fertilized egg, and—should fertilization not occur—it is only the stratum functionalis layer of the endometrium that sheds during menstruation.

Recall that during the follicular phase of the ovarian cycle, the tertiary follicles are growing and secreting estrogen. At the same time, the stratum functionalis of the endometrium is thickening to prepare for a potential implantation. The post-ovulatory increase in progesterone, which characterizes the luteal phase, is key for maintaining a thick stratum functionalis. As long as a functional corpus luteum is present in the ovary, the endometrial lining is prepared for implantation. Indeed, if an embryo implants, signals are sent to the corpus luteum to continue secreting progesterone to maintain the endometrium, and thus maintain the pregnancy. If an embryo does not implant, no signal is sent to the corpus luteum and it degrades, ceasing progesterone production and ending the luteal phase. Without progesterone, the endometrium thins and, under the influence of prostaglandins, the spiral arteries of the endometrium constrict and rupture, preventing oxygenated blood from reaching the endometrial tissue. As a result, endometrial tissue dies and blood, pieces of the endometrial tissue, and white blood cells are shed through the vagina during menstruation, or the **menses**. The first menses after puberty, called **menarche**, can occur either before or after the first ovulation.

Menstrual Cycle

Now that we have discussed the maturation of the cohort of tertiary follicles in the ovary, the build-up and then shedding of the endometrial lining in the uterus, and the function of the uterine tubes and vagina, we can put everything together to talk about the three phases of the **menstrual cycle**—the series of changes in which the uterine lining is shed, rebuilds, and prepares for implantation (Figure 23.3.8). Details of these activities are covered in the following paragraphs.

The timing of the menstrual cycle starts with the first day of menses, referred to as day one of a woman's period. Cycle length is determined by counting the days between the onset of bleeding in two consecutive cycles. Because the average length of a woman's menstrual cycle is 28 days, this is the time period used to identify the timing of events in the cycle. However, the length of the menstrual cycle varies among women, and even in the same woman from one cycle to the next, typically from 21 to 32 days.

Just as the hormones produced by the granulosa and theca cells of the ovary "drive" the follicular and luteal phases of the ovarian cycle, they also control the three distinct phases of the menstrual cycle. These are the menses phase, the proliferative phase, and the secretory phase.

Menses Phase

The **menses phase** of the menstrual cycle is the phase during which the lining is shed; that is, the days that the woman menstruates. Although it averages approximately five days, the menses phase can last from 2 to 7 days, or longer (Figure 23.3.8). The menses phase occurs during the early days of the follicular phase of the ovarian cycle, when progesterone, FSH, and LH levels are low. Recall that progesterone concentrations decline as a result of the degradation of the corpus luteum, marking the end of the luteal phase. This decline in progesterone triggers the shedding of the stratum functionalis of the endometrium.

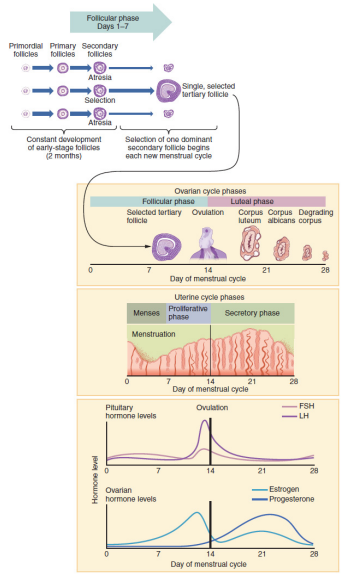

Figure 23.3.8: Hormone Levels in Ovarian and Menstrual Cycles. The correlation of the hormone levels and their effects on the female reproductive system is shown in this timeline of the ovarian and menstrual cycles. The menstrual cycle begins at day one with the start of menses. Ovulation occurs around day 14 of a 28-day cycle, triggered by the LH surge. (Image credit: "Ovarian and Menstrual Cycles" by OpenStax is licensed under CC BY 3.0)

Proliferative Phase

Once menstrual flow ceases, the endometrium begins to proliferate again, marking the beginning of the **proliferative phase** of the menstrual cycle (see Figure 23.3.8). It occurs when the granulosa and theca cells of the tertiary follicles begin to produce increased amounts of estrogen. These rising estrogen concentrations stimulate the endometrial lining to rebuild.

Recall that the high estrogen concentrations will eventually lead to a decrease in FSH as a result of negative feedback, resulting in atresia of all but one of the developing tertiary follicles. The switch to positive feedback—which occurs with the elevated estrogen production from the dominant follicle—then stimulates the LH surge that will trigger ovulation. In a typical 28-day menstrual cycle, ovulation occurs on day 14. Ovulation marks the end of the proliferative phase as well as the end of the follicular phase.

Secretory Phase

In addition to prompting the LH surge, high estrogen levels increase the uterine tube contractions that facilitate the pick-up and transfer of the ovulated oocyte. High estrogen levels also slightly decrease the acidity of the vagina, making it more hospitable to sperm. In the ovary, the luteinization of the granulosa cells of the collapsed follicle forms the progesterone-producing corpus luteum, marking the beginning of the luteal phase of the ovarian cycle. In the uterus, progesterone from the corpus luteum begins the **secretory phase** of the menstrual cycle, in which the endometrial lining prepares for implantation (see Figure 23.3.8). Over the next 10 to 12 days, the endometrial glands secrete a fluid rich in glycogen. If fertilization has occurred, this fluid will nourish the ball of cells now developing from the zygote. At the same time, the spiral arteries develop to provide blood to the thickened stratum functionalis.

If no pregnancy occurs within approximately 10 to 12 days, the corpus luteum will degrade into the corpus albicans. Levels of both estrogen and progesterone will fall, and the endometrium will grow thinner. Prostaglandins will be secreted that cause constriction of the spiral arteries, reducing oxygen supply. The endometrial tissue will die, resulting in menses—or the first day of the next cycle.

DISORDERS OF THE...

Female Reproductive System

Research over many years has confirmed that cervical cancer is most often caused by a sexually transmitted infection with human papillomavirus (HPV). There are over 100 related viruses in the HPV family, and the characteristics of each strain determine the outcome of the infection. In all cases, the virus enters body cells and uses its own genetic material to take over the host cell's metabolic machinery and produce more virus particles.

HPV infections are common in both men and women. Indeed, a recent study determined that 42.5 percent of females had HPV at the time of testing. These women ranged in age from 14 to 59 years and differed in race, ethnicity, and number of sexual partners. Of note, the prevalence of HPV infection was 53.8 percent among women aged 20 to 24 years, the age group with the highest infection rate.

Figure 23.3.9 is a drawing to show the cell life cycle and the different changes seen when HPV is absent or present. HPV strains are classified as high or low risk according to their potential to cause cancer. Though most HPV infections do not cause disease, the disruption of normal cellular functions in the low-risk forms of HPV can cause the male or female human host to develop genital warts. Often, the body is able to clear an HPV infection by normal immune responses within 2 years. However, the more serious, high-risk infection by certain types of HPV can result in cancer of the cervix. Infection with either of the cancer-causing variants HPV 16 or HPV 18 has been linked to more than 70 percent of all cervical cancer diagnoses. Although even these high-risk HPV strains can be cleared from the body over time, infections persist in some individuals. If this happens, the HPV infection can influence the cells of the cervix to develop precancerous changes.

Risk factors for cervical cancer include having unprotected sex; having multiple sexual partners; a first sexual experience at a younger age, when the cells of the cervix are not fully mature; failure to receive the HPV vaccine; a compromised immune system; and smoking. The risk of developing cervical cancer is doubled with cigarette smoking.

The prevalence of cervical cancer in the United States is very low because of regular screening exams called pap smears. Pap smears sample cells of the cervix, allowing the detection of abnormal cells. If pre-cancerous cells are detected, there are several highly effective techniques that are currently in use to remove them before they pose a danger. However, women in developing countries often do not have access to regular pap smears. As a result, these women account for as many as 80 percent of the cases of cervical cancer worldwide.

In 2006, the first vaccine against the high-risk types of HPV was approved. There are now two HPV vaccines available: Gardasil® and Cervarix®. Whereas these vaccines were initially only targeted for women, because HPV is sexually transmitted, both men and women require vaccination for this approach to achieve its maximum efficacy. A recent study suggests that the HPV vaccine has cut the rates of HPV infection by the four targeted strains at least in half. Unfortunately, the high cost of manufacturing the vaccine is currently limiting access to many women worldwide.

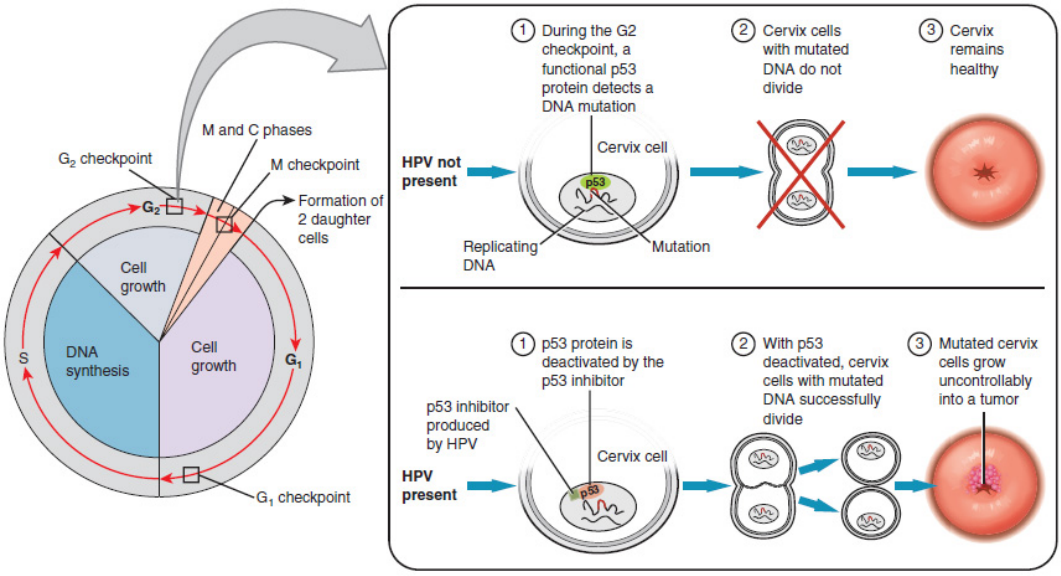

Figure 23.3.9: Development of Cervical Cancer. In most cases, cells infected with the HPV virus heal on their own. In some cases, however, the virus continues to spread and becomes an invasive cancer. (Image credit: "Figure 28 02 08" by OpenStax is licensed under CC BY 3.0)

Breasts

Whereas the breasts are located far from the other female reproductive organs, they are considered accessory organs of the female reproductive system. The function of the breasts is to supply milk to an infant in a process called lactation. The external features of the breast include a nipple surrounded by a pigmented **areola**, whose coloration may deepen during pregnancy. The areola is typically circular and can vary in size from 25 to 100 mm in diameter (Figure 23.3.10). The areolar region is characterized by small, raised areolar glands that secrete lubricating fluid during lactation to protect the nipple from chafing. When a baby nurses, or draws milk from the breast, the entire areolar region is taken into the mouth.

Breast milk is produced by the **mammary glands**, which are modified sweat glands. The milk itself exits the breast through the nipple via 15 to 20 **lactiferous ducts** that open on the surface of the nipple. These lactiferous ducts each extend to a **lactiferous sinus** that connects to a glandular lobe within the breast itself that contains groups of milk-secreting cells in clusters called **alveoli** (see Figure 23.3.10). The clusters can change in size depending on the amount of milk in the alveolar lumen. Once milk is made in the alveoli, stimulated myoepithelial cells that surround the alveoli contract to push the milk to the lactiferous sinuses. From here, the baby can draw milk through the lactiferous ducts by suckling. The lobes themselves are surrounded by fat tissue, which determines the size of the breast; breast size differs between individuals and does not affect the amount of milk produced. Supporting the breasts are multiple bands of connective tissue called **suspensory ligaments** that connect the breast tissue to the dermis of the overlying skin.

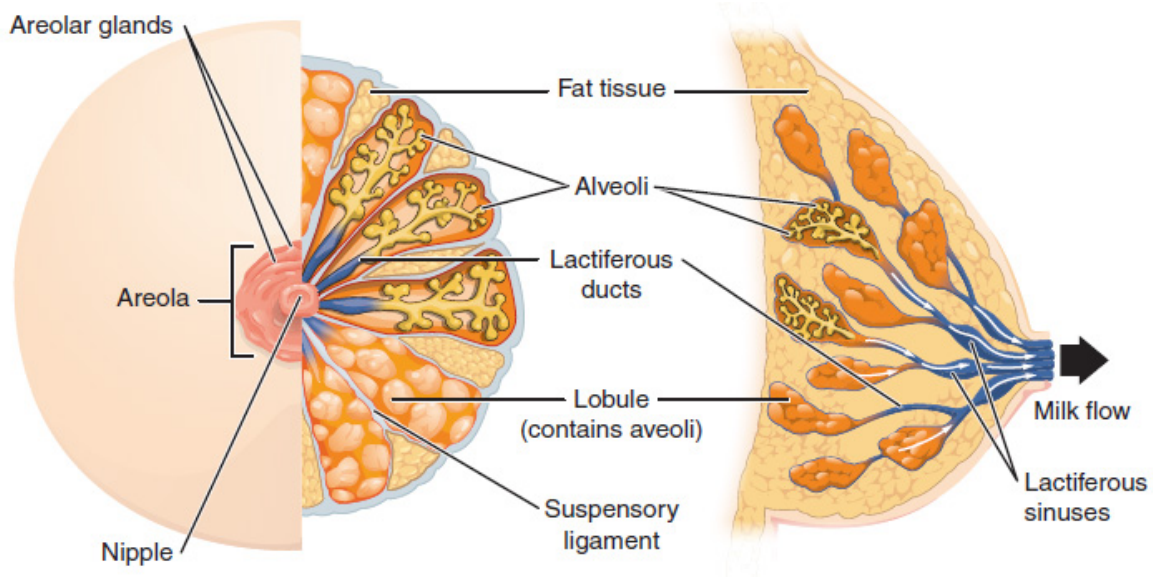

Figure 23.3.10: Anatomy of the Breast. During lactation, milk moves from the alveoli through the lactiferous ducts to the nipple. (Image credit: "Anatomy of the Breast" by OpenStax is licensed under CC BY 3.0)

During the normal hormonal fluctuations in the menstrual cycle, breast tissue responds to changing levels of estrogen and progesterone, which can lead to swelling and breast tenderness in some individuals, especially during the secretory phase. If pregnancy occurs, the increase in hormones leads to further development of the mammary tissue and enlargement of the breasts.

AGING AND THE...

Female Reproductive System

Female fertility (the ability to conceive) peaks when women are in their twenties, and is slowly reduced until a women reaches 35 years of age. After that time, fertility declines more rapidly, until it ends completely at the end of menopause. Menopause is the cessation of the menstrual cycle that occurs as a result of the loss of ovarian follicles and the hormones that they produce. A woman is considered to have completed menopause if she has not menstruated in a full year. After that point, she is considered postmenopausal. The average age for this change is consistent worldwide at between 50 and 52 years of age, but it can normally occur in a woman's forties, or later in her fifties. Poor health, including smoking, can lead to earlier loss of fertility and earlier menopause.

As a woman reaches the age of menopause, depletion of the number of viable follicles in the ovaries due to atresia affects the hormonal regulation of the menstrual cycle. During the years leading up to menopause, there is a decrease in the levels of the hormone inhibin, which normally participates in a negative feedback loop to the pituitary to control the production of FSH. The menopausal decrease in inhibin leads to an increase in FSH. The presence of FSH stimulates more follicles to grow and secrete estrogen. Because small, secondary follicles also respond to increases in FSH levels, larger numbers of follicles are stimulated to grow; however, most undergo atresia and die. Eventually, this process leads to the depletion of all follicles in the ovaries, and the production of estrogen falls off dramatically. It is primarily the lack of estrogens that leads to the symptoms of menopause.

The earliest changes occur during the menopausal transition, often referred to as peri-menopause, when a women's cycle becomes irregular but does not stop entirely. Although the levels of estrogen are still nearly the same as before the transition, the level of progesterone produced by the corpus luteum is reduced. This decline in progesterone can lead to abnormal growth, or hyperplasia, of the endometrium. This condition is a concern because it increases the risk of developing endometrial cancer. Two harmless conditions that can develop during the transition are uterine fibroids, which are benign masses of cells, and irregular bleeding. As estrogen levels change, other symptoms that occur are hot flashes and night sweats, trouble sleeping, vaginal dryness, mood swings, difficulty focusing, and thinning of hair on the head along with the growth of more hair on the face. Depending on the individual, these symptoms can be entirely absent, moderate, or severe.

After menopause, lower amounts of estrogens can lead to other changes. Cardiovascular disease becomes as prevalent in women as in men, possibly because estrogens reduce the amount of cholesterol in the blood vessels. When estrogen is lacking, many women find that they suddenly have problems with high cholesterol and the cardiovascular issues that accompany it. Osteoporosis is another problem because bone density decreases rapidly in the first years after menopause. The reduction in bone density leads to a higher incidence of fractures.

Hormone therapy (HT), which employs medication (synthetic estrogens and progestins) to increase estrogen and progestin levels, can alleviate some of the symptoms of menopause. In 2002, the Women's Health Initiative began a study to observe women for the long-term outcomes of hormone replacement therapy over 8.5 years. However, the study was prematurely terminated after 5.2 years because of evidence of a higher than normal risk of breast cancer in patients taking estrogen-only HT. The potential positive effects on cardiovascular disease were also not realized in the estrogen-only patients. The results of other hormone replacement studies over the last 50 years, including a 2012 study that followed over 1,000 menopausal women for 10 years, have shown cardiovascular benefits from estrogen and no increased risk for cancer. Some researchers believe that the age group tested in the 2002 trial may have been too old to benefit from the therapy, thus skewing the results. In the meantime, intense debate and study of the benefits and risks of replacement therapy is ongoing. Current guidelines approve HT for the reduction of hot flashes or flushes, but this treatment is generally only considered when women first start showing signs of menopausal changes, is used in the lowest dose possible for the shortest time possible (5 years or less), and it is suggested that women on HT have regular pelvic and breast exams.

Concept Review

The external female genitalia are collectively called the vulva. The vagina is the pathway into and out of the uterus. The man's penis is inserted into the vagina to deliver sperm, and the baby exits the uterus through the vagina during childbirth.

The ovaries produce oocytes, the female gametes, in a process called oogenesis. As with spermatogenesis, meiosis produces the haploid gamete (in this case, an ovum); however, it is completed only in an oocyte that has been penetrated by a sperm. In the ovary, an oocyte surrounded by supporting cells is called a follicle. In folliculogenesis, primordial follicles develop into primary, secondary, and tertiary follicles. Early tertiary follicles with their fluid-filled antrum will be stimulated by an increase in FSH, a gonadotropin produced by the anterior pituitary, to grow in the 28-day ovarian cycle. Supporting granulosa and theca cells in the growing follicles produce estrogens, until the level of estrogen in the bloodstream is high enough that it triggers negative feedback at the hypothalamus and pituitary. This results in a reduction of FSH and LH, and most tertiary follicles in the ovary undergo atresia (they die). One follicle, usually the one with the most FSH receptors, survives this period and is now called the dominant follicle. The dominant follicle produces more estrogen, triggering positive feedback and the LH surge that will induce ovulation. Following ovulation, the granulosa cells of the empty follicle luteinize and transform into the progesterone-producing corpus luteum. The ovulated oocyte with its surrounding granulosa cells is picked up by the infundibulum of the uterine tube, and beating cilia help to transport it through the tube toward the uterus. Fertilization occurs within the uterine tube, and the final stage of meiosis is completed.

The uterus has three regions: the fundus, the body, and the cervix. It has three layers: the outer perimetrium, the muscular

myometrium, and the inner endometrium. The endometrium responds to estrogen released by the follicles during the menstrual cycle and grows thicker with an increase in blood vessels in preparation for pregnancy. If the egg is not fertilized, no signal is sent to extend the life of the corpus luteum, and it degrades, stopping progesterone production. This decline in progesterone results in the sloughing of the inner portion of the endometrium in a process called menses, or menstruation.

The breasts are accessory sexual organs that are utilized after the birth of a child to produce milk in a process called lactation. Birth control pills provide constant levels of estrogen and progesterone to negatively feed back on the hypothalamus and pituitary, and suppress the release of FSH and LH, which inhibits ovulation and prevents pregnancy.

Review Questions

Q. What are the female gonads called?

A. oocytes

B. ova

C. oviducts

D. ovaries

Answer

Answer: D

Q. When do the oogonia undergo mitosis?

A. before birth

B. at puberty

C. at the beginning of each menstrual cycle

D. during fertilization

Answer

Answer: A

Q. From what structure does the corpus luteum originate?

A. uterine corpus

B. dominant follicle

C. fallopian tube

D. corpus albicans

Answer

Answer: B

Q. Where does fertilization of the egg by the sperm typically occur?

A. vagina

B. uterus

C. uterine tube

D. ovary

Answer

Answer: C

Q. The vulva includes the _____.

A. lactiferous duct, rugae, and hymen

B. lactiferous duct, endometrium, and bulbourethral glands

C. mons pubis, endometrium, and hymen

D. mons pubis, labia majora, and Bartholin's glands

Answer

Answer: D

Critical Thinking Questions

Q. Follow the path of ejaculated sperm from the vagina to the oocyte. Include all structures of the female reproductive tract that the sperm must swim through to reach the egg.

Answer

A. The sperm must swim upward in the vagina, through the cervix, and then through the body of the uterus to one of the two uterine tubes. Fertilization generally occurs in the lateral third of the uterine tube.

Q. Identify some differences between meiosis in men and women.

Answer

A. Meiosis in the man results in four viable haploid sperm, whereas meiosis in the woman results in a secondary oocyte and, upon completion following fertilization by a sperm, one viable haploid ovum with abundant cytoplasm and up to three polar bodies with little cytoplasm that will die.

Q. Endometriosis is a disorder in which endometrial cells implant and proliferate outside of the uterus—in the uterine tubes, on the ovaries, or even in the pelvic cavity. Offer a theory as to why endometriosis increases a woman's risk of infertility.

Answer

A. Endometrial tissue proliferating outside of the endometrium—for example, in the uterine tubes, on the ovaries, or within the pelvic cavity—could block the passage of sperm, ovulated oocytes, or a zygote, thus reducing fertility.

Glossary

alveoli
(of the breast) milk-secreting cells in the mammary gland

ampulla
(of the uterine tube) middle portion of the uterine tube in which fertilization often occurs

antrum
fluid-filled chamber that characterizes a mature tertiary (antral) follicle

areola
highly pigmented, circular area surrounding the raised nipple and containing areolar glands that secrete fluid important for lubrication during suckling

Bartholin's glands
(also, greater vestibular glands) glands that produce a thick mucus that maintains moisture in the vulva area; also referred to as the greater vestibular glands

body of uterus
middle section of the uterus

broad ligament
wide ligament that supports the uterus by attaching laterally to both sides of the uterus and pelvic wall

cervix
elongate inferior end of the uterus where it connects to the vagina

clitoris
(also, glans clitoris) nerve-rich area of the vulva that contributes to sexual sensation during intercourse

corpus albicans
nonfunctional structure remaining in the ovarian stroma following structural and functional regression of the corpus luteum

corpus luteum
transformed follicle after ovulation that secretes progesterone

endometrium
inner lining of the uterus, part of which builds up during the secretory phase of the menstrual cycle and then sheds with menses

fimbriae
fingerlike projections on the distal uterine tubes

follicle
ovarian structure of one oocyte and surrounding granulosa (and later theca) cells

folliculogenesis
development of ovarian follicles from primordial to tertiary under the stimulation of gonadotropins

fundus
(of the uterus) domed portion of the uterus that is superior to the uterine tubes

granulosa cells
supportive cells in the ovarian follicle that produce estrogen

hymen
membrane that covers part of the opening of the vagina

infundibulum
(of the uterine tube) wide, distal portion of the uterine tube terminating in fimbriae

isthmus
narrow, medial portion of the uterine tube that joins the uterus

labia majora
hair-covered folds of skin located behind the mons pubis

labia minora
thin, pigmented, hairless flaps of skin located medial and deep to the labia majora

lactiferous ducts
ducts that connect the mammary glands to the nipple and allow for the transport of milk

lactiferous sinus
area of milk collection between alveoli and lactiferous duct

mammary glands
glands inside the breast that secrete milk

menarche
first menstruation in a pubertal female

menses
shedding of the inner portion of the endometrium out though the vagina; also referred to as menstruation

menses phase
phase of the menstrual cycle in which the endometrial lining is shed

menstrual cycle
approximately 28-day cycle of changes in the uterus consisting of a menses phase, a proliferative phase, and a secretory phase

mons pubis
mound of fatty tissue located at the front of the vulva

myometrium
smooth muscle layer of uterus that allows for uterine contractions during labor and expulsion of menstrual blood

oocyte
cell that results from the division of the oogonium and undergoes meiosis I at the LH surge and meiosis II at fertilization to become a haploid ovum

oogenesis
process by which oogonia divide by mitosis to primary oocytes, which undergo meiosis to produce the secondary oocyte and, upon fertilization, the ovum

oogonia
ovarian stem cells that undergo mitosis during female fetal development to form primary oocytes

ovarian cycle
approximately 28-day cycle of changes in the ovary consisting of a follicular phase and a luteal phase

ovaries
female gonads that produce oocytes and sex steroid hormones (notably estrogen and progesterone)

ovulation
release of a secondary oocyte and associated granulosa cells from an ovary

ovum
haploid female gamete resulting from completion of meiosis II at fertilization

perimetrium
outer epithelial layer of uterine wall

polar body
smaller cell produced during the process of meiosis in oogenesis

primary follicles
ovarian follicles with a primary oocyte and one layer of cuboidal granulosa cells

primordial follicles
least developed ovarian follicles that consist of a single oocyte and a single layer of flat (squamous) granulosa cells

proliferative phase
phase of the menstrual cycle in which the endometrium proliferates

rugae
(of the vagina) folds of skin in the vagina that allow it to stretch during intercourse and childbirth

secondary follicles
ovarian follicles with a primary oocyte and multiple layers of granulosa cells

secretory phase
phase of the menstrual cycle in which the endometrium secretes a nutrient-rich fluid in preparation for implantation of an embryo

suspensory ligaments
bands of connective tissue that suspend the breast onto the chest wall by attachment to the overlying dermis

tertiary follicles
(also, antral follicles) ovarian follicles with a primary or secondary oocyte, multiple layers of granulosa cells, and a fully formed antrum

theca cells
estrogen-producing cells in a maturing ovarian follicle

uterine tubes
(also, fallopian tubes or oviducts) ducts that facilitate transport of an ovulated oocyte to the uterus

uterus
muscular hollow organ in which a fertilized egg develops into a fetus

vagina
tunnel-like organ that provides access to the uterus for the insertion of semen and from the uterus for the birth of a baby

vulva
external female genitalia

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Answers

Interactive Link

Answer: The fimbriae sweep the oocyte into the uterine tube.

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23.4: Development of the Male and Female Reproductive Systems

By the end of the section, you will be able to:

- Explain how bipotential tissues are directed to develop into male or female sex organs
- Name the rudimentary duct systems in the embryo that are precursors to male or female internal sex organs
- Describe the hormonal changes that bring about puberty, and the secondary sex characteristics of men and women

The sperm has 24 hrs after ovulation to fertilize the ovum. Fertilization is defined as the combining of the 23 chromosomes from the sperm with the 23 chromosomes from the ovum. The fertilized egg, called a **zygote**, will undergo many rounds of cell division while the cilia inside the fallopian tube push it along. As the zygote divides, it is becomes a solid ball of 16 cells called a **morula**. The morula will continue dividing while hollowing out with a space in the center. This hollow ball of cells is now a **blastocyst** and will implant in the uterus. The development of the reproductive systems begins soon after fertilization of the egg, with primordial gonads beginning to develop approximately one month after conception. Reproductive development continues in utero, but there is little change in the reproductive system between infancy and puberty.

Interactive

Watch this video Cell Division to see the early development after fertilization. What is the result if the cilia does not work?

Answer

Answer available at the end of this section.

Development of the Sexual Organs in the Embryo and Fetus

Females are considered the “fundamental” sex—that is, without much chemical prompting, all fertilized eggs would develop into females. To become a male, an individual must be exposed to the cascade of factors initiated by a single gene on the male Y chromosome. This is called the SRY (Sex-determining *R*egion of the *Y* chromosome). Because females do not have a Y chromosome, they do not have the *SRY* gene. Without a functional *SRY* gene, an individual will be female.

In both male and female embryos, the same group of cells has the potential to develop into either the male or female gonads; this tissue is considered bipotential. The *SRY* gene actively recruits other genes that begin to develop the testes, and suppresses genes that are important in female development. As part of this *SRY*-prompted cascade, germ cells in the bipotential gonads differentiate into spermatogonia. Without *SRY*, different genes are expressed, oogonia form, and primordial follicles develop in the primitive ovary.

Soon after the formation of the testis, the Leydig cells begin to secrete testosterone. Testosterone can influence tissues that are

bipotential to become male reproductive structures. For example, with exposure to testosterone, cells that could become either the glans penis or the glans clitoris form the glans penis. Without testosterone, these same cells differentiate into the clitoris.Not all tissues in the reproductive tract are bipotential. The internal reproductive structures (for example the uterus, uterine tubes, and part of the vagina in females; and the epididymis, ductus deferens, and seminal vesicles in males) form from one of two rudimentary duct systems in the embryo. For proper reproductive function in the adult, one set of these ducts must develop properly, and the other must degrade. In males, secretions from sustentacular cells trigger a degradation of the female duct, called the **Müllerian duct**. At the same time, testosterone secretion stimulates growth of the male tract, the **Wolffian duct**. Without such sustentacular cell secretion, the Müllerian duct will develop; without testosterone, the Wolffian duct will degrade. Thus, the developing offspring will be female (Figure 23.4.1).

Drawing of the development of reproductive organs, starting from one common tissue and resulting in 2 rudimentary duct systems.

Figure 23.4.1: Sexual Differentiation. Bipotential and 2 rudimentary duct systems will develop male or female reproductive systems depending on the Y chromosomes. (Image credit: “Sexual Differentiation” by Jonathan Marcus is licensed under CC BY SA 3.0)

Interactive Link

A baby’s gender is determined at conception, and the different genitalia of male and female fetuses develop from the same tissues in the embryo. View this video Baby's Gender that compares the development of structures of the female and male reproductive systems in a growing fetus. Where are the testes located for most of gestational time?

Answer

Answer available at the end of this section.

Further Sexual Development Occurs at Puberty

Puberty is the stage of development at which individuals become sexually mature. Though the outcomes of puberty for boys and girls are very different, the hormonal control of the process is very similar. In addition, though the timing of these events varies between individuals, the sequence of changes that occur is predictable for male and female adolescents. As shown in Figure 23.4.2, a concerted release of hormones from the hypothalamus (GnRH), the anterior pituitary (LH and FSH), and the gonads (either testosterone or estrogen) is responsible for the maturation of the reproductive systems and the development of **secondary sex characteristics**, which are physical changes that serve auxiliary roles in reproduction.

In addition to age, multiple factors can affect the age of onset of puberty, including genetics, environment, and psychological stress. One of the more important influences may be nutrition; historical data demonstrate the effect of better and more consistent nutrition on the age of menarche in girls in the United States, which decreased from an average age of approximately 17 years of age in 1860 to the current age of approximately 12.75 years in 1960, as it remains today. Some studies indicate a link between puberty onset and the amount of stored fat in an individual. This effect is more pronounced in girls, but has been documented in both sexes. Body fat, corresponding with secretion of the hormone leptin by adipose cells, appears to have a strong role in determining menarche. This may reflect to some extent the high metabolic costs of gestation and lactation. In girls who are lean and highly active, such as gymnasts, there is often a delay in the onset of puberty.

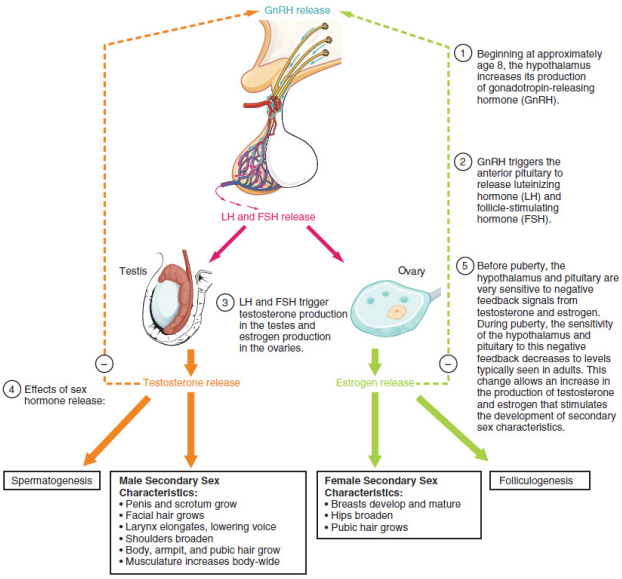

Figure 23.4.2: Hormones of Puberty. During puberty, the release of LH and FSH from the anterior pituitary stimulates the gonads to produce sex hormones in both male and female adolescents. (Image credit: "Hormones at Puberty" by OpenStax is licensed under CC BY 3.0)

Signs of Puberty

Different sex steroid hormone concentrations between the sexes also contribute to the development and function of secondary sexual characteristics. Examples of secondary sexual characteristics are listed in Table 23.4.1.

Table 23.4.1: Development of the Secondary Sexual Characteristics

Male	Female
Increased larynx size and deepening of the voice	Deposition of fat, predominantly in breasts and hips
Increased muscular development	Breast development
Growth of facial, axillary, and pubic hair, and increased growth of body hair	Broadening of the pelvis and growth of axillary and pubic hair

As a girl reaches puberty, typically the first change that is visible is the development of the breast tissue. This is followed by the growth of axillary and pubic hair. A growth spurt normally starts at approximately age 9 to 11, and may last two years or more. During this time, a girl's height can increase 3 inches a year. The next step in puberty is menarche, the start of menstruation.

In boys, the growth of the testes is typically the first physical sign of the beginning of puberty, which is followed by growth and pigmentation of the scrotum and growth of the penis. The next step is the growth of hair, including armpit, pubic, chest, and facial hair. Testosterone stimulates the growth of the larynx and thickening and lengthening of the vocal folds, which causes the voice to drop in pitch. The first fertile ejaculations typically appear at approximately 15 years of age, but this age can vary widely across individual boys. Unlike the early growth spurt observed in females, the male growth spurt occurs toward the end of puberty, at approximately age 11 to 13, and a boy's height can increase as much as 4 inches a year. In some males, pubertal development can continue through the early 20s.

Concept Review

The reproductive systems of males and females begin to develop soon after conception. A gene on the male's Y chromosome called *SRY* is critical in stimulating a cascade of events that simultaneously stimulate testis development and repress the development of female structures. Testosterone produced by Leydig cells in the embryonic testis stimulates the development of male sexual organs. If testosterone is not present, female sexual organs will develop.

Whereas the gonads and some other reproductive tissues are considered bipotential, the tissue that forms the internal reproductive structures stems from ducts that will develop into only male (Wolffian) or female (Müllerian) structures. To be able to

reproduce as an adult, one of these systems must develop properly and the other must degrade.

Further development of the reproductive systems occurs at puberty. The increase in sex steroid hormones leads to maturation of the gonads and other reproductive organs. The initiation of spermatogenesis begins in boys, and girls begin ovulating and menstruating. Increases in sex steroid hormones also lead to the development of secondary sex characteristics such as breast development in girls and facial hair and larynx growth in boys.

Review Questions

Q What controls whether an embryo will develop testes or ovaries?

A. pituitary gland

B. hypothalamus

C. Y chromosome

D. presence or absence of estrogen

Answer

Answer: C

Q. Without *SRY* expression, an embryo will develop _____.

A. male reproductive structures

B. female reproductive structures

C. no reproductive structures

D. male reproductive structures 50 percent of the time and female reproductive structures 50 percent of the time

Answer

Answer: B

Q. The timing of puberty can be influenced by which of the following?

A. genes

B. stress

C. amount of body fat

D. all of the above

Answer

Answer: D

Critical Thinking Questions

Q. Explain how the internal female and male reproductive structures develop from two different duct systems.

Answer

A. The internal reproductive structures form from one of two rudimentary duct systems in the embryo. Testosterone secretion stimulates growth of the male tract, the Wolffian duct. Secretions of sustentacular cells trigger a

degradation of the female tract, the Müllerian duct. Without these stimuli, the Müllerian duct will develop and the Wolffian duct will degrade, resulting in a female embryo.

Q. Explain what would occur during fetal development to an XY individual with a mutation causing a nonfunctional *SRY* gene.

Answer

A. If the *SRY* gene were not functional, the XY individual would be genetically a male, but would develop female reproductive structures.

Glossary

Müllerian duct
duct system present in the embryo that will eventually form the internal female reproductive structures

puberty
life stage during which a male or female adolescent becomes anatomically and physiologically capable of reproduction

secondary sex characteristics
physical characteristics that are influenced by sex steroid hormones and have supporting roles in reproductive function

Wolffian duct
duct system present in the embryo that will eventually form the internal male reproductive structures

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Answers

Interactive
Answer: The fertilized egg will remain in the fallopian tube resulting in a tubal pregnancy. The tube will eventually rupture, leading to internal bleeding and death if the bleeding continues.

Interactive Link
Answer: The testes are located in the abdomen.

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