# BIOL 250: HUMAN ANATOMY



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# BIOL 250 - Human Anatomy

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# TABLE OF CONTENTS


Attribution Statement

Licensing

## 1: An Introduction to the Human Body

- 1.1: Introduction
- 1.2: Overview of Anatomy and Physiology
- 1.3: Structural Organization of the Human Body
- 1.4: Anatomical Terminology
- 1.5: Medical Imaging

## 2: The Cellular Level of Organization

- 2.1: Prelude 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

## 3: The 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 Supports and Protects
- 3.5: Muscle Tissue
- 3.6: Nervous Tissue

## 4: The Integumentary System

- 4.1: Introduction
- 4.2: Layers of the Skin
- 4.3: Accessory Structures of the Skin
- 4.4: Diseases, Disorders, and Injuries of the Integumentary System

## 5: Bone Tissue and the Skeletal System

- 5.1: Introduction
- 5.2: The Functions of the Skeletal System
- 5.3: Bone Classification
- 5.4: Bone Structure
- 5.5: Bone Formation and Development
- 5.6: Fractures - Bone Repair

## 6: Axial Skeleton

- 6.1: Introduction to the Axial Skeleton
- 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

## 7: The Appendicular Skeleton

- 7.1: Introduction
- 7.2: The Pectoral Girdle
- 7.3: Bones of the Upper Limb
- 7.4: The Pelvic Girdle and Pelvis
- 7.5: Bones of the Lower Limb

## 8: Joints

- 8.1: Introduction
- 8.2: Classification of Joints
- 8.3: Fibrous Joints
- 8.4: Cartilaginous Joints
- 8.5: Synovial Joints
- 8.6: Types of Body Movements
- 8.7: Anatomy of Selected Synovial Joints

## 9: Muscle Tissue

- 9.1: Prelude 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: Cardiac Muscle Tissue
- 9.7: Smooth Muscle

## 10: The Muscular System

- 10.1: Prelude 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: Muscles of the Pectoral Girdle and Upper Limbs
- 10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs

## 11: The Nervous System and Nervous Tissue

- 11.1: Prelude to the Nervous System
- 11.2: Basic Structures of the Nervous System
- 11.3: Nervous Tissue

## 12: Anatomy of the Nervous Tissue

- 12.1: Prelude Anatomy of the Nervous Tissue
- 12.2: The Central Nervous System
- 12.3: Circulation and the Central Nervous System

- 12.4: The Peripheral Nervous System

## 13: The Somatic Nervous System
- 13.1: Prelude to The Somatic Nervous System
- 13.2: Sensory Perception

## 14: The Autonomic Nervous System
- 14.1: Prelude to The Autonomic Nervous System
- 14.2: Divisions of the Autonomic Nervous System
- 14.3: Autonomic Reflexes and Homeostasis

## 15: The Endocrine System
- 15.1: Prelude to the Endocrine System
- 15.2: An Overview of the Endocrine System
- 15.3: The Pituitary Gland and Hypothalamus
- 15.4: The Thyroid Gland
- 15.5: The Parathyroid Glands
- 15.6: The Adrenal Glands
- 15.7: The Pineal Gland
- 15.8: The Endocrine Pancreas
- 15.9: Organs with Secondary Endocrine Functions

## 16: The Cardiovascular System - Blood
- 16.1: Prelude to Blood
- 16.2: An Overview of Blood
- 16.3: Production of the Formed Elements
- 16.4: Erythrocytes
- 16.5: Leukocytes and Platelets

## 17: The Cardiovascular System - The Heart
- 17.1: Prelude to The Heart
- 17.2: Heart Anatomy
- 17.3: Cardiac Muscle

## 18: The Cardiovascular System - Blood Vessels and Circulation
- 18.1: Introduction to the Cardiovascular System - Blood Vessels and Circulation
- 18.2: Structure of Blood Vessels
- 18.3: Circulatory Pathways

## 19: The Lymphatic and Immune System
- 19.1: Introduction
- 19.2: Anatomy of the Lymphatic and Immune Systems

## 20: The Respiratory System
- 20.1: Prelude to the Respiratory System
- 20.2: Organs and Structures of the Respiratory System

- 20.3: The Lungs

## 21: The Digestive System

- 21.1: Introduction
- 21.2: Overview of the Digestive System
- 21.3: The Mouth, Pharynx, and Esophagus
- 21.4: The Stomach
- 21.5: The Small and Large Intestines
- 21.6: Accessory Organs in Digestion- The Liver, Pancreas, and Gallbladder

## 22: The Urinary System

- 22.1: Prelude to the Urinary System
- 22.2: Gross Anatomy of Urine Transport
- 22.3: Gross Anatomy of the Kidney
- 22.4: Microscopic Anatomy of the Kidney

## 23: The Reproductive System

- 23.1: Prelude to the Reproductive System
- 23.2: Anatomy and Physiology of the Male Reproductive System
- 23.3: Anatomy and Physiology of the Female Reproductive System
- 23.4: Development of the Male and Female Reproductive Systems

## Index

## Glossary

## Detailed Licensing

# Licensing

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# CHAPTER OVERVIEW

## 1: An Introduction to the Human Body

This chapter begins with an overview of anatomy and physiology and a preview of the body regions and functions. It then covers the characteristics of life and how the body works to maintain stable conditions. It introduces a set of standard terms for body structures and for planes and positions in the body that will serve as a foundation for more comprehensive information covered later in the text. It ends with examples of medical imaging used to see inside the living body.


1.1: Introduction

1.2: Overview of Anatomy and Physiology

1.3: Structural Organization of the Human Body

1.4: Anatomical Terminology

1.5: Medical Imaging


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# 1.1: Introduction



Figure **1.1.1**: Blood **Pressure.** A proficiency in anatomy and physiology is fundamental to any career in the health professions. (credit: Bryan Mason/flickr)

Though you may approach a course in anatomy and physiology strictly as a requirement for your field of study, the knowledge you gain in this course 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.

This chapter begins with an overview of anatomy and physiology and a preview of the body regions and functions. It then covers the characteristics of life and how the body works to maintain stable conditions. It introduces a set of standard terms for body structures and for planes and positions in the body that will serve as a foundation for more comprehensive information covered later in the text. It ends with examples of medical imaging used to see inside the living body.

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# 1.2: Overview of Anatomy and Physiology

## Learning Objectives

- 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.

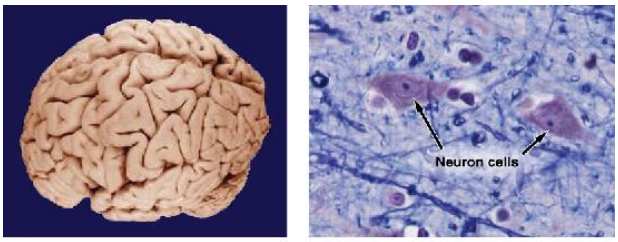



Figure 1.2.1: Gross and Microscopic Anatomy. (a) Gross anatomy considers large structures such as the brain. (b) Microscopic anatomy can deal with the same structures, though at a different scale. This is a micrograph of nerve cells from the brain. LM × 1600. (credit a: "WriterHound"/Wikimedia Commons; credit 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.

Your study of anatomy and physiology will make more sense if you continually relate the form of the structures you are studying to their function. In fact, it can be somewhat frustrating to attempt to study anatomy without an understanding of the physiology that a body structure supports. Imagine, for example, trying to appreciate the unique arrangement of the bones of the human hand if you had no conception of the function of the hand. Fortunately, your understanding of how the human hand manipulates tools—from pens to cell phones—helps you appreciate the unique alignment of the thumb in opposition to the four fingers, making your hand a structure that allows you to pinch and grasp objects and type text messages.

# Chapter 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. It is difficult to study structure (anatomy) without knowledge of function (physiology). The two disciplines are typically studied together because form and function are closely related in all living things.

## 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: 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: A

## Critical Thinking Questions

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

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?

> 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 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

## Learning Objectives

- 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: subatomic particles, atoms, molecules, organelles, cells, tissues, organs, organ systems, organisms and biosphere (Figure **1.3.1**).

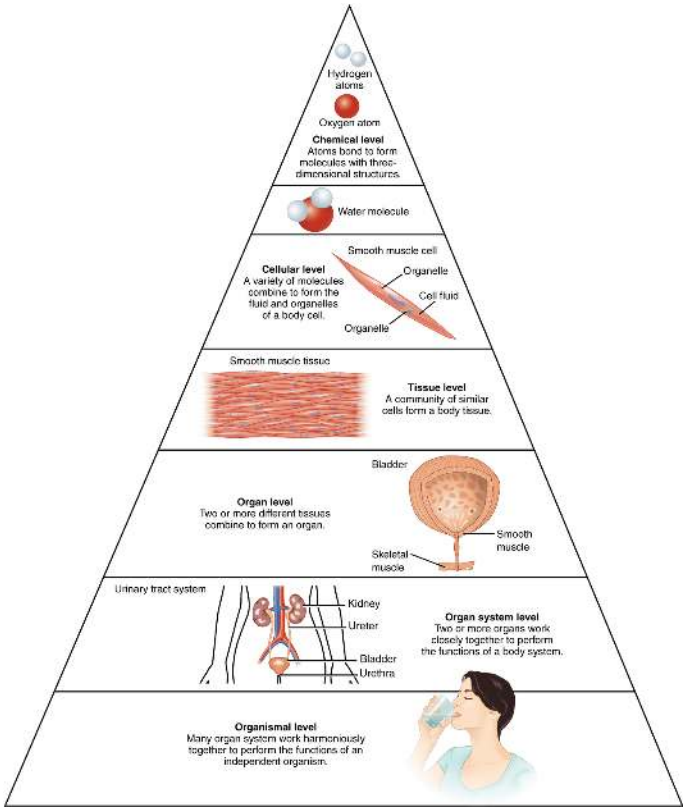



Figure **1.3.1**: Levels of Structural Organization of the Human Body. The organization of the body often is discussed in terms of six distinct levels of increasing complexity, from the smallest chemical building blocks to a unique human organism.

## The Levels of Organization

To study the chemical level of organization, scientists consider the simplest building blocks of matter: subatomic particles, atoms and molecules. 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.

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 typically consists of flexible membranes that enclose cytoplasm, a water-based cellular fluid together with a variety of tiny functioning units called **organelles**. In humans, as in all organisms, cells perform all functions of life. 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. An **organ** is an anatomically distinct structure of the body composed of two or more tissue types. Each organ performs one or more specific physiological functions. An **organ system** is a group of organs that work together to perform major functions or meet physiological needs of the body.

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.

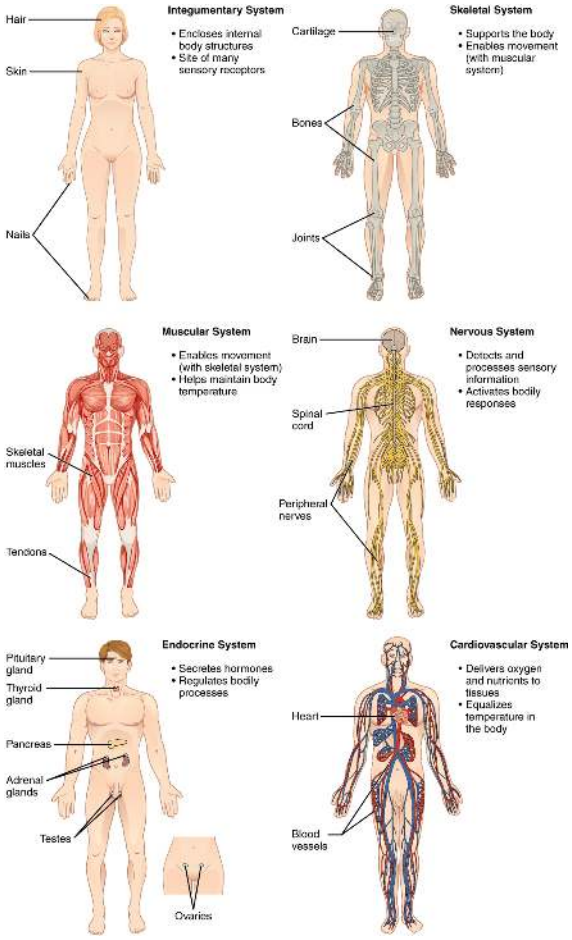



Figure **1.3.2**: Organ Systems of the Human Body. Organs that work together are grouped into organ systems.

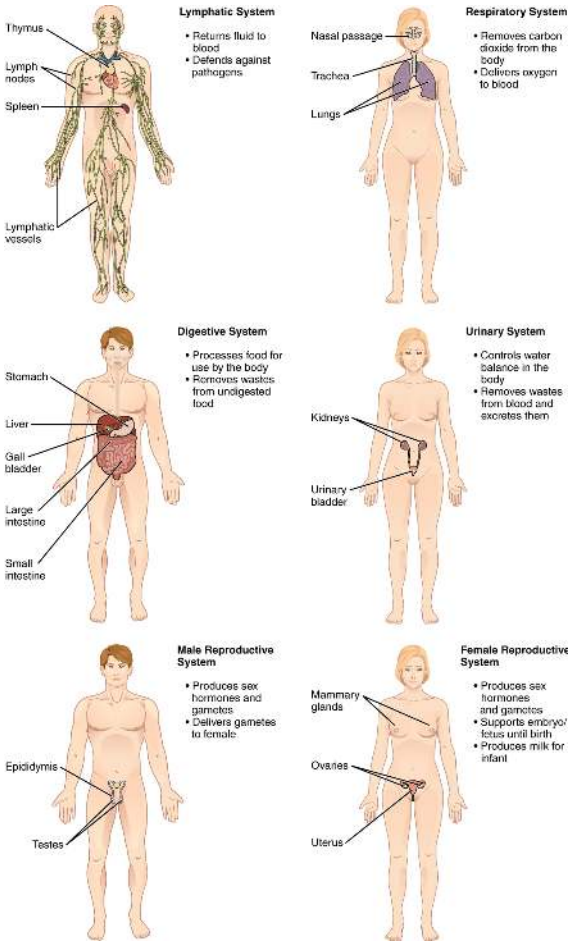



Figure **1.3.3**: Organ Systems of the Human Body (continued). Organs that work together are grouped into organ systems.

The organism level is the highest level of organization. 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.

## Chapter 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: A

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

A. organ

B. organelle

C. organism

D. organ system

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: D

## Critical Thinking Questions

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

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?

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

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

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

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

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

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

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# 1.4: Anatomical Terminology

**Learning Objectives**

- Demonstrate the anatomical position
- Describe the human body using directional and regional terms
- Identify three planes most commonly used in te study of anatomy
- Distinguish between the posterior (dorsal) and anterior (ventral) body cavities, identifying their subdivisions and representative organs found in each
- Describe 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 **1.4.1**. 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.

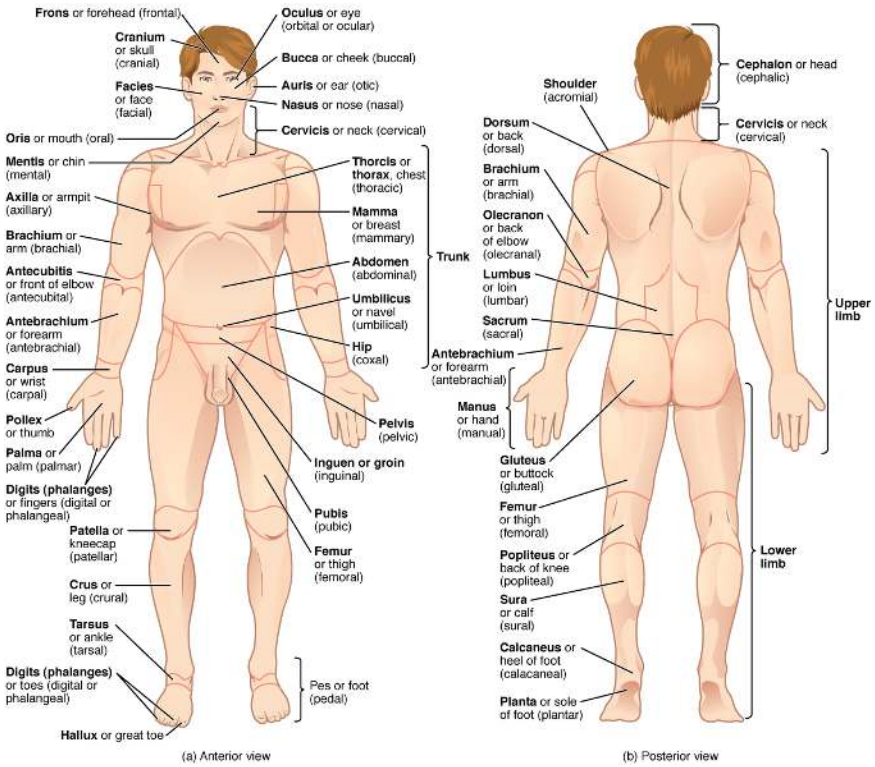



Figure **1.4.1**: Regions of the Human **Body.** The human body is shown in anatomical position in an (a) anterior view and a (b) posterior view. The regions of the body are labeled in boldface.

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 (see Figure **1.4.1**). Notice that the term "brachium" or "arm" is reserved for the "upper arm" and "antebrachium" or "forearm" is used rather than "lower arm." Similarly, "femur" or "thigh" is correct, and "leg" or "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 **1.4.2**). 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 thumb (pollex) is lateral to the digits.
- **Medial** describes the middle or direction toward the middle of the body. The hallux 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.

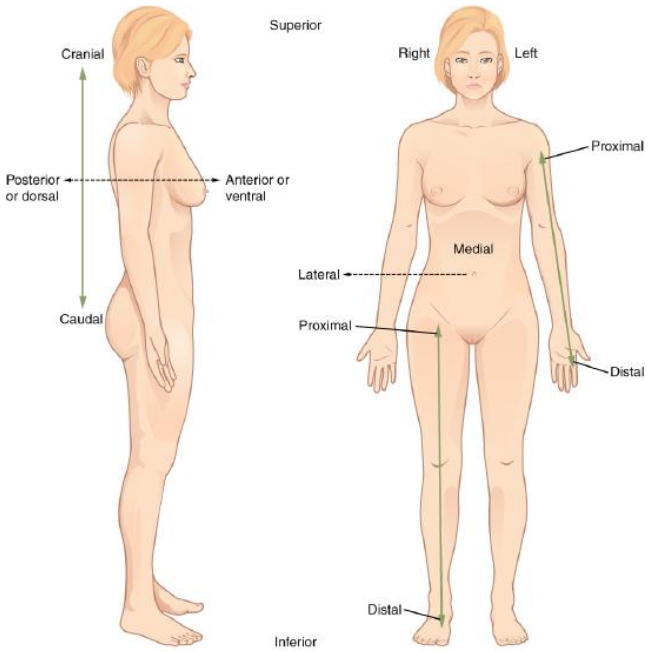



Figure 1.4.2: Directional Terms Applied to the Human Body. Paired directional terms are shown as applied to the human body.

## 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 1.4.3.

- 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 into an anterior (front) portion and a posterior (rear) portion. The frontal plane is often 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.

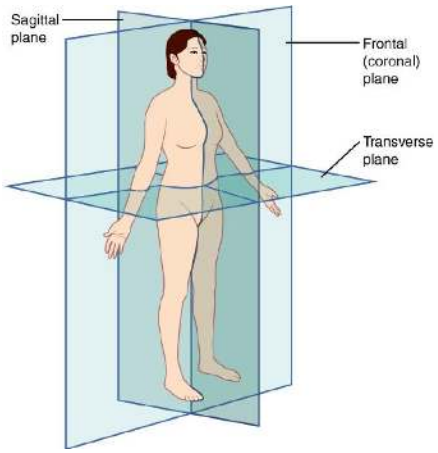



Figure **1.4.3**: Planes of the Body. The three planes most commonly used in anatomical and medical imaging are the sagittal, frontal (or coronal), and transverse plane.

## 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 **1.4.4**). 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.

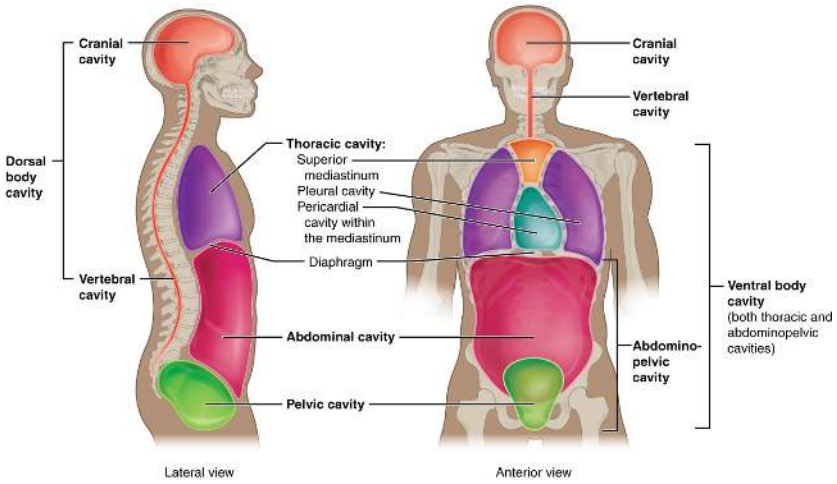



Figure **1.4.4**: Dorsal and Ventral Body **Cavities.** The ventral cavity includes the thoracic and abdominopelvic cavities and their subdivisions. The dorsal cavity includes the cranial and spinal cavities.

### 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 **1.4.4**). The **thoracic cavity** is the more superior subdivision of the anterior cavity, and it is enclosed by the rib cage. The thoracic cavity contains the lungs and the heart, which is located in the mediastinum. 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, 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 **1.4.5**).

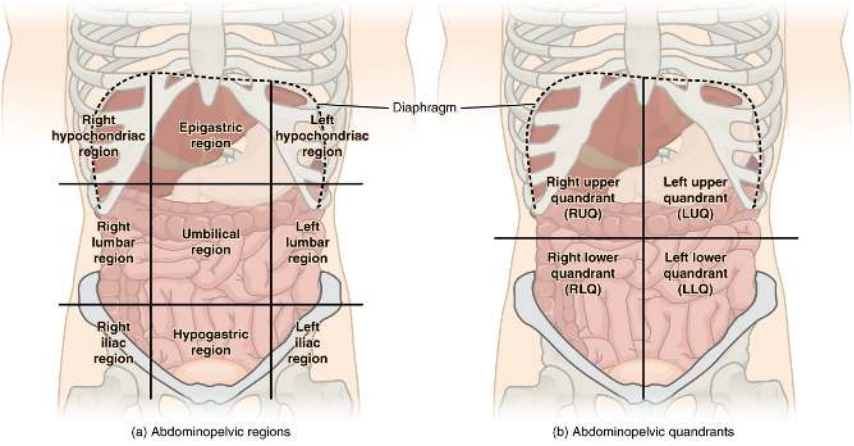



Figure **1.4.5**: Regions and Quadrants of the Peritoneal **Cavity.** There are (a) nine abdominal regions and (b) four abdominal quadrants in the peritoneal cavity.

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. 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).

## 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 **1.4.6**).

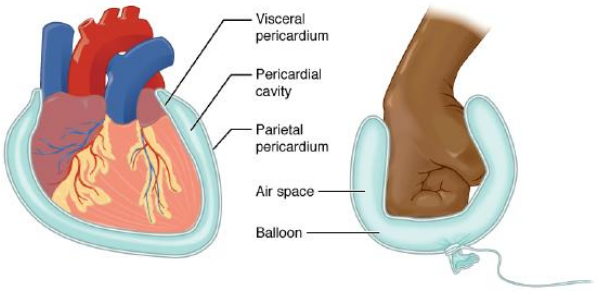



Figure **1.4.6**: Serous Membrane. Serous membrane lines the pericardial cavity and reflects back to cover the heart—much the same way that an underinflated balloon would form two layers surrounding a fist.

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.

## Chapter Review

Ancient Greek and Latin words are used to build anatomical terms. 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 (also referred to posterior) and ventral (also referred to anterior)—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 Chapter

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: 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: C

Q. The lumbar region is _____.

A. inferior to the gluteal region

B. inferior to the umbilical region

C. superior to the cervical region

D. superior to the popliteal region

Answer: D

Q. The heart is within the _____.

A. cranial cavity

B. mediastinum

C. posterior (dorsal) cavity

D. All of the above

Answer: B

## Critical Thinking Question

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?

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. 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?

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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# 1.5: Medical Imaging

**Learning Objectives**

- 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 **1.5.1**). 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 **1.5.1**: 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. (credit: Trace Meek/flickr)

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 **1.5.2.*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."

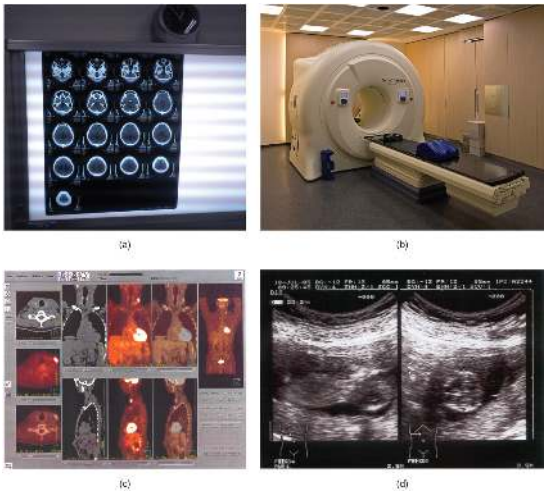
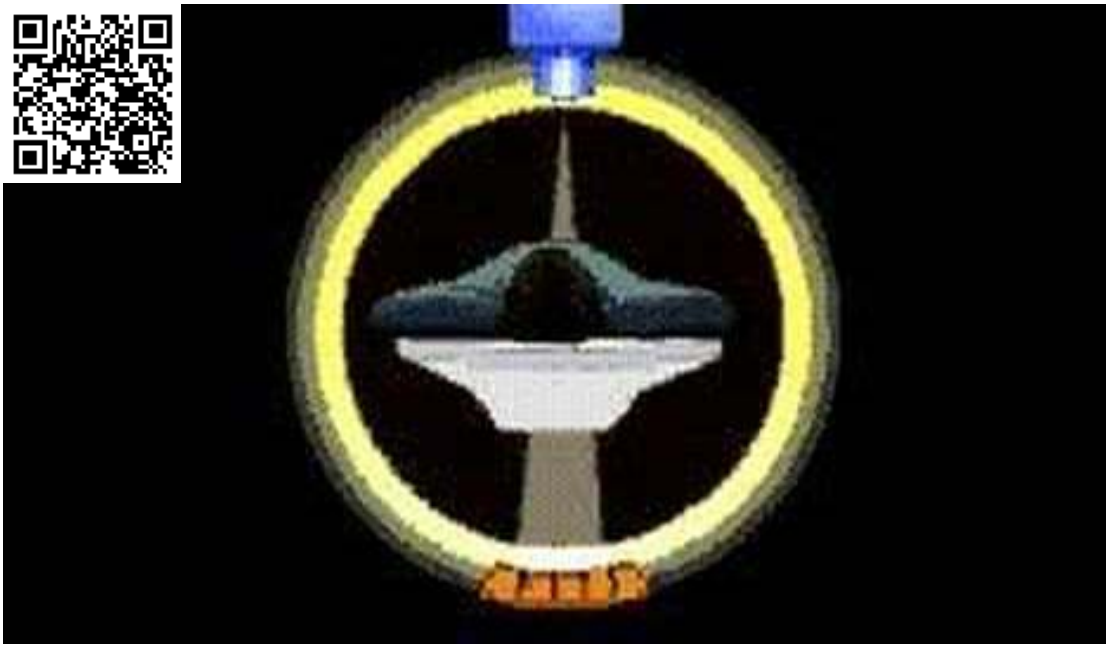


Figure 1.5.2: Medical Imaging Techniques. (a) The results of a CT scan of the head are shown as successive transverse sections. (b) An MRI machine generates a magnetic field around a patient. (c) PET scans use radiopharmaceuticals to create images of active blood flow and physiologic activity of the 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. (credit a: Akira Ohgaki/flickr; credit b: "Digital Cate"/flickr; credit c: "Raziel"/Wikimedia Commons; credit d: "Isis"/Wikimedia Commons)

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.

QR Code representing a URL

A CT or CAT scan relies on a circling scanner that revolves around the patient's body. Watch this video to learn more about CT and CAT scans. What type of radiation does a CT scanner use?



## 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 **1.5.2.*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 **1.5.2.*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

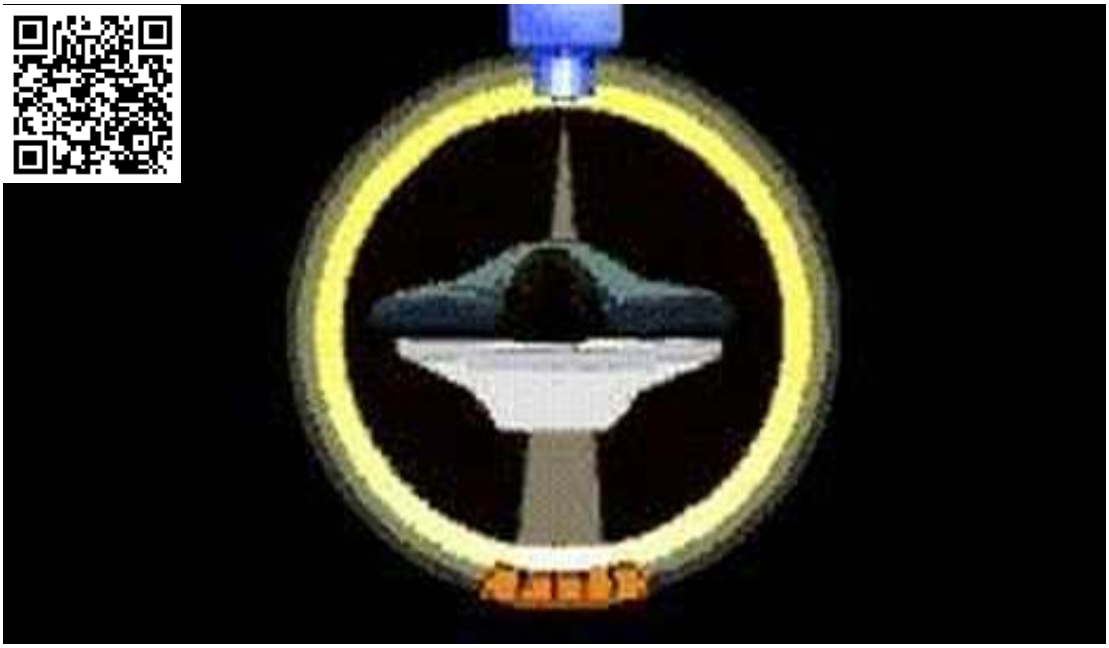
**Ultrasonography** is an imaging technique that uses the transmission of high-frequency sound waves into the body to generate an echo signal that is converted by a computer into a real-time image of anatomy and physiology (see Figure **1.5.2.*d***). Ultrasonography is the least invasive of all imaging 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.

## Chapter 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.

## Interactive Link Questions

A CT or CAT scan relies on a circling scanner that revolves around the patient's body. Watch this video to learn more about CT and CAT scans. What type of radiation does a CT scanner use?



Answer: X-rays.

A patient undergoing an MRI is surrounded by a tube-shaped scanner. Watch this video to learn more about MRIs. What is the function of magnets in an MRI?



Answer: The magnets induce tissue to emit radio signals that can show differences between different types of tissue.

PET relies on radioactive substances administered several minutes before the scan. Watch this video to learn more about PET. How is PET used in chemotherapy?



Answer: PET scans can indicate how patients are responding to chemotherapy.

## 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: 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: 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: 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: B

## Critical Thinking Questions

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

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

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

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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# CHAPTER OVERVIEW

## 2: The Cellular Level of Organization

Cellular and developmental biologists study how the continued division of a single cell leads to such complexity and differentiation. 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.


2.1: Prelude 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


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# 2.1: Prelude to The Cellular Level of Organization

**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, as well as the process of DNA replication
- Explain the process by which a cell builds proteins using the DNA code
- 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
- List the morphological and physiological characteristics of some representative cell types in the human body

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 differentiation.

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.

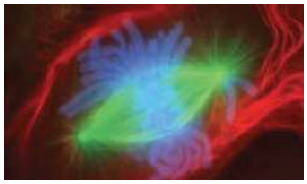


Figure **2.1.1**: Fluorescence-stained Cell Undergoing Mitosis. A lung cell from a newt, commonly studied for its similarity to human lung cells, is stained with fluorescent dyes. The green stain reveals mitotic spindles, red is the cell membrane and part of the cytoplasm, and the structures that appear light blue are chromosomes. This cell is in anaphase of mitosis. (credit: "Mortadelo2005"/Wikimedia Commons)

A primary responsibility of each 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.

The concept of a cell started with microscopic observations of dead cork tissue by scientist Robert Hooke in 1665. Without realizing their function or importance, Hook coined the term "cell" based on the resemblance of the small subdivisions in the cork to the rooms that monks inhabited, called cells. About ten years later, Antonie van Leeuwenhoek became the first person to observe living and moving cells under a microscope. In the century that followed, the theory that cells represented the basic unit of life would develop. These tiny fluid-filled sacs house components responsible for the thousands of biochemical reactions necessary for

an organism to grow and survive. In this chapter, you will learn about the major components and functions of a prototypical, generalized cell and discover some of the different types of cells in the human body.

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# 2.2: The Cell Membrane

**Learning Objectives**

- Describe the molecular components that make up the cell membrane
- Explain the major features and properties of the cell membrane

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 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 and some contain unsaturated fatty acids. 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.

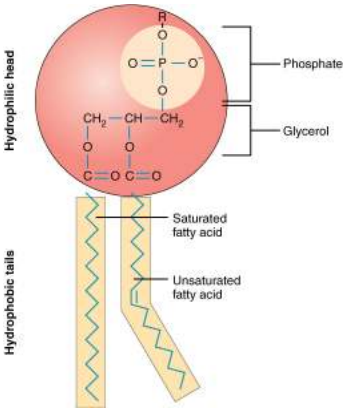



Figure **2.2.1**: Phospholipid Structure. A phospholipid molecule consists of a polar phosphate "head," which is hydrophilic and a non-polar lipid "tail," which is hydrophobic. Unsaturated fatty acids result in kinks in the hydrophobic tails.

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 (IF)** 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.

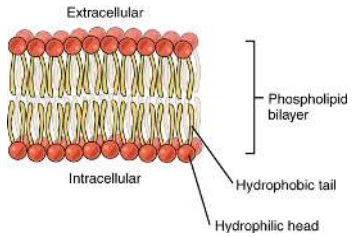



Figure **2.2.2**: Phospolipid Bilayer.The phospholipid bilayer consists of two adjacent sheets of phospholipids, arranged tail to tail. The hydrophobic tails associate with one another, forming the interior of the membrane. The polar heads contact the fluid inside and outside of the cell.

## 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 protein (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.

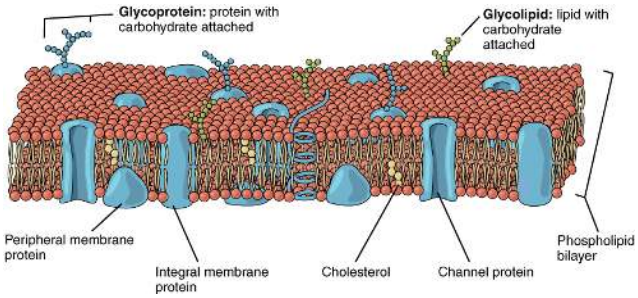



Figure **2.2.3**: Cell Membrane.The cell membrane of the cell is a phospholipid bilayer containing many different molecular components, including proteins and cholesterol, some with carbohydrate groups attached.

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 a person's body are products of that person's genetic makeup. They give each of the individual's trillions of cells the "identity" of belonging in the person's body. This identity is the primary way that a person's immune defense cells "know" not to attack the person's 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.

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, many CF patients live into their 30s.

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 $Cl^-$ 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.

## Chapter 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 in a direction against their concentration gradient. Active transport may take place with the help of protein pumps or through the use of vesicles.

## Interactive Link Questions

Visit this link to see diffusion and how it is propelled by the kinetic energy of molecules in solution. How does temperature affect diffusion rate, and why?

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

## 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: B

## 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

**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

**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

**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 peripherally to 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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# 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 of gases

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 membrane-enclosed bodies 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).

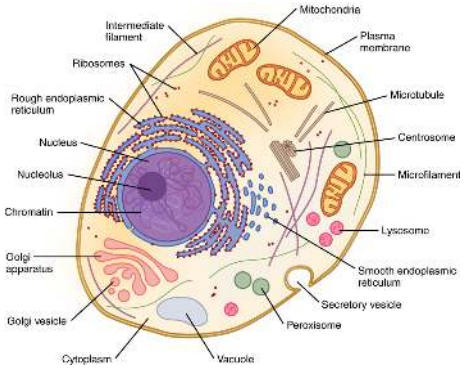



Figure 2.3.1: Prototypical Human Cell. While this image is not indicative of any one particular human cell, it is a prototypical example of a cell containing the primary organelles and internal structures.

## 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).

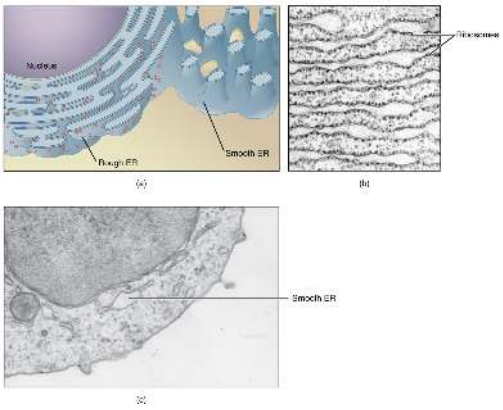



Figure **2.3.2**: Endoplasmic Reticulum (ER). (a) The ER is a winding network of thin membranous sacs found in close association with the cell nucleus. The smooth and rough endoplasmic reticula are very different in appearance and function (source: mouse tissue). (b) Rough ER is studded with numerous 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. (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. It is composed of two ribosomal RNA subunits that wrap around mRNA to start the process of translation, followed by 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 synthesis and 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. These products are sorted 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 (Figure **2.3.3**).

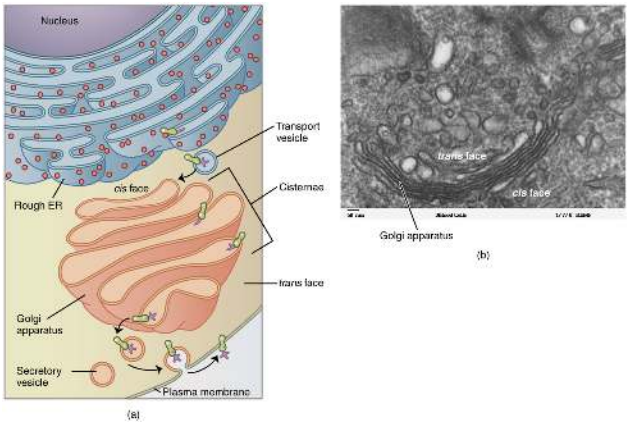



Figure **2.3.3**: Golgi Apparatus. (a) The Golgi apparatus manipulates products from the rough ER, and also produces new organelles called lysosomes. Proteins and other products of the ER are sent to the Golgi apparatus, which organizes, modifies, packages, and tags them. Some of these products are transported 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.

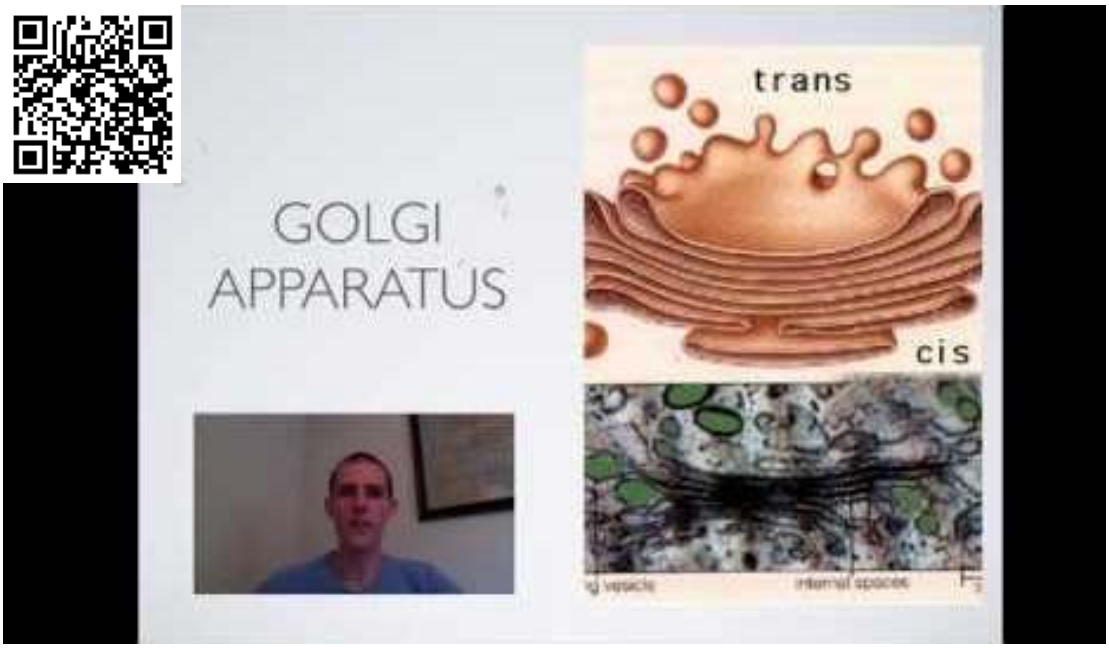
### Lysosomes

Some of the protein products packaged by the Golgi include digestive enzymes that are meant to remain inside the cell for use in breaking down certain materials. The enzyme-containing vesicles released by the Golgi may form new lysosomes, or fuse with existing, lysosomes. 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").

QR Code representing a URL

*Watch this video to learn about the endomembrane system, which includes the rough and smooth ER and the Golgi body as well as lysosomes and vesicles. What is the primary role of the endomembrane system?*




## 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 uses huge amounts of 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.

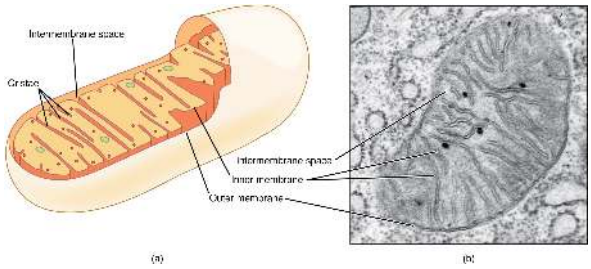



Figure **2.3.4**: Mitochondrion.The mitochondria are the energy-conversion factories of the cell. (a) A mitochondrion is composed of two separate lipid bilayer membranes. Along the inner membrane are various molecules that work together to produce ATP, the cell's major energy currency. (b) An electron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

## Peroxisomes

Like lysosomes, 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 poisons such as alcohol. In order to appreciate the importance of peroxisomes, it is necessary to understand the concept of reactive oxygen species.

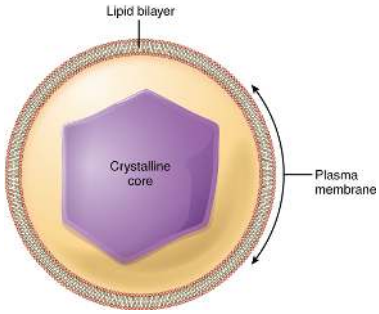



Figure **2.3.5**: Peroxisome.Peroxisomes are membrane-bound organelles that contain an abundance of enzymes for detoxifying harmful substances and lipid metabolism.

**Reactive oxygen species (ROS)** such as peroxides and free radicals are the highly reactive products of many normal cellular processes, including the mitochondrial reactions that produce ATP and oxygen metabolism. Examples of ROS include the hydroxyl radical OH, $H_2O_2$, and superoxide ($O_2^-$). Some ROS are important for certain cellular functions, such as cell signaling processes and immune responses against foreign substances. Free radicals are reactive because they contain free unpaired electrons; they can easily oxidize other molecules throughout the cell, causing cellular damage and even cell death. Free radicals are thought to play a role in many destructive processes in the body, from cancer to coronary artery disease.

Peroxisomes, on the other hand, oversee reactions that neutralize free radicals. Peroxisomes produce large amounts of the toxic $H_2O_2$ in the process, but peroxisomes contain enzymes that convert $H_2O_2$ into water and oxygen. These byproducts are safely released into the cytoplasm. Like miniature sewage treatment plants, peroxisomes neutralize harmful toxins so that they do not wreak havoc in the cells. The liver is the organ primarily responsible for detoxifying the blood before it travels throughout the body, and liver cells contain an exceptionally high number of peroxisomes.

Defense mechanisms such as detoxification within the peroxisome and certain cellular antioxidants serve to neutralize many of these molecules. Some vitamins and other substances, found primarily in fruits and vegetables, have antioxidant properties. Antioxidants work by being oxidized themselves, halting the destructive reaction cascades initiated by the free radicals. Sometimes though, ROS accumulate beyond the capacity of such defenses.

*Oxidative stress* is the term used to describe damage to cellular components caused by ROS. Due to their characteristic unpaired electrons, ROS can set off chain reactions where they remove electrons from other molecules, which then become oxidized and reactive, and do the same to other molecules, causing a chain reaction. ROS can cause permanent damage to cellular lipids, proteins, carbohydrates, and nucleic acids. Damaged DNA can lead to genetic mutations and even cancer. A **mutation** is a change in the nucleotide sequence in a gene within a cell's DNA, potentially altering the protein coded by that gene. Other diseases believed to be triggered or exacerbated by ROS include Alzheimer's disease, cardiovascular diseases, diabetes, Parkinson's disease, arthritis, Huntington's disease, and schizophrenia, among many others. It is noteworthy that these diseases are largely age-related. Many scientists believe that oxidative stress is a major contributor to the aging process.

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. **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 in 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.

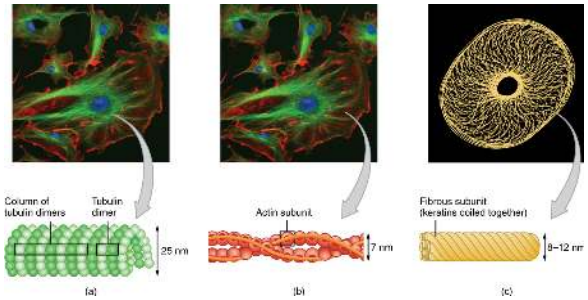



Figure **2.3.6**: The Three Components of the Cytoskeleton.The cytoskeleton consists of (a) microtubules, (b) microfilaments, and (c) intermediate filaments. The cytoskeleton plays an important role in maintaining cell shape and structure, promoting cellular movement, and aiding cell division.

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.

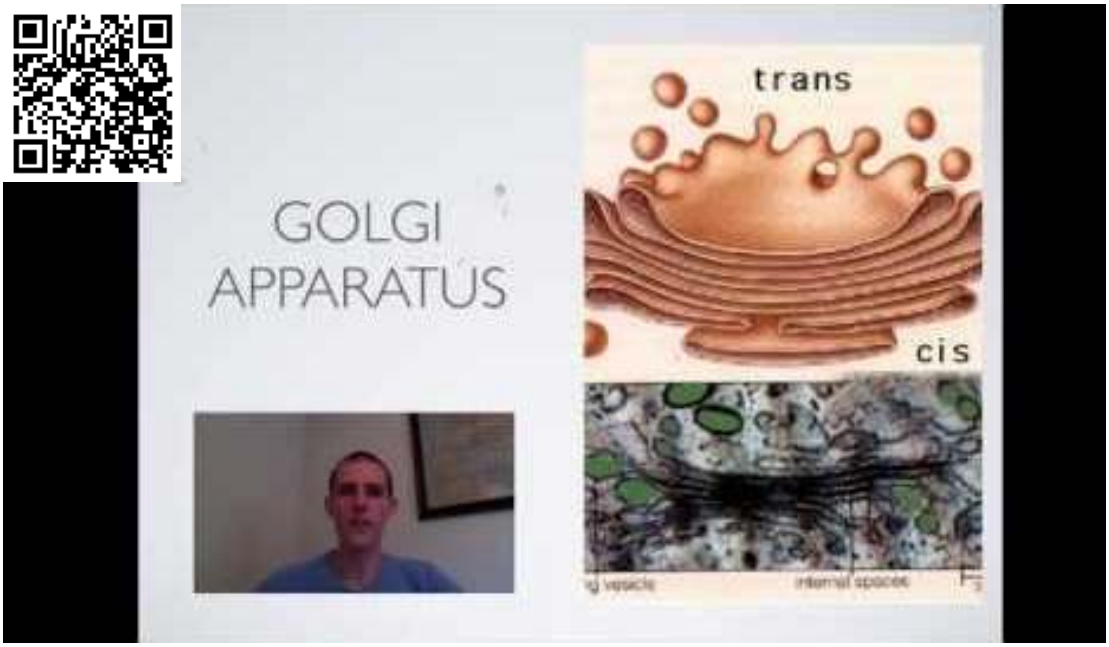
## Chapter Review

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.

## Interactive Link Questions

Watch this video to learn about the endomembrane system, which includes the rough and smooth ER and the Golgi body as well as lysosomes and vesicles. What is the primary role of the endomembrane system?




Answer: Processing, packaging, and moving materials manufactured by 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: D

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

A. Golgi apparatus

B. ribosomes

C. lysosomes

D. proteins

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: 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: 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: A

## Critical Thinking Questions

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

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.

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.

## References

Kolata, G. Severe diet doesn't prolong life, at least in monkeys. *New York Times* [Internet]. 2012 Aug. 29 [cited 2013 Jan 21]; Available from:

http://www.nytimes.com/2012/08/30/sc...icrestriction&

## 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

**Learning Objectives**

- 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
- Describe the process of DNA replication

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**), which is known as multinucleated. 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.

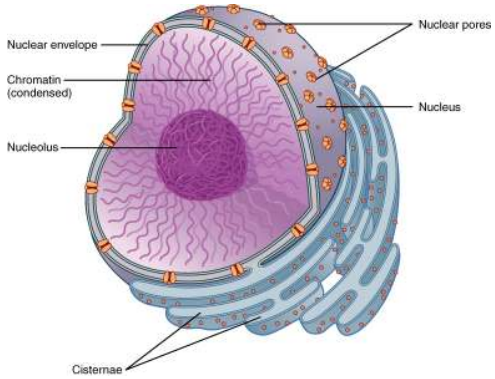



Figure **2.4.1**: The Nucleus. The nucleus is the control center of the cell. The nucleus of living cells contains the genetic material that determines the entire structure and function of that cell.

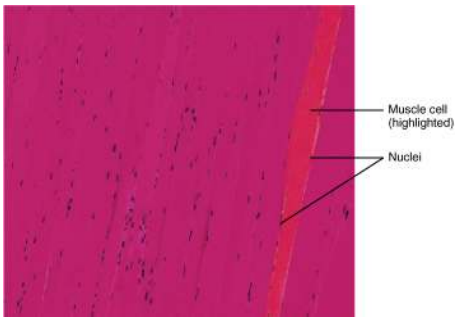



Figure **2.4.2**: Multinucleate Muscle Cell.Unlike cardiac muscle cells and smooth muscle cells, which have a single nucleus, a skeletal muscle cell contains many nuclei, and is referred to as "multinucleated." These muscle cells are long and fibrous (often referred to as muscle fibers). During development, 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 × 104.3. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

*View the University of Michigan WebScope at 141.214.65.171/Histology/Basi....svs/view.apml to explore the tissue sample in greater detail.*

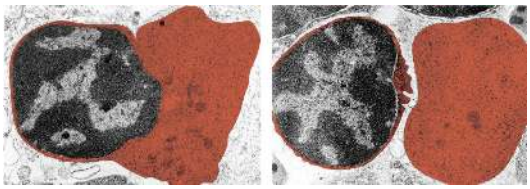


Figure **2.4.3**: Red Blood Cell Extruding Its Nucleus.Mature red blood cells lack a nucleus. As they mature, erythroblasts extrude their nucleus, making room for more hemoglobin. The two panels here show an erythroblast before and after ejecting its nucleus, respectively. (credit: modification of micrograph provided by the Regents of University of Michigan Medical School © 2012)



*View the University of Michigan WebScope at virtualslides.med.umich.edu/H....svs/view.apml to explore the tissue sample in greater detail.*

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. The nucleus sends "commands" to the cell via molecular messengers that translate the information from DNA. Each cell in your body (with the exception of germ cells) 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. The following section will explore the structure of the nucleus and its contents, as well as the process of DNA replication.

## Chapter 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.

There is a pool of cells constantly dividing within your body. The result is billions of new cells being created each day. Before any cell is ready to divide, it must replicate its DNA so that each new daughter cell will receive an exact copy of the organism's genome. A variety of enzymes are enlisted during DNA replication. These enzymes unwind the DNA molecule, separate the two strands, and assist with the building of complementary strands along each parent strand. The original DNA strands serve as templates from which the nucleotide sequence of the new strands are determined and synthesized. When replication is completed, two identical DNA molecules exist. Each one contains one original strand and one newly synthesized complementary strand.

## Review Questions

Q. The nucleus and mitochondria share which of the following features?

A. protein-lined membrane pores

B. a double cell membrane

C. the synthesis of ribosomes

D. the production of cellular energy

Answer: B

Q. Which of the following structures could be found within the nucleolus?

A. chromatin

B. histones

C. ribosomes

D. nucleosomes

Answer: C

## Glossary

**chromatin**
substance consisting of DNA and associated proteins

**chromosome**
condensed version of chromatin

**DNA polymerase**
enzyme that functions in adding new nucleotides to a growing strand of DNA during DNA replication

**DNA replication**
process of duplicating a molecule of DNA

**genome**
entire complement of an organism's DNA; found within virtually every cell

**helicase**
enzyme that functions to separate the two DNA strands of a double helix during DNA replication

**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 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). A **homologous** pair of chromosomes is 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.

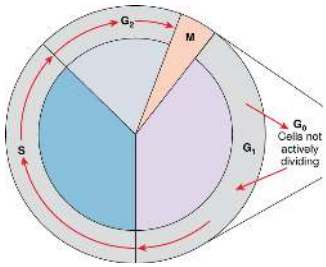



Figure **2.5.1**: Cell Cycle.The two major phases of the cell cycle include mitosis (cell division), and interphase, when the cell grows and performs all of its normal functions. Interphase is further subdivided into $G_1$, S, and $G_2$ phases.

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**).

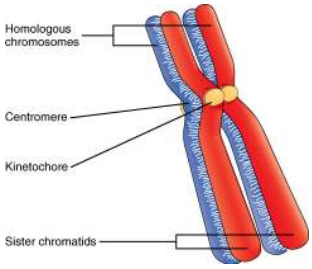



Figure 2.5.2: A Homologous Pair of Chromosomes with their Attached Sister Chromatids.The red and blue colors correspond to a homologous pair of chromosomes. Each member of the pair was separately inherited from one parent. Each chromosome in the homologous pair is also bound to an identical sister chromatid,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

## 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.

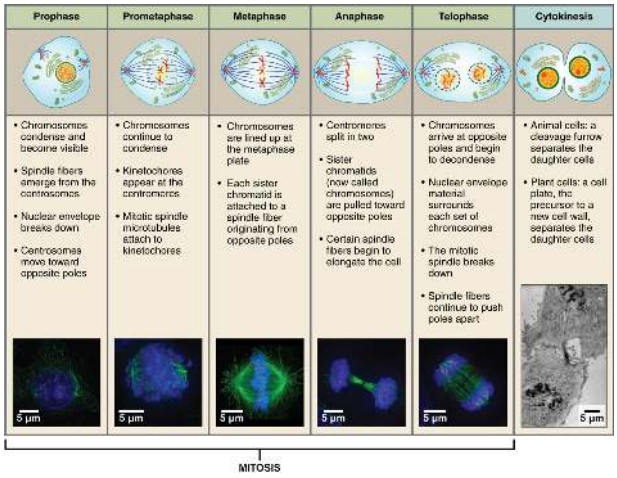



Figure 2.5.3: Cell Division: Mitosis Followed by Cytokinesis.The stages of cell division oversee the separation of identical genetic material into two new nuclei, followed by the division of the cytoplasm.

**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 (Figure **2.5.4**). A **cyclin-dependent kinase (CDK)** 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. 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.

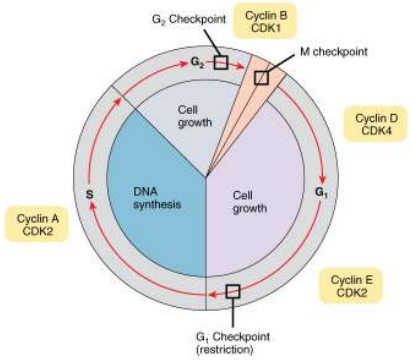



Figure **2.5.4**: Control of the Cell Cycle.Cells proceed through the cell cycle under the control of a variety of molecules, such as cyclins and cyclin-dependent kinases. These control molecules determine whether or not the cell is prepared to move into the following stage.

### 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.




*Visit this link to learn about mitosis. Mitosis results in two identical diploid cells. What structures forms during prophase?*

## Chapter 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.

## Interactive Link Questions

Visit this link to learn about mitosis. Mitosis results in two identical diploid cells. What structures form during prophase?

Answer: the spindle

## 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: 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: 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: 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?

> A. 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?

> A. 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**
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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# CHAPTER OVERVIEW

## 3: The 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 Supports and Protects
3.5: Muscle Tissue
3.6: Nervous Tissue


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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

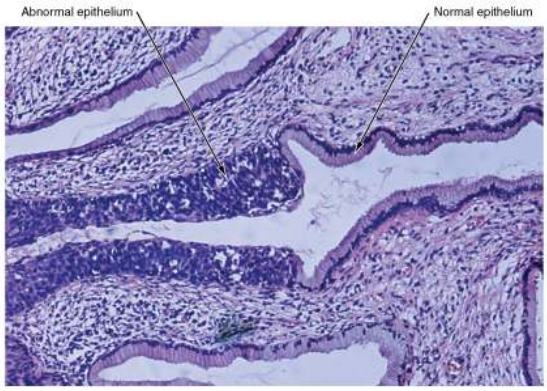



Figure **3.1.1**: Micrograph of Cervical Tissue. This figure is a view of the regular architecture of normal tissue contrasted with the irregular arrangement of cancerous cells. (credit: “Haymanj”/Wikimedia Commons)

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 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.

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

**8Learning Objectives**

- Identify the four main tissue types
- Discuss the functions of each tissue type
- Relate the structure of each tissue type to their function
- 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.

## 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, lines internal cavities and passageways, 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. **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**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. The epithelial and connective tissues are discussed in detail in this chapter. Muscle and nervous tissues will be discussed only briefly in this chapter.

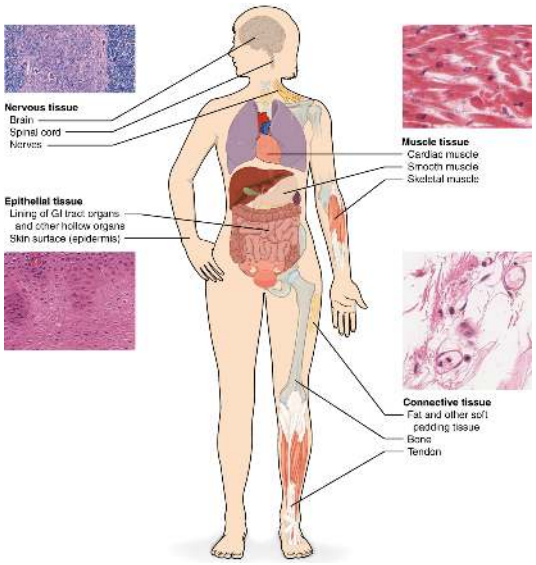



Figure **3.2.1**: Four Types of Tissue: Body.The four types of tissues are exemplified in nervous tissue, stratified squamous epithelial tissue, cardiac muscle tissue, and connective tissue in small intestine. Clockwise from nervous tissue, LM × 872, LM × 282, LM × 460, LM × 800. (Micrographs provided by the Regents of University of Michigan Medical School © 2012)

## 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. Note that epithelial tissue originates in all three layers, whereas nervous tissue derives primarily from the ectoderm and muscle tissue from mesoderm.

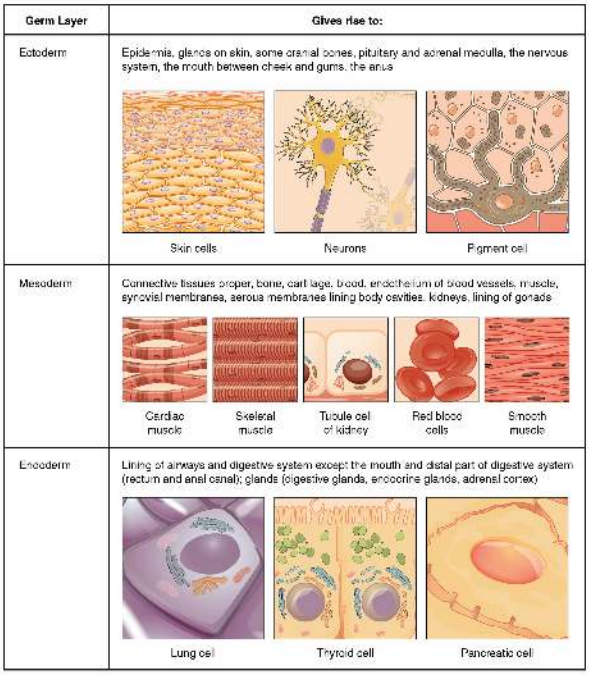



Figure **3.2.2**: Embryonic Origin of Tissues and Major Organs.

QR Code representing a URL

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

## 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, abdominal mesenteries), and the lining of the moveable joint cavities. There are two basic types of tissue membranes: connective tissue and epithelial membranes (Figure **3.2.3**).

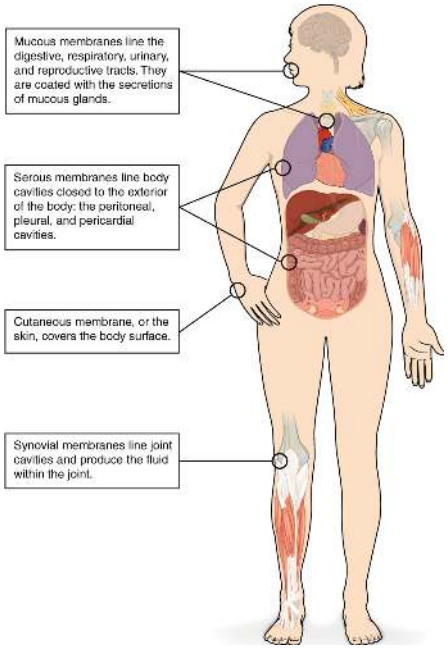



Figure **3.2.3**: Tissue Membranes.The two broad categories of tissue membranes in the body are (1) connective tissue membranes, which include synovial membranes, and (2) epithelial membranes, which include mucous membranes, serous membranes, and the cutaneous membrane, in other words, the skin.

## 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. 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.

## 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, these epithelial membranes line the body cavities and hollow passageways that open to the external environment, and include the digestive, respiratory, excretory, and reproductive tracts. Mucous, produced by the epithelial exocrine glands, covers the epithelial layer. 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 locations. 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 and pathogens.

## Chapter 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 controlling the movement of materials across the surface. 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.

## Interactive Link Questions

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

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

## Review Questions

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

A. muscle

B. nervous

C. embryonic

D. epithelial

> 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: 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: 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: D

## Critical Thinking Questions

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

> 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.

> 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?

> 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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# 3.3: Epithelial Tissue

**Learning Objectives**

- 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 serous membranes, 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.

## 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**).

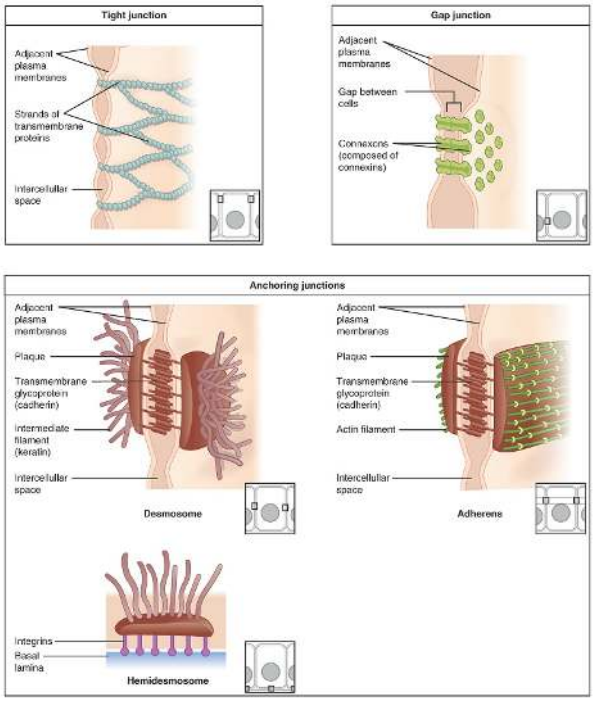



Figure **3.3.1**: Types of Cell Junctions.The three basic types of cell-to-cell junctions are tight junctions, gap junctions, and anchoring junctions.

At one end of the spectrum is the **tight junction**, which separates the cells into apical and basal compartments. 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.

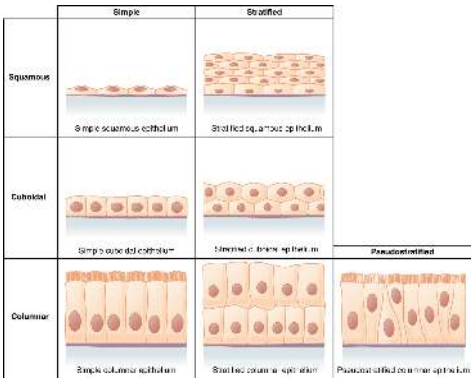



Figure **3.3.2**: Cells of Epithelial Tissue.Simple epithelial tissue is organized as a single layer of cells and stratified epithelial tissue is formed by several layers of cells.

## Simple Epithelium

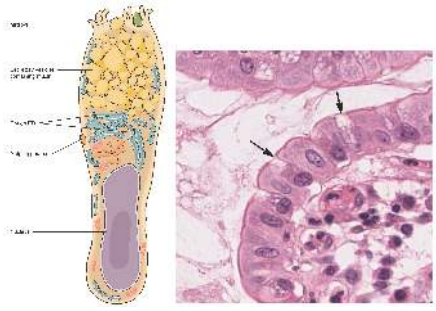
The shape of the cells in the single cell layer of simple epithelium reflects the functioning of those cells. The cells in **simple squamous epithelium** have the appearance of thin scales. Squamous cell nuclei tend to be flat, horizontal, and elliptical, mirroring the form of the cell. The **endothelium** 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.

In **simple cuboidal epithelium**, 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 absorptions of molecules. Simple cuboidal epithelia are observed in the lining of the kidney tubules and in the ducts of glands.

In **simple columnar epithelium**, 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.

**Pseudostratified columnar epithelium** 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.

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 **3.3.3**).



**(a) (b)**

***Figure 3.3.3: 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. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)*

QR Code representing a URL

*View the University of Michigan WebScope at virtualslides.med.umich.edu/H....svs/view.apml to explore the tissue sample in greater detail.*

## Stratified Epithelium

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** 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. Mammalian skin is an example of this dry, keratinized, stratified squamous epithelium. The lining of the mouth cavity is an example of an unkeratinized, stratified squamous epithelium. **Stratified cuboidal epithelium** and **stratified columnar epithelium** can also be found in certain glands and ducts, but are uncommon in the human body.

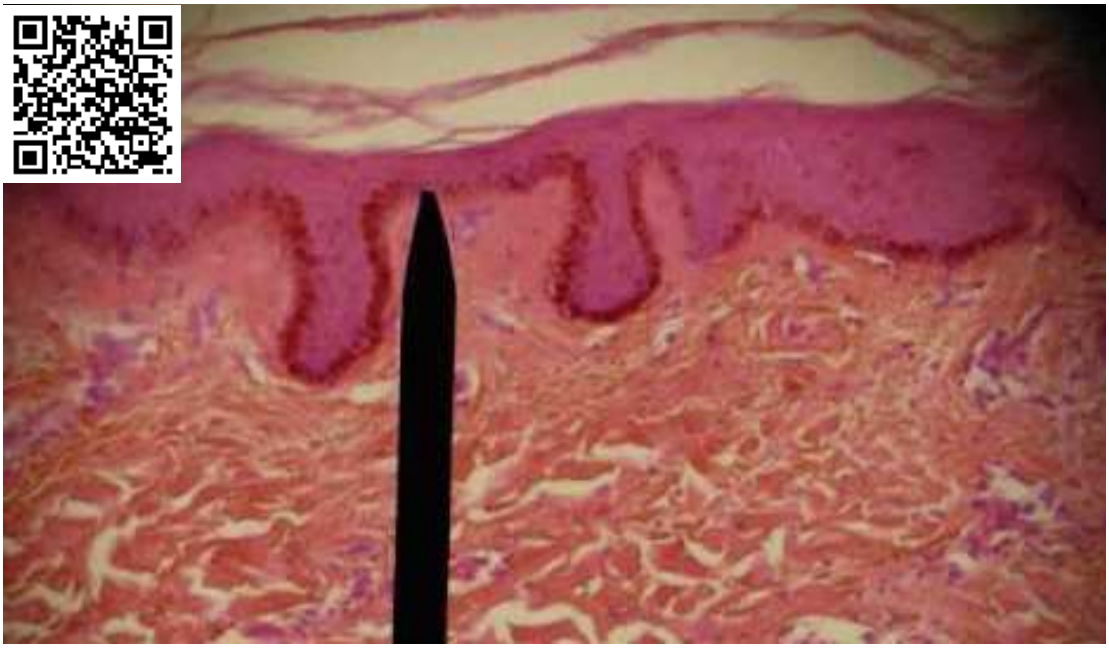
Another kind of stratified epithelium is **transitional epithelium**, so-called because of the gradual changes in the shapes of the apical cells as the bladder fills with urine. It is found only in the urinary system, specifically the ureters and urinary bladder. When the bladder is empty, this epithelium 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 **3.3.4** summarizes the different categories of epithelial cell tissue cells.

| Cells | Location | Function |
|---|---|---|
| Simple squamous epithelium | Air sacs of lungs and the lining of the heart, blood vessels, and lymphatic vessels | Allows materials to pass through by diffusion and filtration, and secretes lubricating substance |
| Simple cuboidal epithelium | In ducts and secretory portions of small glands and in 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 |
| Pseudostratified columnar epithelium | Ciliated tissue lines the trachea and much of the upper respiratory tract | Secretes mucus; ciliated tissue moves mucus |
| 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 |
| Transitional epithelium | Lines the bladder, urethra, and the ureters | Allows the urinary organs to expand and stretch |

Figure **3.3.4**: Summary of Epithelial Tissue Cells

QR Code representing a URL

*Watch this video to find out more about the anatomy of epithelial tissues. Where in the body would one find non-keratinizing stratified squamous epithelium?*



## 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.

### 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 **3.3.5**). In tubular glands, the ducts can be straight or coiled, whereas tubes that form pockets are alveolar (acinar), such as the exocrine portion of the pancreas. 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.

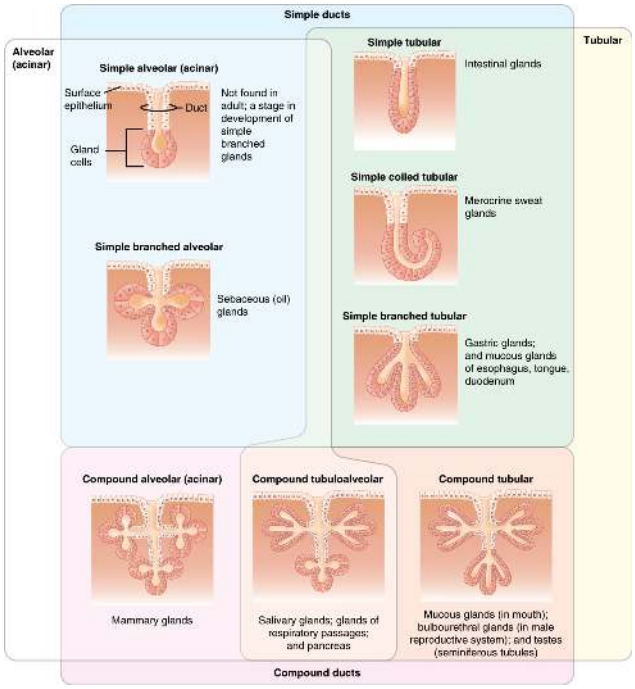



Figure **3.3.5**: Types of Exocrine Glands. Exocrine glands are classified by their structure.

## 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 **3.3.6**). **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.

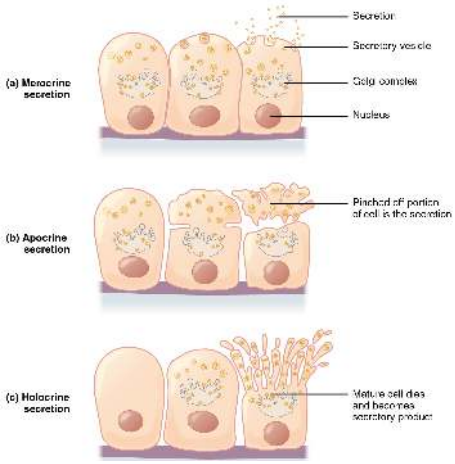



Figure **3.3.6**: Modes of Glandular Secretion.(a) In merocrine secretion, the cell remains intact. (b) In apocrine secretion, the apical portion of the cell is released, as well. (c) In holocrine secretion, the cell is destroyed as it releases its product and the cell itself becomes part of the secretion.

**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. The sweat glands of the armpit 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 **3.3.7**).

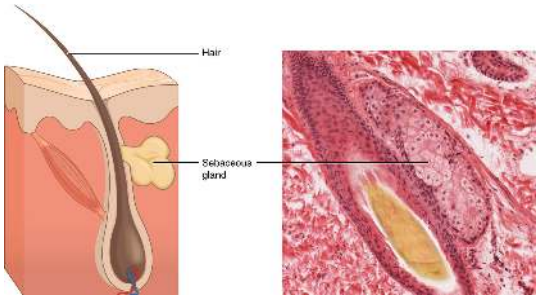



Figure **3.3.7**: Sebaceous Glands. These glands secrete oils that lubricate and protect the skin. They are holocrine glands and they are destroyed after releasing their contents. New glandular cells form to replace the cells that are lost. LM × 400. (Micrograph provided by the Regents of University 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.

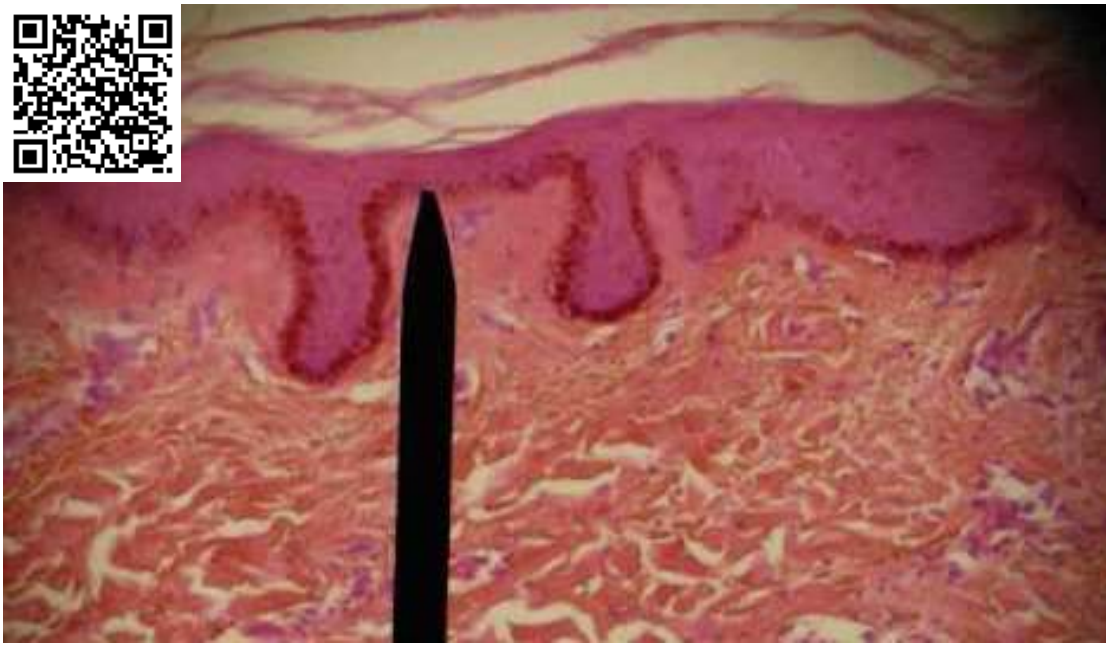
## Chapter Review

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.

## Interactive Link Questions

Watch this video to find out more about the anatomy of epithelial tissues. Where in the body would one find non-keratinizing stratified squamous epithelium?



Answer: The inside of the mouth, esophagus, vaginal canal, and anus.

## 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: 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: C

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

A. transitional

B. stratified columnar

C. pseudostratified ciliated columnar

D. stratified squamous

Answer: B

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: 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.

A. Columnar epithelia, which form the lining of the digestive tract, can be either simple or stratified. The cells are long and narrow. The nucleus is elongated and located on the basal side of the cell. Ciliated columnar epithelium is composed of simple columnar epithelial cells that display cilia on their apical surfaces.

## 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

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# 3.4: Connective Tissue Supports and Protects

**Learning Objectives**

- 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, a phagocytic cell that engulfs pathogens and also rids tissue of cellular debris.

## 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 (see [link]). 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<br>• Areolar<br>• Adipose<br>• Reticular | Cartilage<br>• Hyaline<br>• Fibrocartilage<br>• Elastic | Blood |
| Dense connective tissue<br>• Regular elastic<br>• Irregular elastic | Bones<br>• Compact bone<br>• 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, plasma cells, and phagocytic cells are found in connective tissue proper but are actually part of the immune system protecting the body.

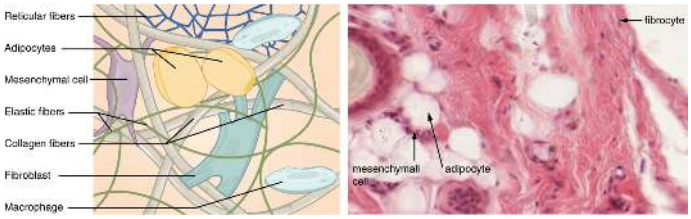



Figure **3.4.1**: Connective Tissue Proper. Fibroblasts produce this fibrous tissue. Connective tissue proper includes the fixed cells fibrocytes, adipocytes, and mesenchymal cells. LM × 400. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

## 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. 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 fiber** is 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 fiber** contains 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 fiber** is 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 imbedded 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.

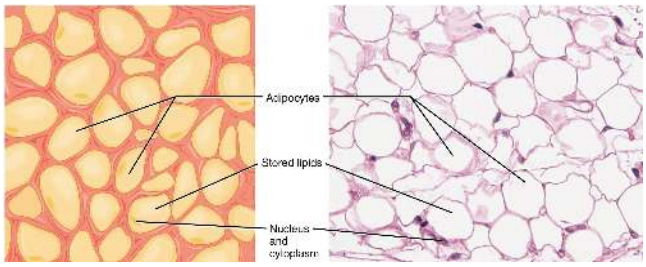



Figure **3.4.2**: Adipose Tissue.This is a loose connective tissue that consists of fat cells with little extracellular matrix. It stores fat for energy and provides insulation. LM × 800. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

**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.

**Reticular tissue** is a mesh-like, supportive framework for soft organs such as lymphatic tissue, the spleen, and the liver (Figure **3.4.3**). 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.”

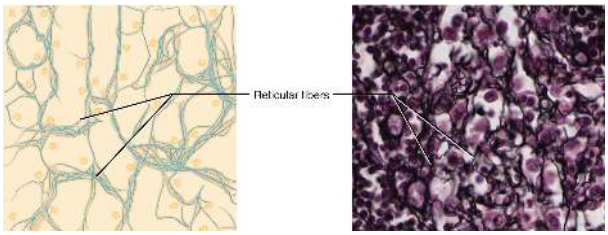



Figure **3.4.3**: Reticular Tissue.This is a loose connective tissue made up of a network of reticular fibers that provides a supportive framework for soft organs. LM × 1600. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

## 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 elastin fibers in addition to collagen fibers, which allows 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 elastic.

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. Dense irregular elastic tissues give arterial walls the strength and the ability to regain original shape after stretching (Figure **3.4.4**).

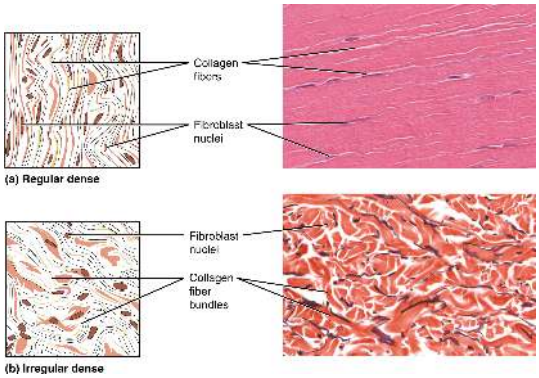



Figure 3.4.4: Dense Connective Tissue.(a) Dense regular connective tissue consists of collagenous fibers packed into parallel bundles. (b) Dense irregular connective tissue consists of collagenous fibers interwoven into a mesh-like network. From top, LM × 1000, LM × 200. (Micrographs provided by the 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.

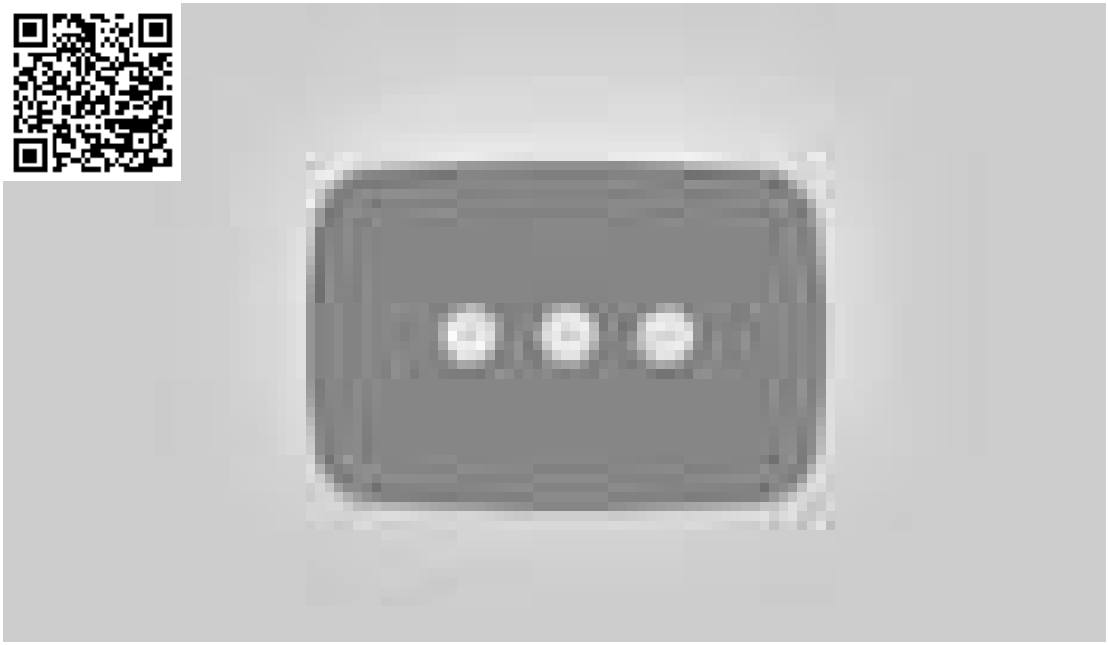
What is tendinitis and how did it happen? Tendinitis is the inflammation of a tendon, the thick band of fibrous connective tissue that attaches a muscle to a bone. The condition causes pain and tenderness in the area around a joint. On rare occasions, a sudden serious injury will cause tendinitis. Most 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, 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.

QR Code representing a URL

*Watch this animation to learn more about tendonitis, a painful condition caused by swollen or injured tendons.*



## 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 **3.4.5**). **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. The knee and jaw joints and the 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.

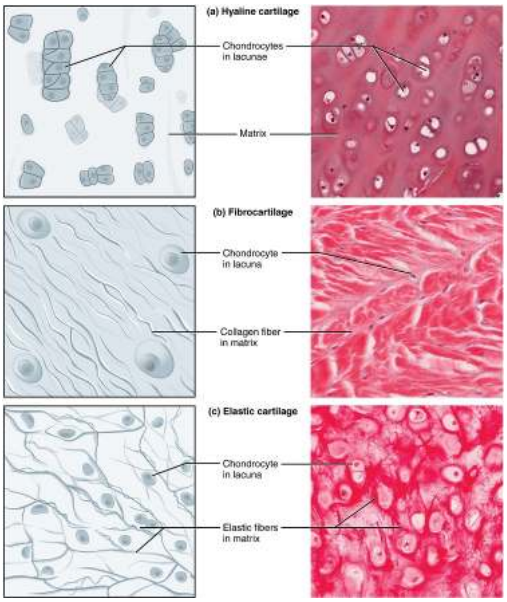



Figure **3.4.5**: Types of Cartilage.Cartilage is a connective tissue consisting of collagenous fibers embedded in a firm matrix of chondroitin sulfates. (a) Hyaline cartilage provides support with some flexibility. The example is from dog tissue. (b) Fibrocartilage provides some compressibility and can absorb pressure. (c) Elastic cartilage provides firm but elastic support. From top, LM × 300, LM × 1200, LM × 1016. (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 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 looks like a sponge under the microscope 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.

## 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 **3.4.6**). 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.

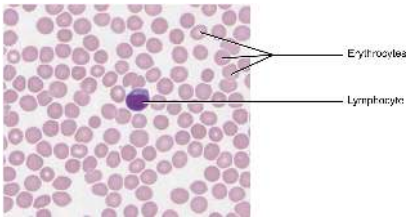


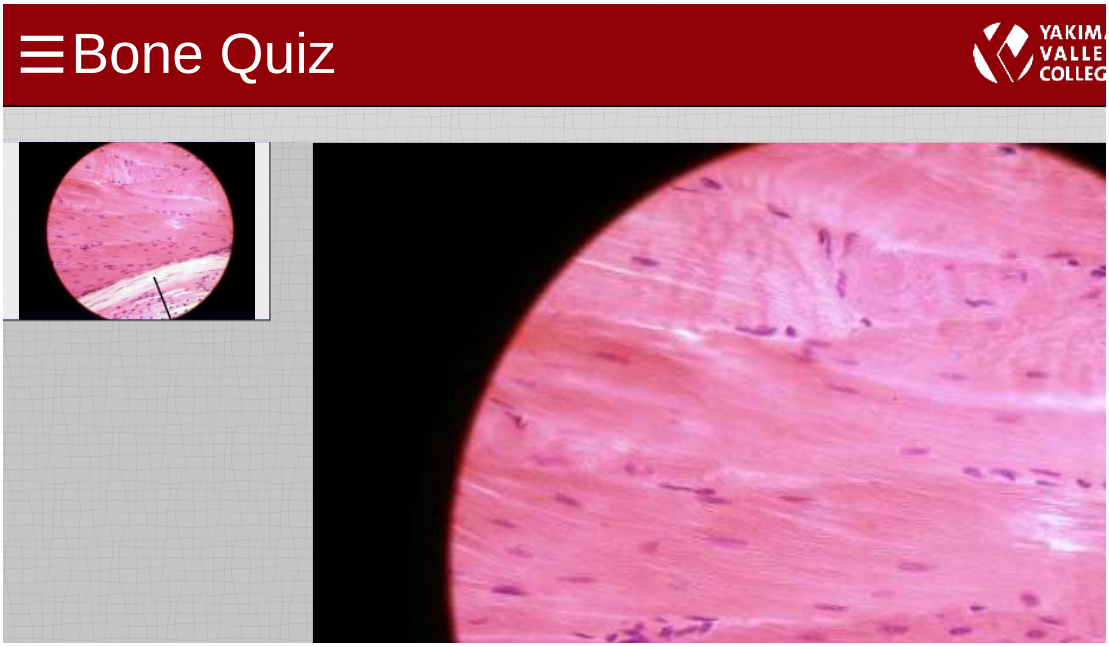

Figure **3.4.6**: Blood: A Fluid Connective Tissue.Blood is a fluid connective tissue containing erythrocytes and various types of leukocytes that circulate in a liquid extracellular matrix. LM × 1600. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

QR Code representing a URL

*View the University of Michigan Webscope at virtualslides.med.umich.edu/H....svs/view.apml to explore the tissue sample in greater detail.*

QR Code representing a URL

*Visit this link to test your connective tissue knowledge with this 10-question quiz. Can you name the 10 tissue typesshown in the histology slides?*




## Chapter Review

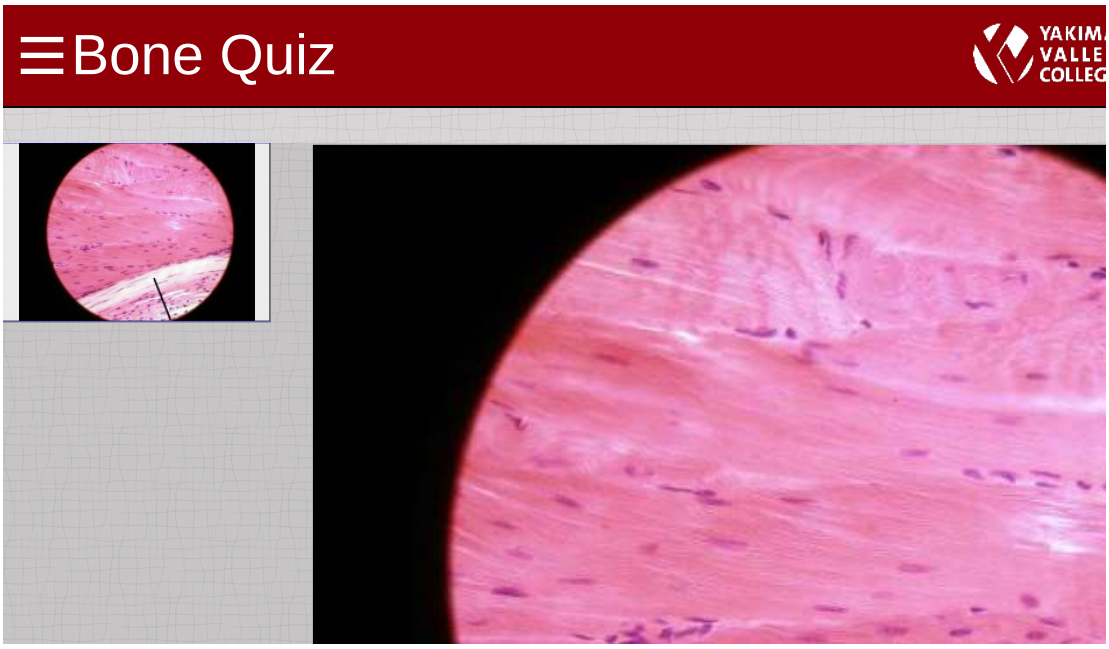
Connective tissue is a heterogeneous tissue with many cell shapes and tissue architecture. Structurally, all connective tissues contain cells that are embedded in an extracellular matrix stabilized by proteins. The chemical nature and physical layout of the extracellular matrix and proteins vary enormously 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. Connect 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 joints, 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.

## Interactive Link Questions

Visit this 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: Click at the bottom of the quiz for the answers.

## 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: 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: D

Q. Which connective tissue specializes in storage of fat?

A. tendon

B. adipose tissue

C. reticular tissue

D. dense connective tissue

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: C

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

A. mesoderm

B. mesenchyme

C. ectoderm

D. endoderm

Answer: B

Q. In bone, the main cells are _____.

A. fibroblasts

B. chondrocytes

C. lymphocytes

D. osteocytes

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.

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?

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.

**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

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

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# 3.5: Muscle Tissue

**Learning Objectives**

- 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, in other words, bones, 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**).

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.

**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. Cardiomyocyte attach to one another with specialized cell junctions called intercalated discs. 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 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.

**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. Each cell is spindle shaped with a single nucleus and no visible striations (Figure **3.5.1**).

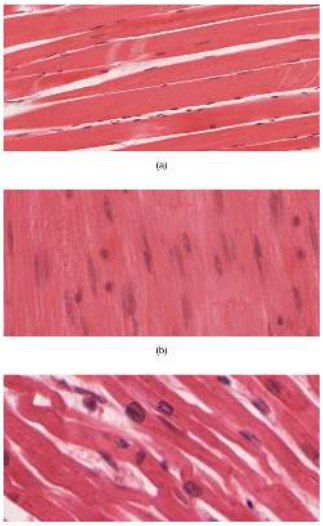
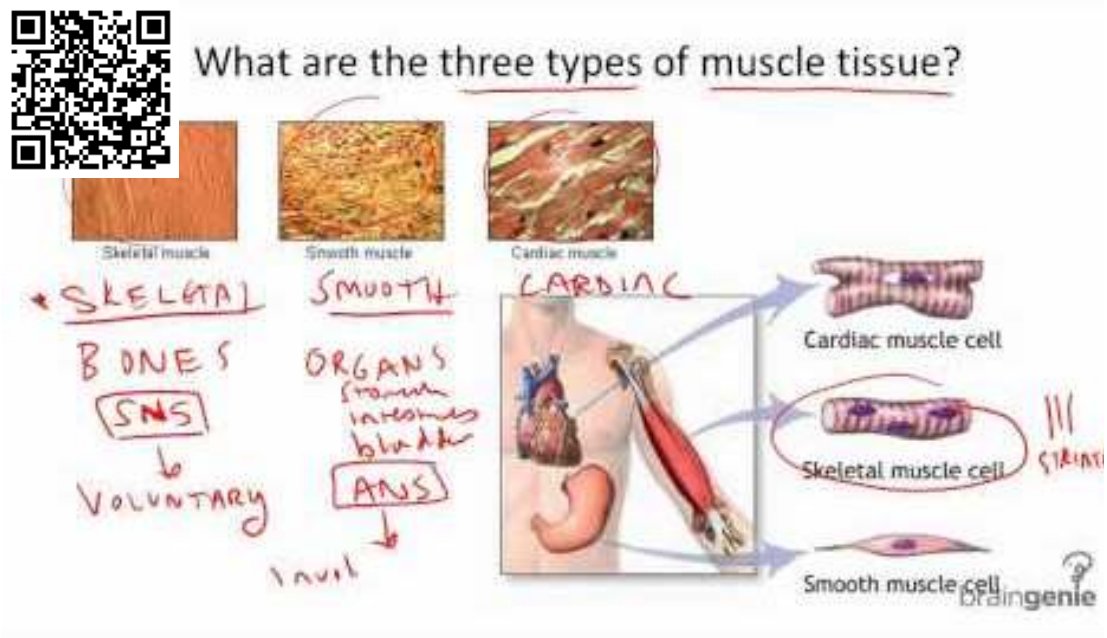


Figure **3.5.1**: Muscle Tissue. (a) Skeletal muscle cells have prominent striation and nuclei on their periphery. (b) Smooth muscle cells have a single nucleus and no visible striations. (c) Cardiac muscle cells appear striated and have a single nucleus. From top, LM × 1600, LM × 1600, LM × 1600. (Micrographs provided by the Regents of University of Michigan Medical School © 2012)

Watch this video to learn more about muscle tissue. In looking through a microscope how could you distinguish skeletal muscle tissue from smooth muscle?

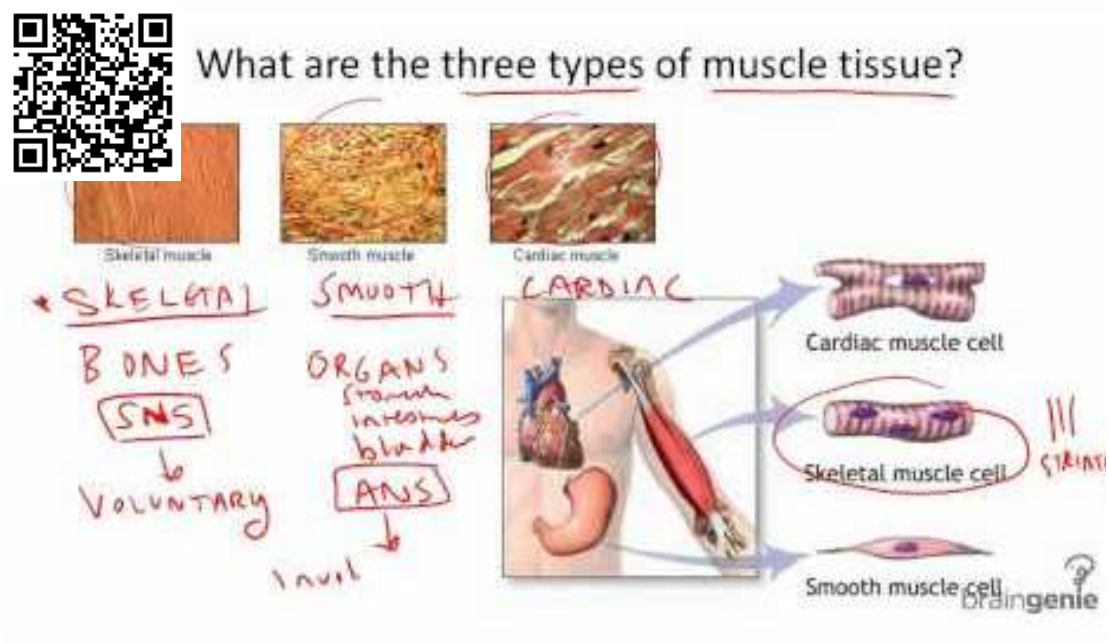



## Chapter Review

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 disks. 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.

## Interactive Link Questions

Watch this video to learn more about muscle tissue. In looking through a microscope how could you distinguish skeletal muscle tissue from smooth muscle?




Answer: Skeletal muscle cells are striated.

## 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: A

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

A. myoblasts

B. endoderm

C. fibrocytes

D. chondrocytes

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: 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.

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?

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

**Learning Objectives**

- 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.

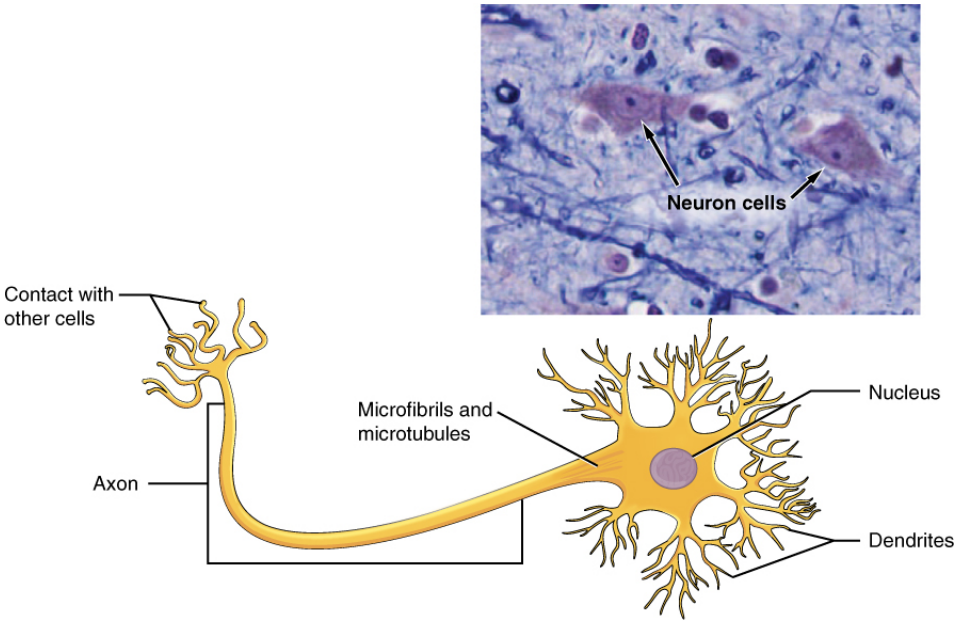



Figure **3.6.1**: The Neuron.The cell body of a neuron, also called the soma, contains the nucleus and mitochondria. The dendrites transfer the nerve impulse to the soma. The axon carries the action potential away to another excitable cell. LM × 1600. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

**Exercise 3.6.1**

*Follow this link to learn more about nervous tissue. What are the main parts of a nerve cell?*

www.nobelprize.org/education...ng.html#/plot2

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**).

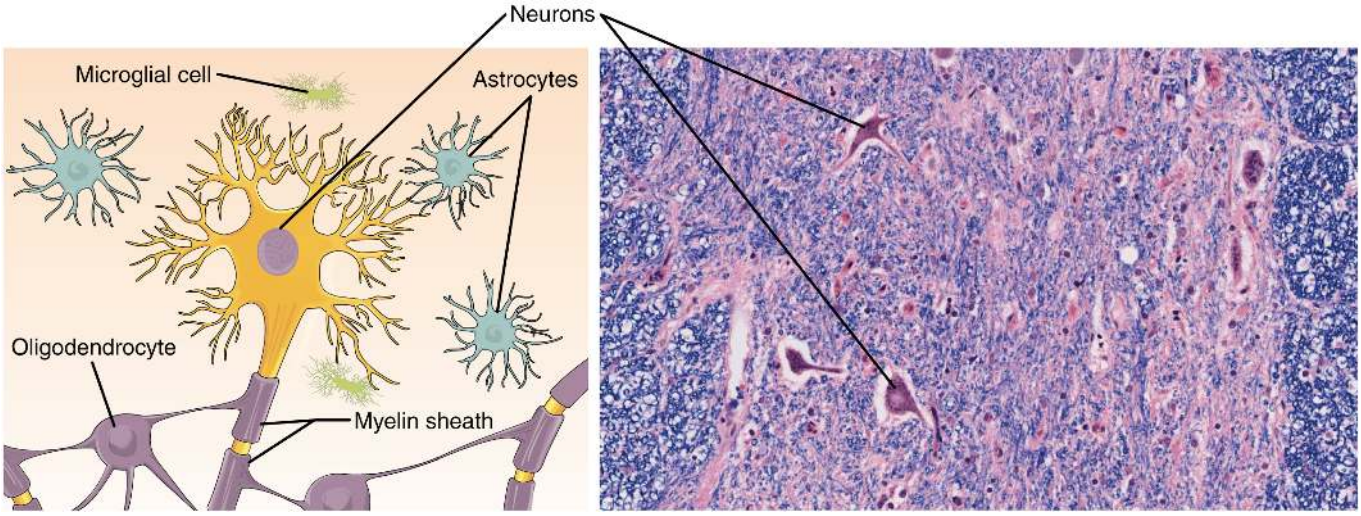



***Figure 3.6.2: Nervous Tissue.*** *Nervous tissue is made up of neurons and neuroglia. The cells of nervous tissue are specialized to transmit and receive impulses. LM × 872. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)*

## Chapter 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.

## Interactive Link Questions

Follow this link to learn more about nervous tissue. What are the main parts of a nerve cell?

Please read the important information regarding these games at the bottom of the page.

# Nerve Signalling: Tracing the wiring of life

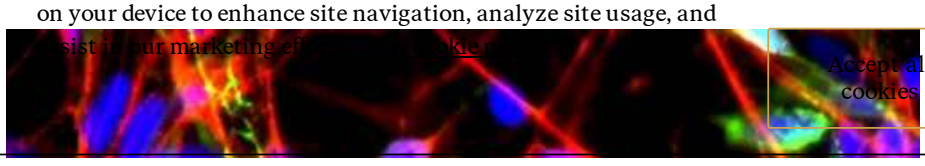
by John Farndon

First published 16 September 2009

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Answer: Dendrites, cell body, and the axon.

## Review Questions

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

A. neurons

B. oligodendrocytes

C. astrocytes

D. microglia

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: 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: D

## Critical Thinking Questions

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

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?

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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http://stke.sciencemag.org/cgi/conte...ans;3/147/eg11

Ming GL, Song H. Adult neurogenesis in the mammalian central nervous system. Annu. Rev. Neurosci. 2005 [cited 2012 Dec 4]; 28:223–250.

## 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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# CHAPTER OVERVIEW

## 4: The Integumentary System


4.1: Introduction

4.2: Layers of the Skin

4.3: Accessory Structures of the Skin

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


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# 4.1: Introduction

**Chapter 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.

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.

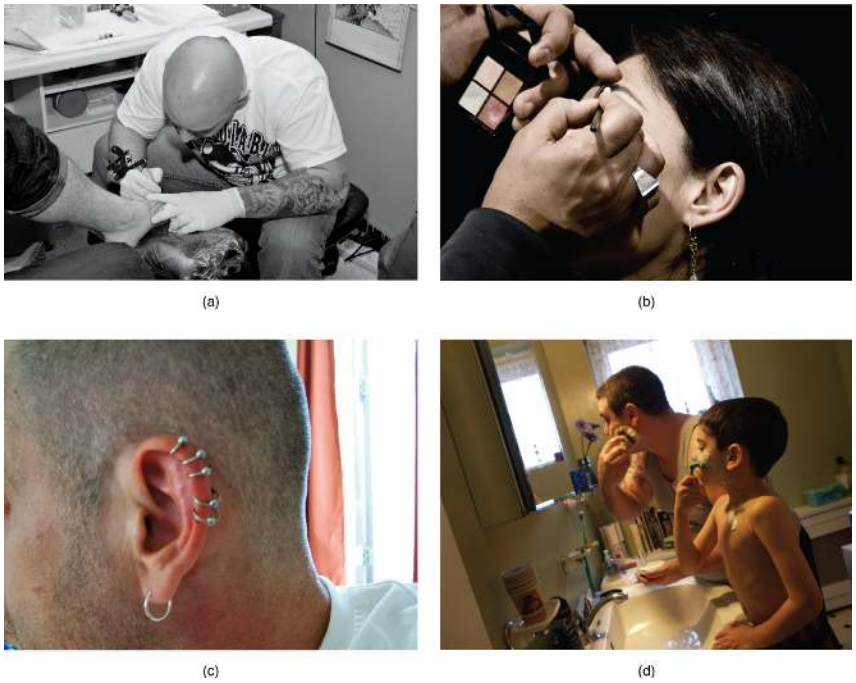



Figure **4.1.1**: Your skin is a vital part of your life and appearance (a–d). Some people choose to embellish it with tattoos (a), makeup (b), and even piercings (c). (credit a: Steve Teo; credit b: "spaceodissey"/flickr; credit c: Mark/flickr; credit d: Lisa Schaffer)

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# 4.2: Layers of the Skin

**Learning Objectives**

- 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 deeper layer of skin is well vascularized (has numerous blood vessels). It also has numerous sensory, and autonomic and sympathetic nerve fibers ensuring communication to and from the brain.

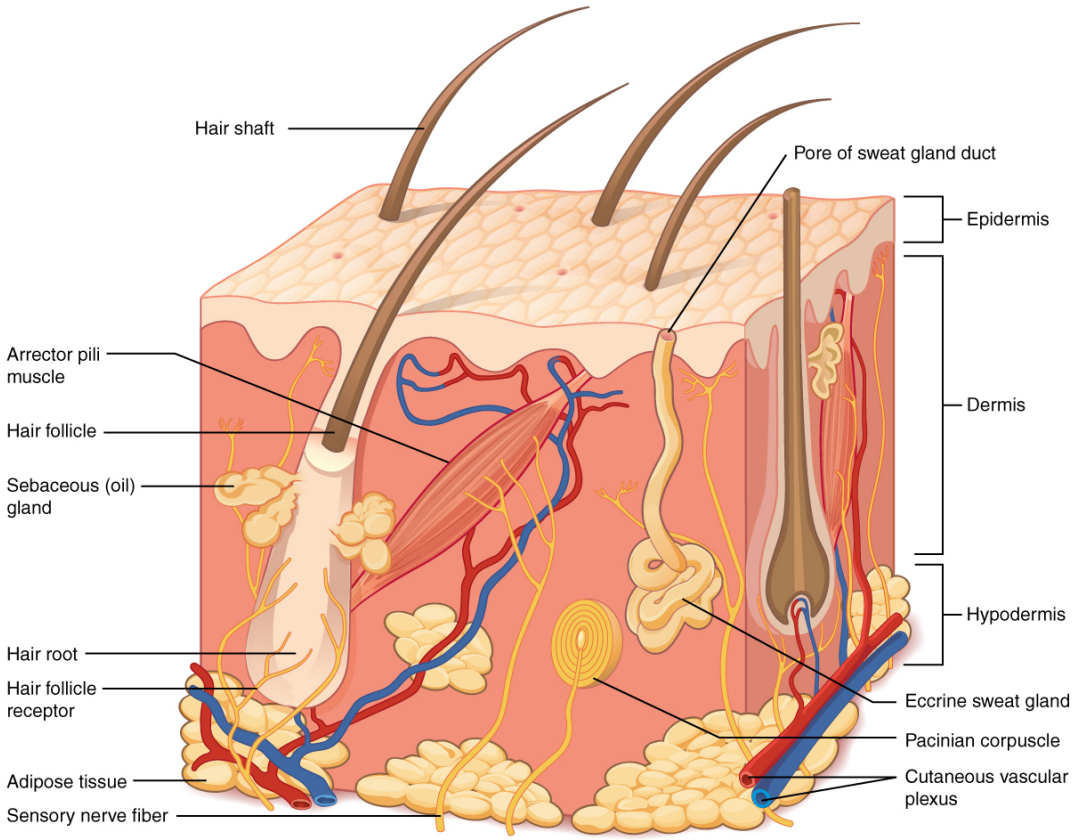



Figure 4.2.1: Layers of Skin. The skin is composed of two main layers: the epidermis, made of closely packed epithelial cells, and the dermis, made of dense, irregular connective tissue that houses blood vessels, hair follicles, sweat glands, and other structures. Beneath the dermis lies the hypodermis, which is composed mainly of loose connective and fatty tissues.

## 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).

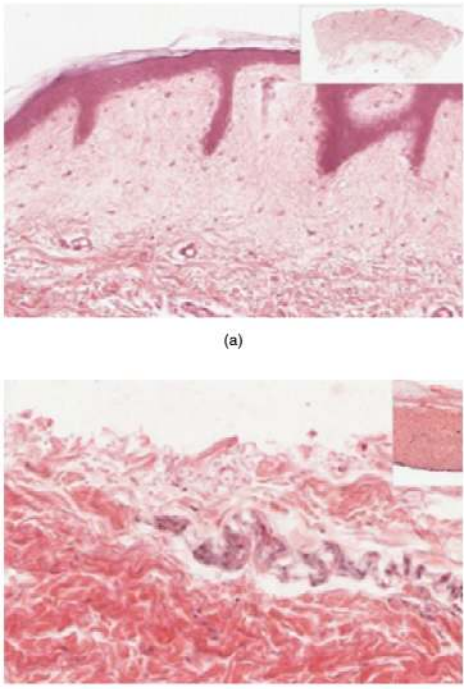



Figure 4.2.2: Thin Skin versus Thick Skin.These slides show cross-sections of the epidermis and dermis of (a) thin and (b) thick skin. Note the significant difference in the thickness of the epithelial layer of the thick skin. From top, LM × 40, LM × 40. (Micrographs provided by the Regents of University of Michigan Medical School © 2012)

The cells in all of the layers except the stratum basale 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 (Figure 4.2.3).

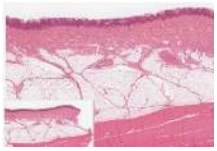


Figure 4.2.3: Epidermis.The epidermis is epithelium composed of multiple layers of cells. The basal layer consists of cuboidal cells, whereas the outer layers are squamous, keratinized cells, so the whole epithelium is often described as being keratinized stratified squamous epithelium. LM × 40. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

## 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 folding, the stronger the connections made (Figure 4.2.4).

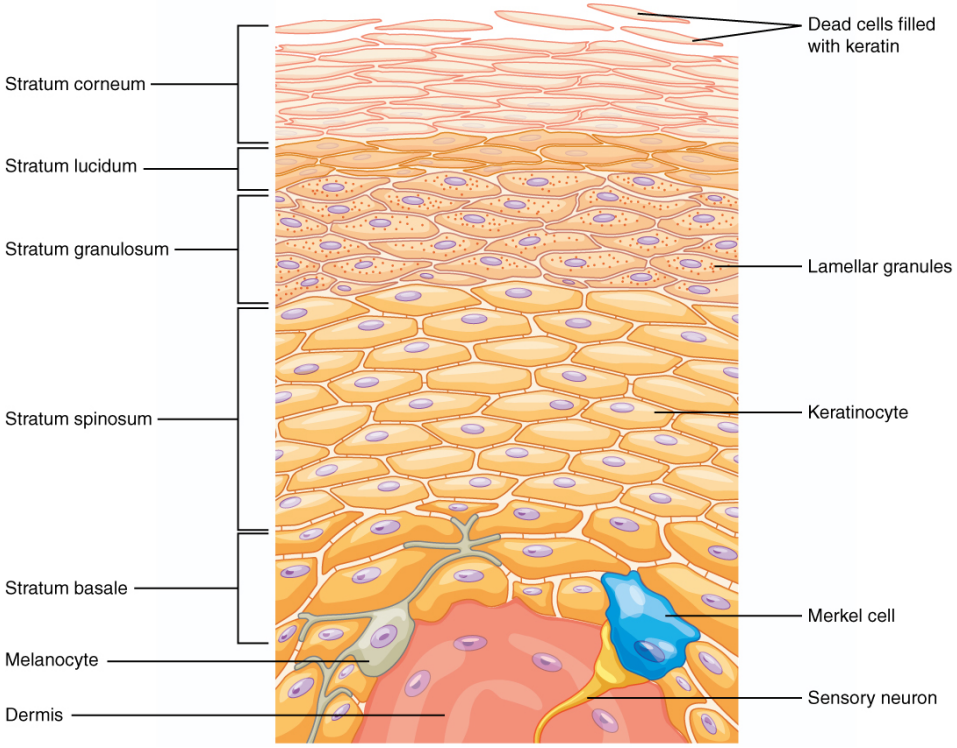



Figure **4.2.4**: Layers of the Epidermis. The epidermis of thick skin has five layers: stratum basale, stratum spinosum, stratum granulosum, stratum lucidum, and stratum corneum.

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**, 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 a structure 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 10 layers of keratinocytes, formed as a result of cell division in the stratum basale (Figure **4.2.5**). Interspersed among the keratinocytes of this layer is a type of dendritic cell called the **Langerhans cell**, which functions as a macrophage by engulfing bacteria, foreign particles, and damaged cells that occur in this layer.

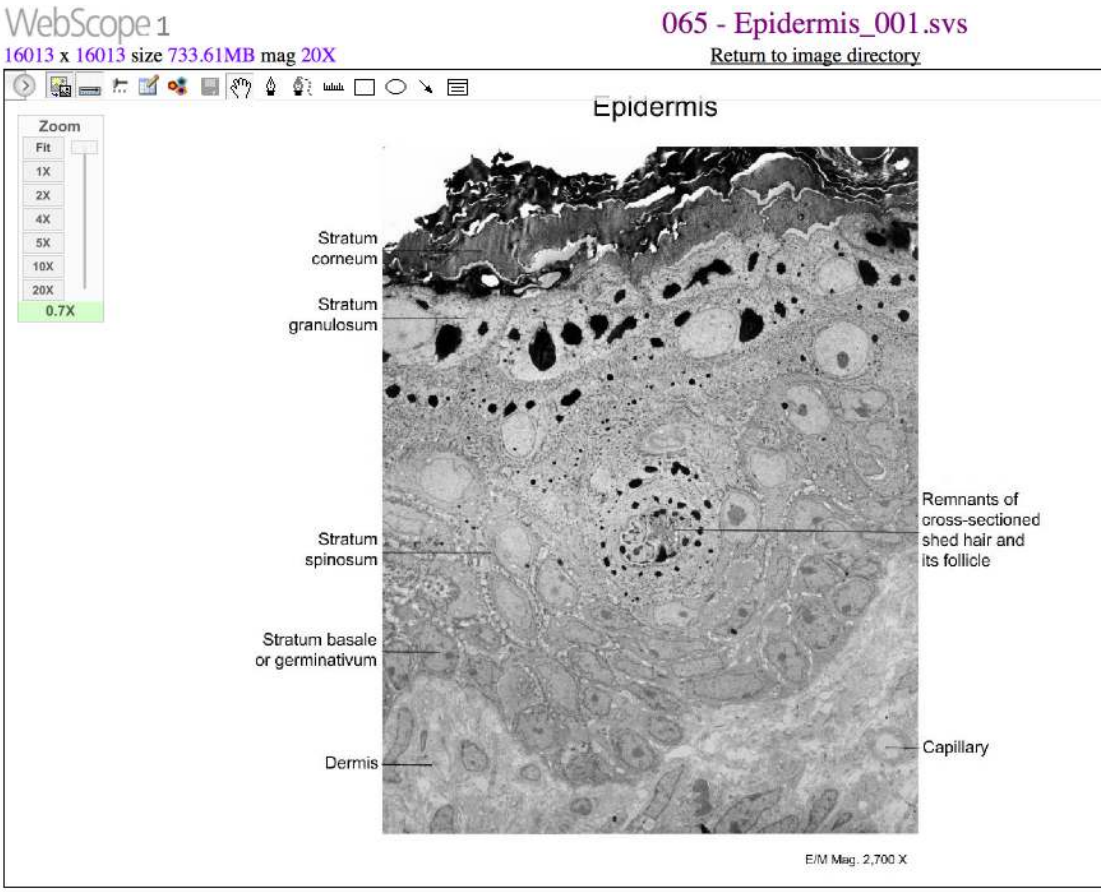



Figure 4.2.5: Cells of the Epidermis.The cells in the different layers of the epidermis originate from basal cells located in the stratum basale, yet the cells of each layer are distinctively different. EM × 2700. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

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.

### 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 (three to five layers deep) become flatter, their cell membranes thicken, and they generate large amounts of the proteins keratin, which is fibrous, and **keratohyalin**, which accumulates as lamellar granules within the cells (see Figure 4.2.4). These two proteins make up the bulk of the keratinocyte mass in the stratum granulosum and give the layer its grainy appearance. The nuclei and other cell organelles disintegrate as the cells die, leaving behind the keratin, keratohyalin, and 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 4.2.4). 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 4.2.4). 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 that compose an interconnected mesh of elastin and collagenous fibers, produced by fibroblasts (Figure **4.2.6**).




Figure **4.2.6**: 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. (credit: modification of work by “kilbad”/Wikimedia Commons)

### Papillary Layer

The **papillary layer** is made of loose, areolar connective tissue, which means the collagen and elastin 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 **4.2.6**). Within the papillary layer are fibroblasts, a small number of fat cells (adipocytes), and an abundance of small blood vessels. In addition, the papillary layer contains phagocytes, defensive cells that help fight bacteria or other infections that have breached the skin. This layer also contains lymphatic capillaries, nerve fibers, and touch receptors called the Meissner corpuscles.

### 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. **Elastin 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 integument.

### 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 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 4.2.7).

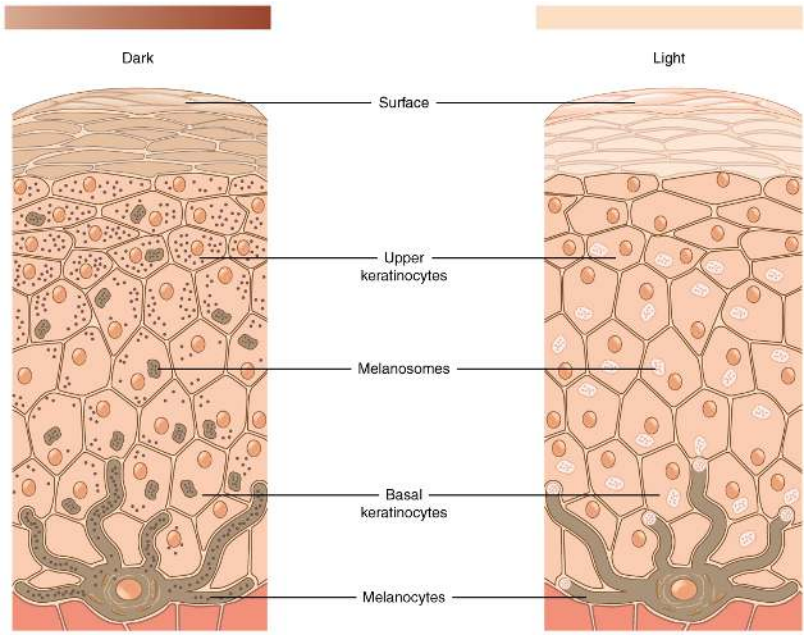



Figure **4.2.7**: Skin Pigmentation. The relative coloration of the skin depends of the amount of melanin produced by melanocytes in the stratum basale and taken up by keratinocytes.

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 protects the DNA of epidermal cells from UV ray damage and the breakdown of folic acid, a nutrient necessary for our health and well-being. In contrast, too much melanin can interfere with the production of vitamin D, an important nutrient involved in calcium absorption. 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 **4.2.8**).



Figure **4.2.8**: Moles.Moles range from benign accumulations of melanocytes to melanomas. These structures populate the landscape of our skin. (credit: the National Cancer Institute)

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 **4.2.9**). Neither albinism nor vitiligo directly affects the lifespan of an individual.



Figure **4.2.9**: Vitiligo.Individuals with vitiligo experience depigmentation that results in lighter colored patches of skin. The condition is especially noticeable on darker skin. (credit: Klaus D. Peter)

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. 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 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.

## Chapter 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 cells from UV rays.

The dermis connects the epidermis to the hypodermis, and provides strength and elasticity due to the presence of collagen and elastin fibers. It has only two layers: the papillary layer with papillae that extend into the epidermis and the lower, reticular layer

composed of loose 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.

## Interactive Link Questions

The skin consists of two layers and a closely associated layer. View this animation to learn more about layers of the skin. What are the basic functions of each of these layers?

> Answer: The epidermis provides protection, the dermis provides support and flexibility, and the hypodermis (fat layer) provides insulation and padding.

Figure **4.2.3**. If you zoom on the cells at the outermost layer of this section of skin, what do you notice about the cells?

> Answer: Figure **4.2.3**. These cells do not have nuclei, so you can deduce that they are dead. They appear to be sloughing off.

Figure **4.2.5**. If you zoom on the cells of the stratum spinosum, what is distinctive about them?

> Answer: Figure **4.2.5**. These cells have desmosomes, which give the cells their spiny appearance.

This ABC video follows the story of a pair of fraternal African-American twins, one of whom is albino. Watch this video to learn about the challenges these children and their family face. Which ethnicities do you think are exempt from the possibility of albinism?

> Answer: There are none.

## 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: D

Q. Langerhans cells are commonly found in the _____.

A. stratum spinosum

B. stratum corneum

C. stratum granulosum

D. stratum basale

> 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: C

Q. Collagen lends _____ to the skin.

A. elasticity

B. structure

C. color

D. UV protection

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: 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?

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 have a lighter shade of skin and less 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.

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

**elastin 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

**Learning Objectives**

- 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).

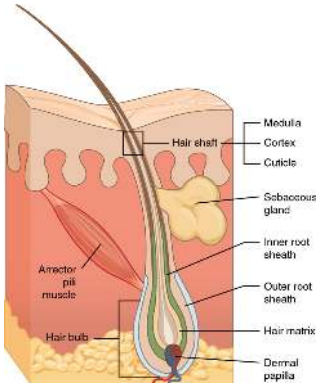



Figure 4.3.1: Hair. *Hair follicles originate in the epidermis and have many different parts.*

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.

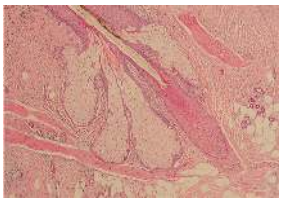
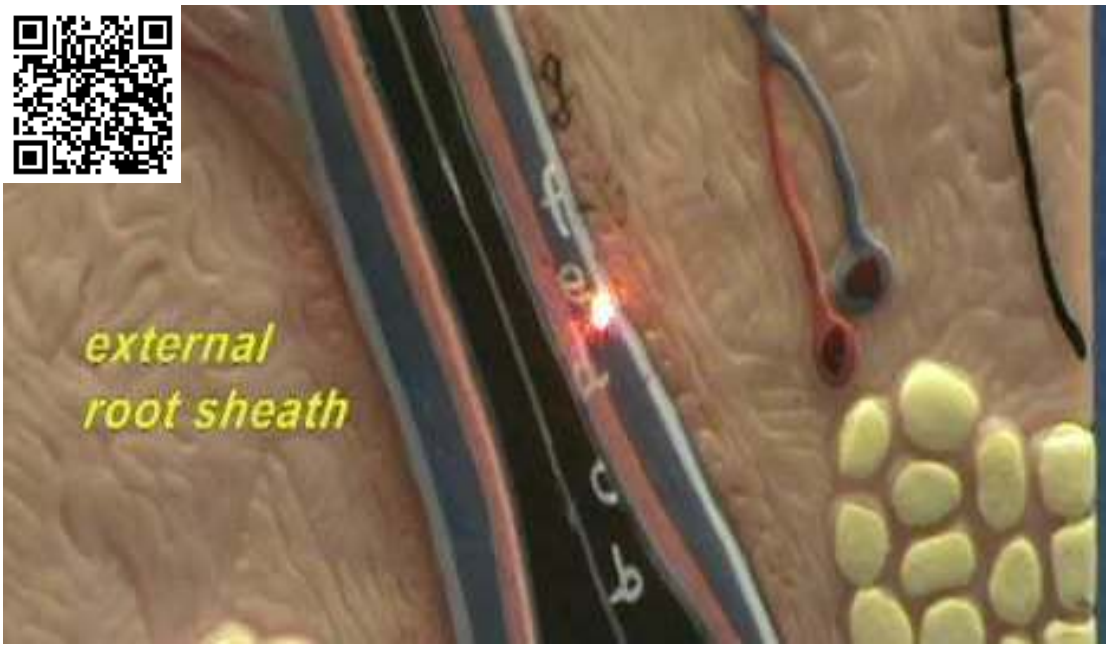


Figure 4.3.2: Hair Follicle. The slide shows a cross-section of a hair follicle. Basal cells of the hair matrix in the center differentiate into cells of the inner root sheath. Basal cells at the base of the hair root form the outer root sheath. LM × 4. (credit: modification of work by "kilbad"/Wikimedia Commons)

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.

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*The hair follicle is made of multiple layers of cells that form from basal cells in the hair matrix and the hair root. Cells of the hair matrix divide and differentiate to form the layers of the hair. Watch this video to learn more about hair follicles.*




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, such as when a frightened cat raises its fur. Of course, this is much more obvious in organisms with a heavier coat than most humans, such as dogs and cats.

### 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.

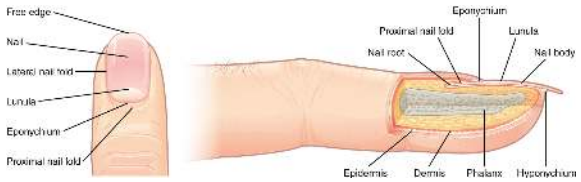
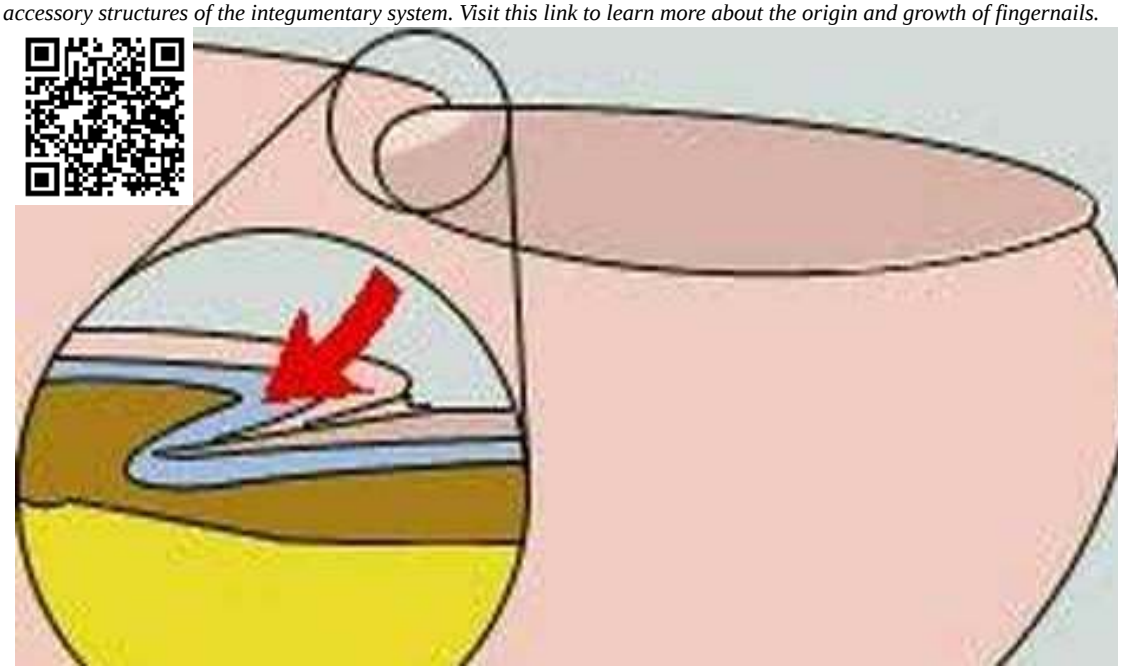



Figure **4.3.3**: Nails.The nail is an accessory structure of the integumentary system.

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*Nails are accessory structures of the integumentary system. Visit this link to learn more about the origin and growth of fingernails.*



## Sweat Glands

When the body becomes warm, **sudoriferous glands** produce sweat to cool the body. Sweat glands develop from epidermal projections into the dermis and are classified as merocrine glands; that is, the secretions are excreted by exocytosis through a duct without affecting the cells of the gland. 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.

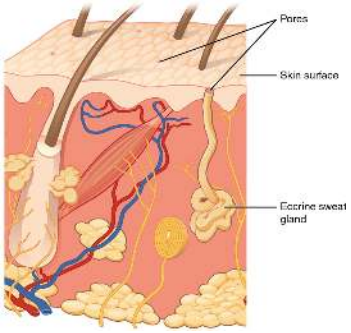



Figure **4.3.4**: Eccrine Gland.Eccrine glands are coiled glands in the dermis that release sweat that is mostly water.

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.

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*Sweating regulates body temperature. The composition of the sweat determines whether body odor is a byproduct of sweating. Visit this link to learn more about sweating and body odor.*

## 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.

## Chapter 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: 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: 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: 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: 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: B

## Critical Thinking Questions

Q. Explain the differences between eccrine and apocrine sweat glands.

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.

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: Diseases, Disorders, and Injuries of the Integumentary System

**Learning Objectives**

- 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 4.4.1). 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 4.4.1: 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. (credit: John Hendrix, MD)

### 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 4.4.2). It is the second most common skin cancer. The American Cancer Society reports that two of 10 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 **4.4.2**: Squa mous *Cell Carcinoma.Squamous cell carcinoma presents here as a lesion on an individual's nose. (credit: the National Cancer Institute)*

### 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 **4.4.3**). Treatment typically involves surgical excision and immunotherapy.



Figure **4.4.3** Melanoma. Melanomas typically present as large brown or black patches with uneven borders and a raised surface. (credit: the National Cancer Institute)

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 **4.4.4**). 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 4.4.4: Eczema. Eczema is a common skin disorder that presents as a red, flaky rash. (credit: “Jambula”/Wikimedia Commons)

## 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 plug is initially white. The sebum, when oxidized by exposure to air, turns black. Acne results from infection by acne-causing bacteria (*Propionibacterium* and *Staphylococcus*), which can lead to redness and potential scarring due to the natural wound healing process (Figure 4.4.5).

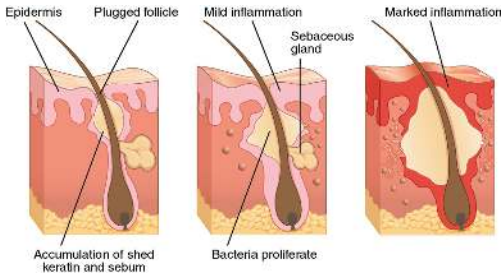



Figure 4.4.5: Acne.Acne is a result of over-productive sebaceous glands, which leads to formation of blackheads and inflammation of the skin.

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. Visit this site for additional information.

## Chapter 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: 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: D

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: C

## Critical Thinking Questions

Q. Why do teenagers often experience acne?

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.

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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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# CHAPTER OVERVIEW

## 5: Bone Tissue and the Skeletal System

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.


5.1: Introduction

5.2: The Functions of the Skeletal System

5.3: Bone Classification

5.4: Bone Structure

5.5: Bone Formation and Development

5.6: Fractures - Bone Repair


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# 5.1: Introduction

**Chapter Objectives:**

After studying this chapter, you will be able to:

- List and descrive 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 effect of exercise, nutrition, and hormones on bone tissues
- Describe how an imbalance of calcium can affect bone tissue

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 Bones. *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. (credit: James Emery)*

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# 5.2: The Functions of the Skeletal System

**Learning Objectives**

- Define bone, cartilage, and the skeletal system
- List and describe the functions of the skeletal system

**Bone**, or **osseous tissue**, is a hard, dense 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 also 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 joints serve as fulcrums (Figure **5.2.1**). Unless a muscle spans a joint and contracts, a bone is not going to move. For information on the interaction of the skeletal and muscular systems, that is, the musculoskeletal system, seek additional content.



Figure **5.2.1**: Bones Support Movement.Bones act as levers when muscles span a joint and contract. (credit: Benjamin J. DeLong)

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 **5.2.2**).

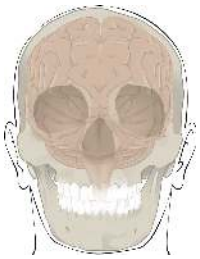


Figure **5.2.2**: Bones Protect Brain.The cranium completely surrounds and protects the brain from non-traumatic injury.

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 **5.2.3**).

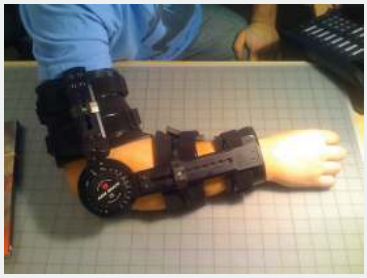


Figure **5.2.3**: Arm Brace.An orthopedist will sometimes prescribe the use of a brace that reinforces the underlying bone structure it is being used to support. (credit: Juhan Sonin).

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 and red marrow. **Yellow marrow** contains adipose tissue; the triglycerides 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.

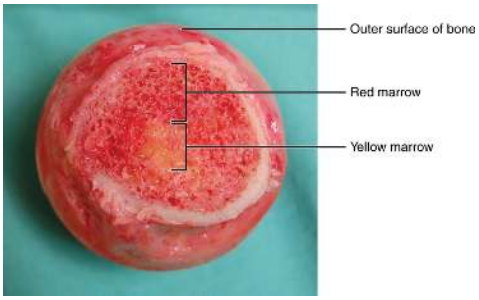



Figure **5.2.4**: Head of Femur Showing Red and Yellow Marrow.The head of the femur contains both yellow and red marrow. Yellow marrow stores fat. Red marrow is responsible for hematopoiesis. (credit: modification of work by "stevenfruitsmaak"/Wikimedia Commons)

## Chapter 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: B

Q. Bone tissue can be described as _____.

A. dead calcified tissue

B. cartilage

C. the skeletal system

D. dense, hard connective tissue

Answer: D

Q. Without red marrow, bones would not be able to _____.

A. store phosphate

B. store calcium

C. make blood cells

D. move like levers

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: A

Q. Which of the following can be found in areas of movement?

A. hematopoiesis

B. cartilage

C. yellow marrow

D. red marrow

Answer: B

Q. The skeletal system is made of _____.

A. muscles and tendons

B. bones and cartilage

C. vitreous humor

D. minerals and fat

Answer: B

## Critical Thinking Questions

The skeletal system is composed of bone and cartilage and has many functions. Choose three of these functions and discuss what features of the skeletal system allow it to accomplish these functions.

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 movable joints allow the skeleton to change shape and positions; that is, move.

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 produces blood cells. 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 Classification

**Learning Objectives**

- 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 **5.3.1**). Their shapes and their functions are related such that each categorical shape of bone has a distinct function.

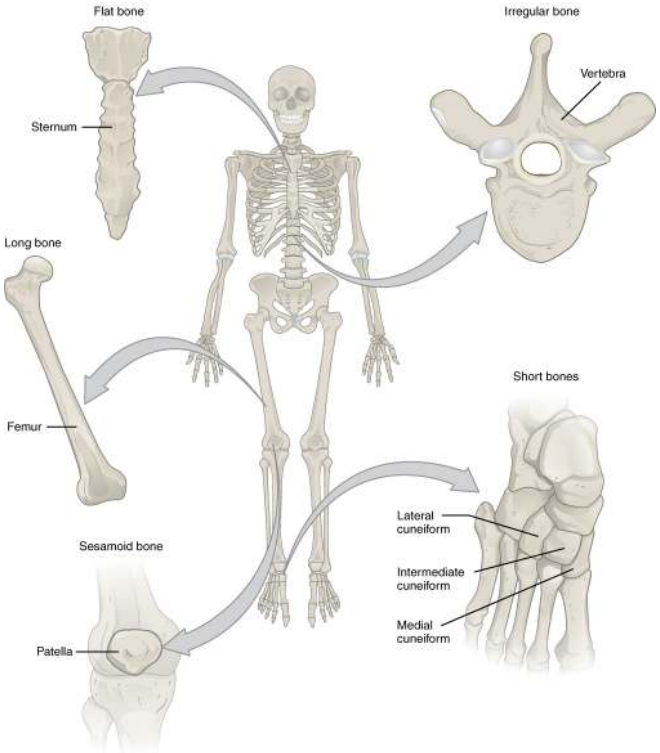



Figure **5.3.1**: Classifications of Bones.Bones are classified according to their shape.

## 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 fingers (metacarpals, phalanges) and toes (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 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.

## 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 **5.3.1** reviews bone classifications with their associated features, functions, and examples.

Table **5.3.1**: 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 |

## Chapter 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: B

Q. Sesamoid bones are found embedded in _____.

A. joints

B. muscles

C. ligaments

D. tendons

Answer: D

Q. Bones that surround the spinal cord are classified as _____ bones.

A. irregular

B. sesamoid

C. flat

D. short

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: A

Q. Long bones enable body movement by acting as a _____.

A. counterweight

B. resistive force

C. lever

D. fulcrum

Answer: C

## Critical Thinking Questions

Q. What are the structural and functional differences between a tarsal and a metatarsal?

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?

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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# 5.4: Bone Structure

**Learning Objectives**

- 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 5.4.1). 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 and hard **compact bone**.

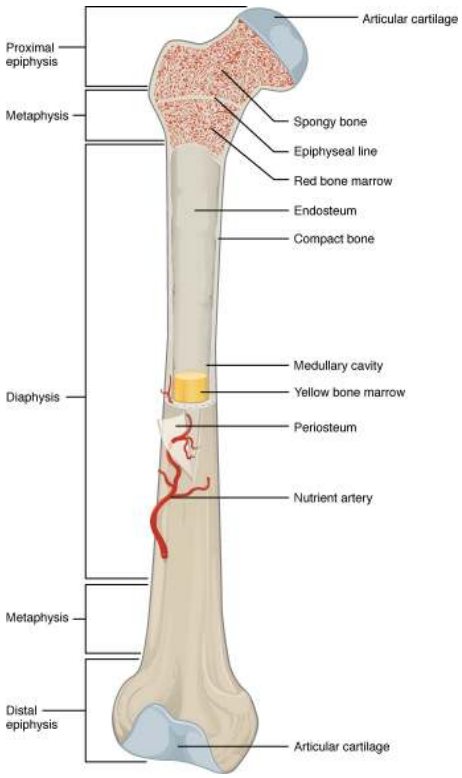



Figure 5.4.1: Anatomy of a Long Bone.A typical long bone shows the gross anatomical characteristics of bone.

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 contains blood vessels, nerves, and lymphatic vessels that nourish compact bone. Tendons and ligaments also attach to bones at the periosteum. The periosteum covers the entire outer surface except where the epiphyses meet other bones to form joints (Figure 5.4.2). In this region, the epiphyses are covered with **articular cartilage**, a thin layer of cartilage that reduces friction and acts as a shock absorber.

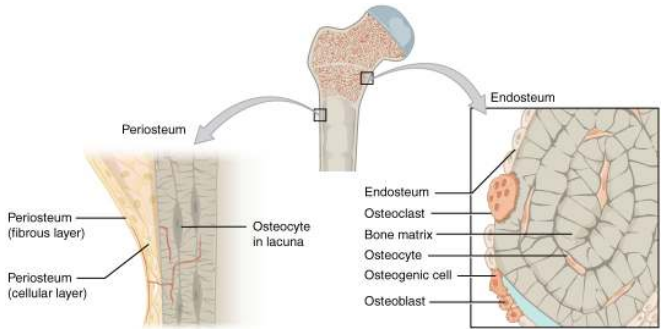



Figure 5.4.2: Periosteum and Endosteum.The periosteum forms the outer surface of bone, and the endosteum lines the medullary cavity.

Flat bones, like those of the cranium, consist of a layer of **diploë** (spongy bone), lined on either side by a layer of compact bone (Figure \Pageindex3). 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.

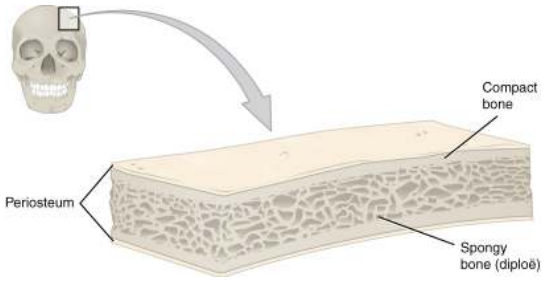



Figure 5.4.3: Anatomy of a Flat Bone.This cross-section of a flat bone shows the spongy bone (diploë) lined on either side by a layer of compact bone.

## Bone Markings

The surface features of bones vary considerably, depending on the function and location in the body. Table 5.4.1 describes the bone markings, which are illustrated in (Figure 5.4.4). 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* 5.4.1**

| Bone Markings | | |
|---|---|---|
| Marking | Description | Example |
| Articulations | Where two bones meet | Knee joint |
| Head | Prominent rounded surface | Head of femur |
| Facet | Flat surface | 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 |

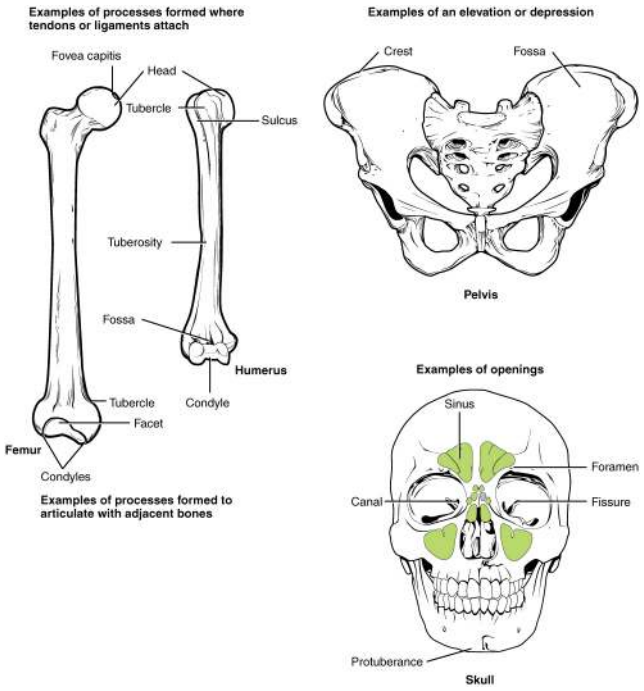



Figure 5.4.4: Bone Features.The surface features of bones depend on their function, location, attachment of ligaments and tendons, or the penetration of blood vessels and nerves.

## Bone Cells and Tissue

Bone contains a relatively small number of cells entrenched in a matrix of collagen fibers that provide a surface for inorganic salt crystals to 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 5.4.5).

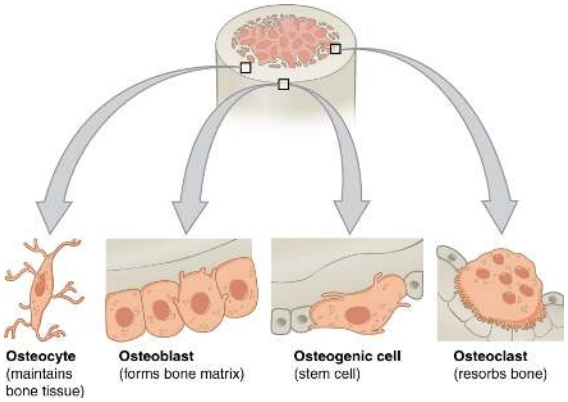



Figure 5.4.5: Bone Cells.Four types of cells are found within bone tissue. Osteogenic cells are undifferentiated and develop into osteoblasts. When osteoblasts get trapped within the calcified matrix, their structure and function changes, and they become osteocytes. Osteoclasts develop from monocytes and macrophages and differ in appearance from other bone cells.

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 become 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. They can 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 marrow. 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 **5.4.2** reviews the bone cells, their functions, and locations.

***Table* 5.4.2**

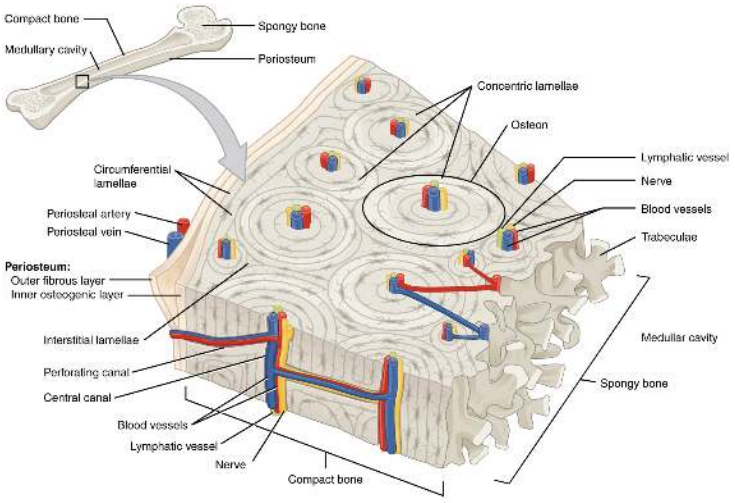
| Bone Cells | | |
|---|---|---|
| Cell type | Function | Location |
| Osteogenic cells | Develop into osteoblasts | Deep layers of the periosteum and the marrow |
| Osteoblasts | Bone formation | Growing portions of bone, including periosteum and endosteum |
| Osteocytes | Maintain mineral concentration of matrix | Entrapped in matrix |
| Osteoclasts | Bone resorption | Bone surfaces and at sites of old, injured, or unneeded bone |

## Compact and Spongy Bone

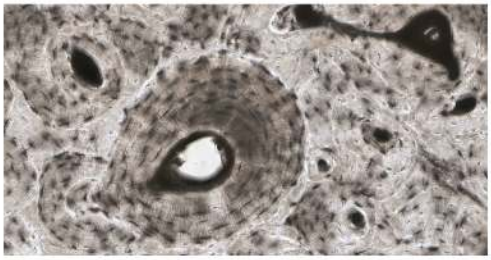
The differences between compact and spongy bone are best explored via their histology. Most bones contain compact and spongy osseous tissue, but their distribution and concentration vary based on the bone's overall function. Compact bone is dense so that it can withstand compressive forces, while spongy (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 **5.4.6**). It can be found under the periosteum and in the diaphyses of long bones, where it provides support and protection.




(a)



(b)

Figure 5.4.6: 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 × 40. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

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). Running down the center of each osteon 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 connect with the canaliculi of other lacunae and eventually with the central canal. This system allows nutrients to be transported to the osteocytes and wastes to be removed from them.

## Spongy (Cancellous) Bone

Like compact bone, **spongy bone**, also known as cancellous bone, contains osteocytes housed in lacunae, but they are not arranged in concentric circles. Instead, the lacunae and osteocytes are found in a lattice-like network of matrix spikes called **trabeculae** (singular = trabecula) (Figure 5.4.7). The trabeculae may appear to be a random network, but each trabecula 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.

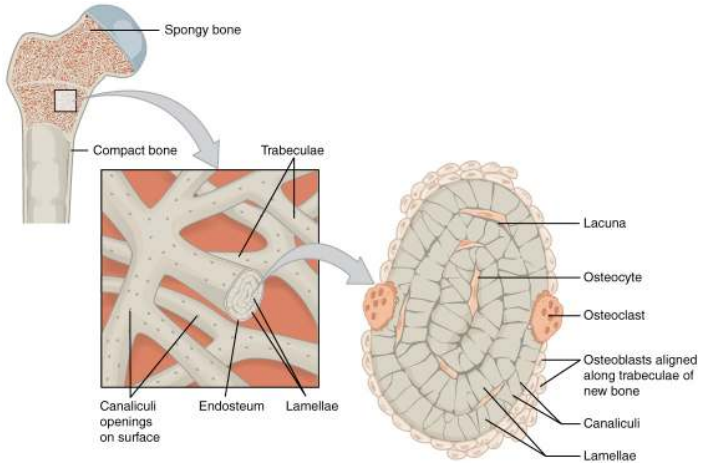



Figure 5.4.7: Diagram of Spongy Bone.Spongy bone is composed of trabeculae that contain the osteocytes. Red marrow fills the spaces in some bones.

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 5.4.8). 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.

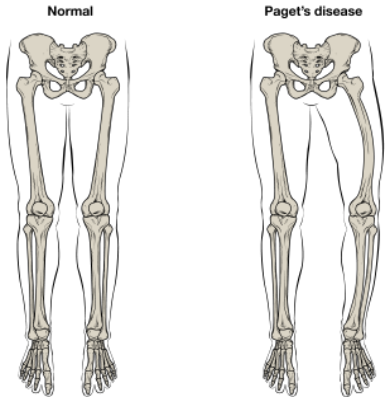



Figure 5.4.8: Paget's Disease.Normal leg bones are relatively straight, but those affected by Paget's disease are porous and curved.

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 risks and complications.

## Chapter 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.

Bone matrix consists of collagen fibers and organic 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: C

Q. The diaphysis contains _____.

A. the metaphysis

B. fat stores

C. spongy bone

D. compact bone

Answer: B

Q. The fibrous membrane covering the outer surface of the bone is the _____.

A. periosteum

B. epiphysis

C. endosteum

D. diaphysis

Answer: A

Q. Which of the following are incapable of undergoing mitosis?

A. osteoblasts and osteoclasts

B. osteocytes and osteoclasts

C. osteoblasts and osteocytes

D. osteogenic cells and osteoclasts

Answer: C

Q. Which cells do not originate from osteogenic cells?

A. osteoblasts

B. osteoclasts

C. osteocytes

D. osteoprogenitor cells

Answer: D

Q. Which of the following are found in compact bone and cancellous bone?

A. Haversian systems

B. Haversian canals

C. lamellae

D. lacunae

Answer: C

Q. Which of the following are *only* found in cancellous bone?

A. canaliculi

B. Volkmann's canals

C. trabeculae

D. calcium salts

Answer: C

## 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?

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?

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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# 5.5: Bone Formation and Development

**Learning Objectives**

- 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. Unlike most connective tissues, cartilage is avascular, meaning that it has no blood vessels supplying nutrients and removing metabolic wastes. All of 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 **5.5.1.*a***). Some of these cells will differentiate into 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 **5.5.1.*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, while osteoblasts on the surface of the spongy bone become the periosteum (Figure **5.5.1.*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 **5.5.1.*d***).

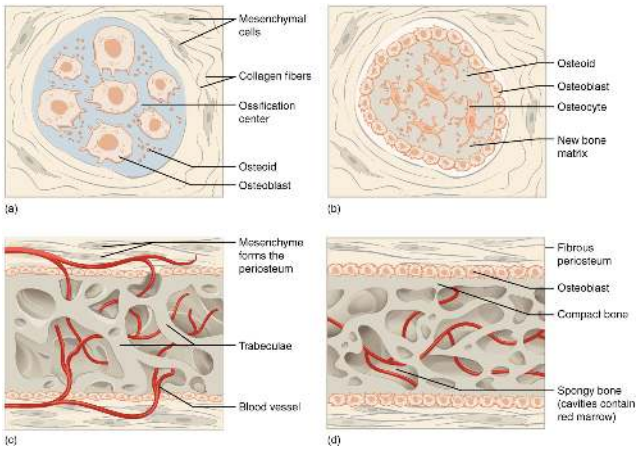



Figure **5.5.1**: Intramembranous Ossification. Intramembranous ossification follows four steps. (a) Mesenchymal cells group into clusters, and ossification centers form. (b) Secreted osteoid traps osteoblasts, which then become osteocytes. (c) Trabecular matrix and periosteum form. (d) Compact bone develops superficial to the trabecular bone, and crowded blood vessels condense into red marrow.

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 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 **5.5.2.*a***). Soon after, the **perichondrium**, a membrane that covers the cartilage, appears Figure **5.5.2.*b***).

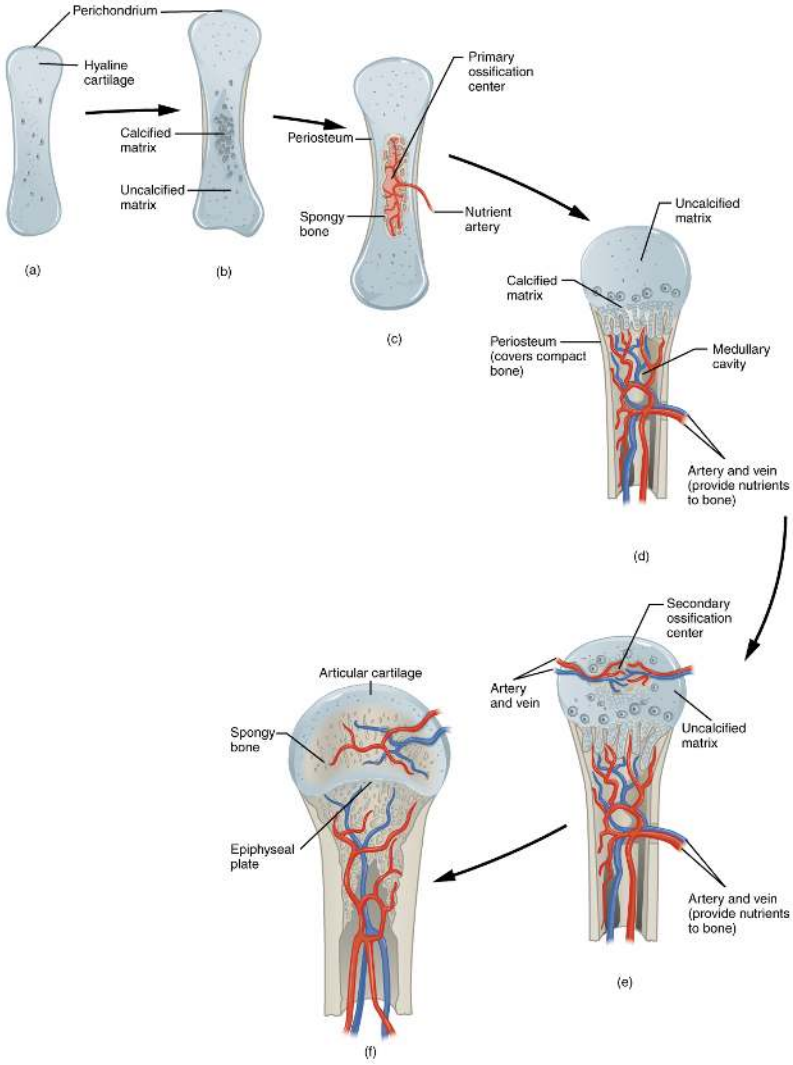



Figure **5.5.2**: Endochondral Ossification.Endochondral ossification follows five steps. (a) Mesenchymal cells differentiate into chondrocytes. (b) The cartilage model of the future bony skeleton and the perichondrium form. (c) Capillaries penetrate cartilage. Perichondrium transforms into periosteum. 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.

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.

As the cartilage grows, capillaries penetrate it. This penetration 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 5.5.2.*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 5.5.2.*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 5.5.3). 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.

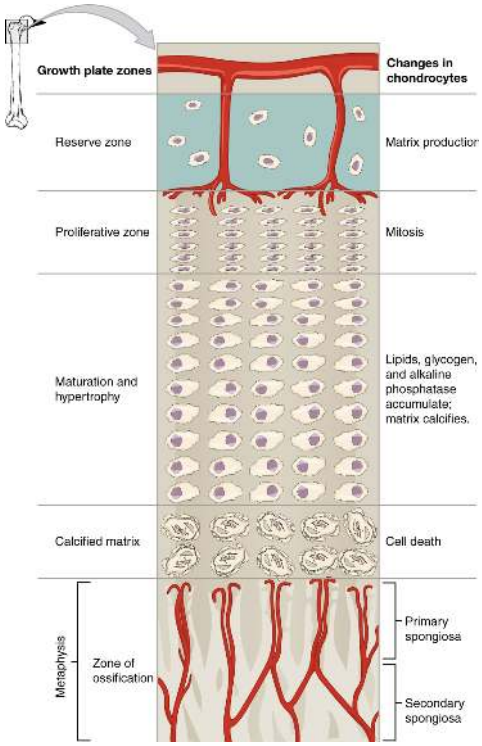



Figure 5.5.3: Longitudinal Bone Growth.The epiphyseal plate is responsible for longitudinal bone growth.

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 5.5.4).

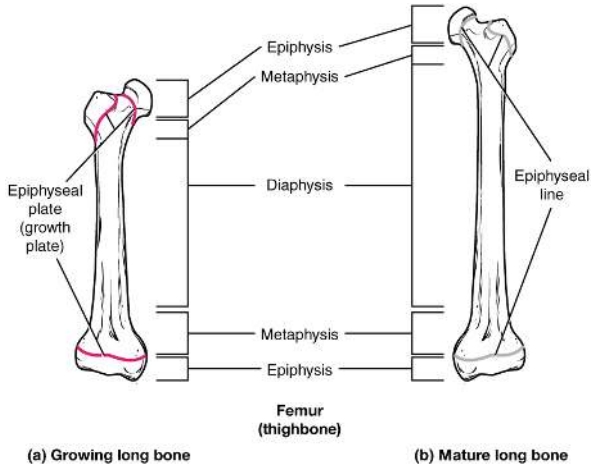



Figure 5.5.4: Progression from Epiphyseal Plate to Epiphyseal Line.As a bone matures, the epiphyseal plate progresses to an epiphyseal line. (a) Epiphyseal plates are visible in a growing bone. (b) Epiphyseal lines are the remnants of epiphyseal plates in a mature bone.

## 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. Osteoclasts resorb old bone that lines the medullary cavity, while osteoblasts, via intramembranous ossification, 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**.

## 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 just 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.

QR Code representing a URL




*Watch this video to see how a bone grows*

## Chapter 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: C

Q. Why are osteocytes spread out in bone tissue?

A. They develop from mesenchymal cells.

B. They are surrounded by osteoid.

C. They travel through the capillaries.

D. Formation of osteoid spreads out the osteoblasts that formed the ossification centers.

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: 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: D

Q. Bones grow in length due to activity in the _____.

A. epiphyseal plate

B. perichondrium

C. periosteum

D. medullary cavity

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: 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: C

## Critical Thinking Questions

Q. In what ways do intramembranous and endochondral ossification differ?

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?

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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# 5.6: Fractures - Bone Repair

**Learning Objectives**

- 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 **5.6.1**). Table **5.6.1** 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).

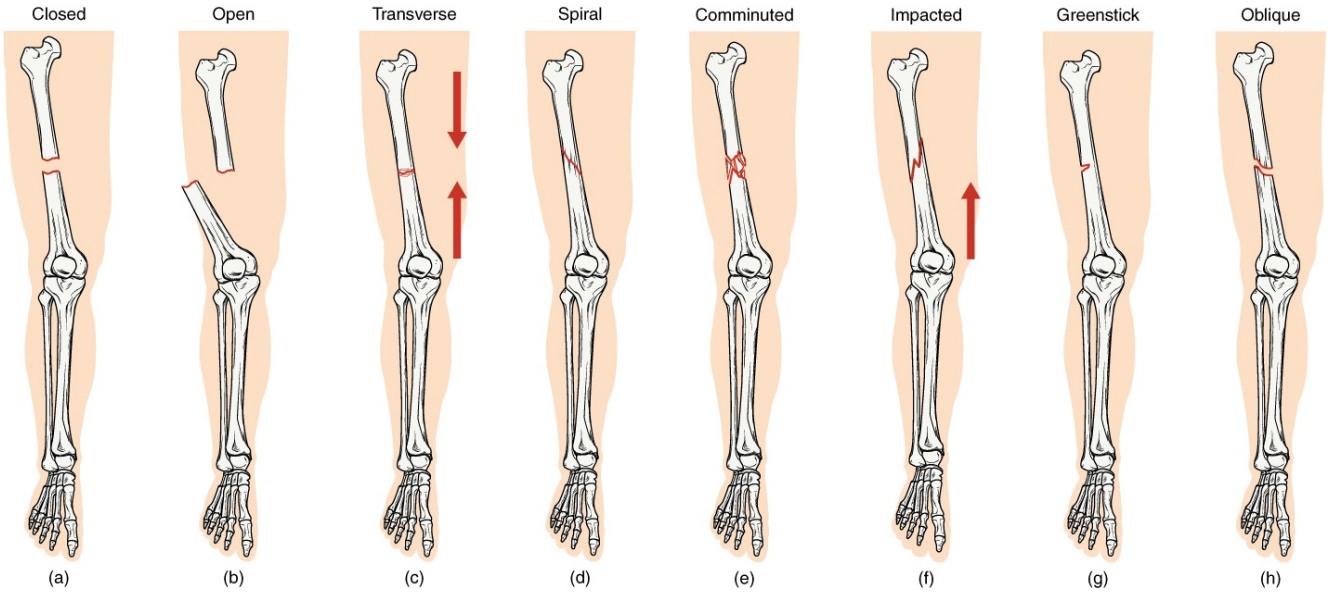



***Figure* 5.6.1*:*** *Types of Fractures. Compare healthy bone with different types of fractures: (a) closed fracture, (b) open fracture, (c) transverse fracture, (d) spiral fracture, (e) comminuted fracture, (f) impacted fracture, (g) greenstick fracture, and (h) oblique fracture.*

Table **5.6.1**: 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 |
| 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 5.6.2.*a*). The disruption of blood flow to the bone results in the death of bone cells around the fracture.

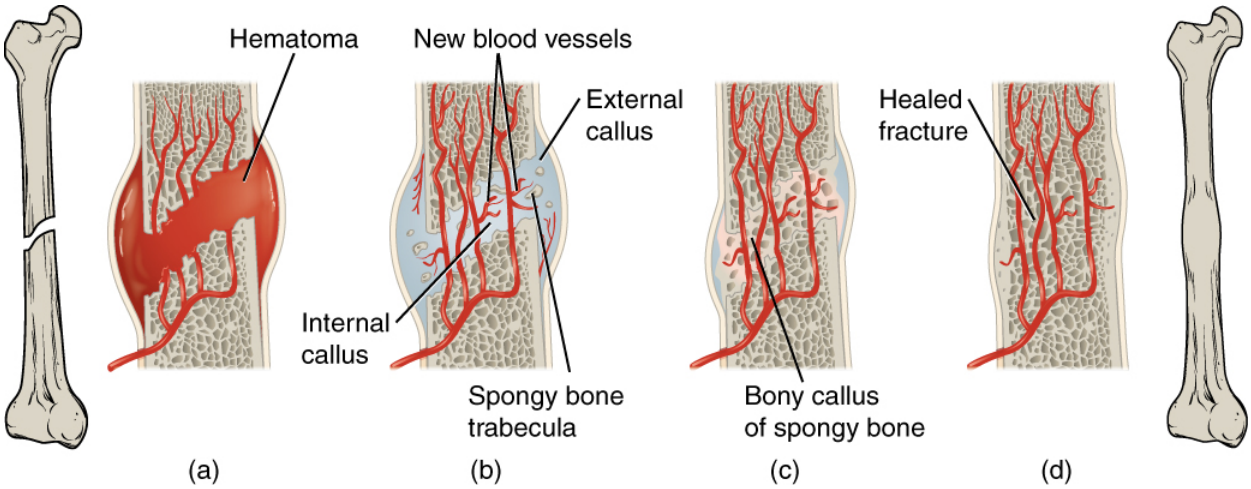



Figure 5.6.2: Stages in Fracture Repair. The healing of a bone fracture follows a series of progressive steps: (a) A fracture hematoma forms. (b) Internal and external calli form. (c) Cartilage of the calli is replaced by trabecular bone. (d) Remodeling occurs.

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 5.6.2.*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 5.6.2.*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 5.6.2.d), and no external evidence of the fracture remains.

*Visit this website to review different types of fractures and then take a short self-assessment quiz.*

## Chapter 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: 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: 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: D

Q. The internal and external calli are replaced by _____.

A. hyaline cartilage

B. trabecular bone

C. osteogenic cells

D. osteoclasts

Answer: B

Q. The first type of bone to form during fracture repair is _____ bone.

A. compact

B. lamellar

C. spongy

D. dense

> 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?

> 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?

> 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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# CHAPTER OVERVIEW

## 6: Axial Skeleton

The axial skeleton is the part of the skeleton that consists of the bones of the head and trunk of a vertebrate. It consists of 80 bones and is composed of six parts: the skull bones, the ossicles of the middle ear, the hyoid bone, the rib cage, sternum and the vertebral column.


6.1: Introduction to the Axial Skeleton
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 Axial Skeleton

**Chapter Objectives**

- 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

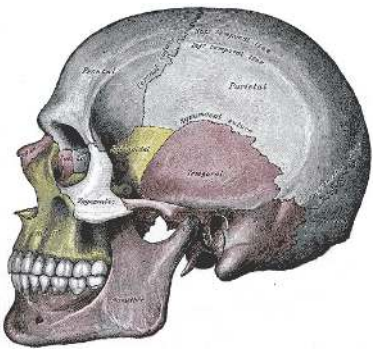


Figure **6.1.1**: Lateral View of the Human Skull.

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. Providing movement of the skeleton are the muscles of the body, which are firmly attached to the skeleton 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

**Learning Objectives**

- Discuss the functions of the skeletal system
- Distinguish between 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 skeleton is subdivided into two major divisions—the axial and appendicular. 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 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.

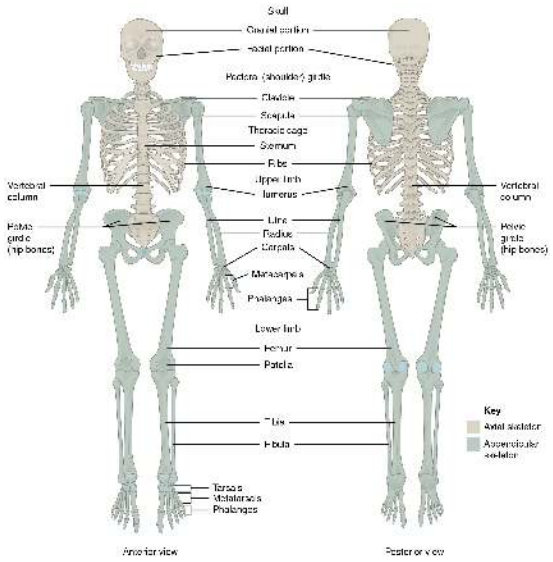



Figure **6.2.1**: Axial and Appendicular Skeleton. The axial skeleton supports the head, neck, back, and chest and thus forms the vertical axis of the body. It consists of the skull, vertebral column (including the sacrum and coccyx), and the thoracic cage, formed by the ribs and sternum. The appendicular skeleton is made up of all bones of the upper and lower limbs.

## 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 of the appendicular skeleton are covered in a separate chapter.

## Chapter 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: 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: 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: B

## Critical Thinking Question

Q. Define the two divisions of the skeleton.

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.

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

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# 6.3: The Skull

**Learning Objectives**

- 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.

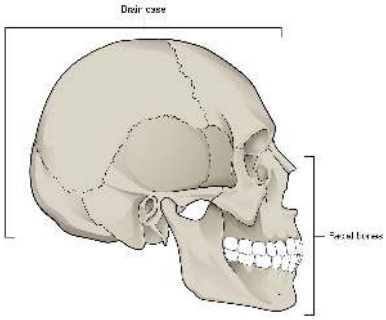
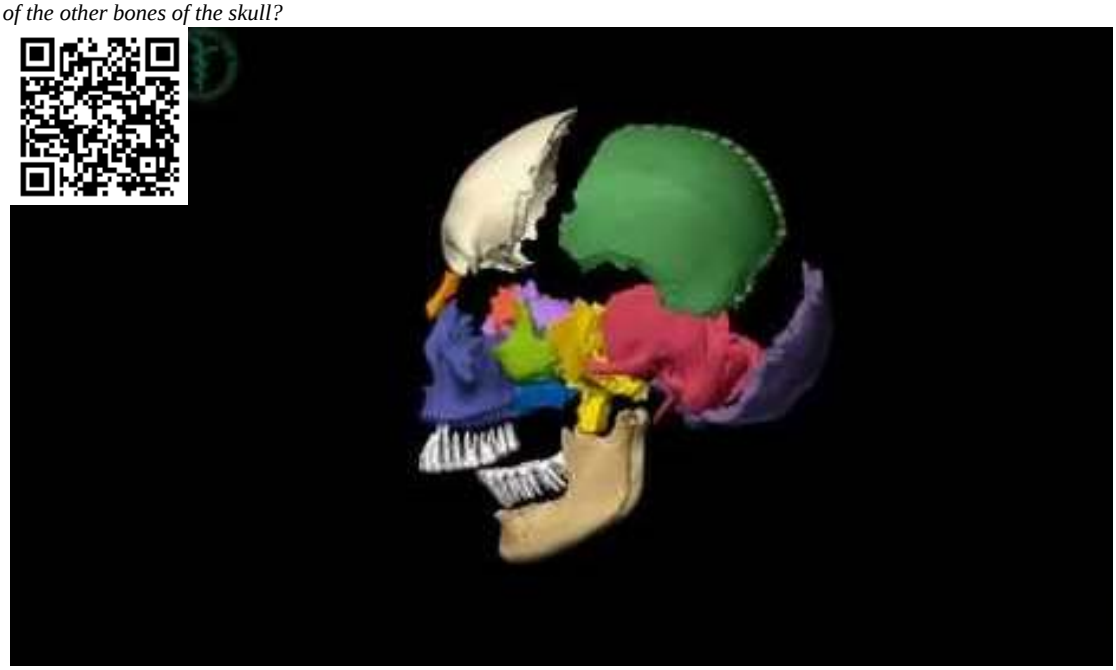



Figure **6.3.1**: Parts of the Skull. The skull consists of the rounded brain case that houses the brain and the facial bones that form the upper and lower jaws, nose, orbits, and other facial structures.

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?*



## 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 is dominated by the openings of the orbits and the nasal cavity. Also seen are the upper and lower jaws, with their respective teeth (Figure **6.3.2**).

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 supplies the anterior face below the orbit.

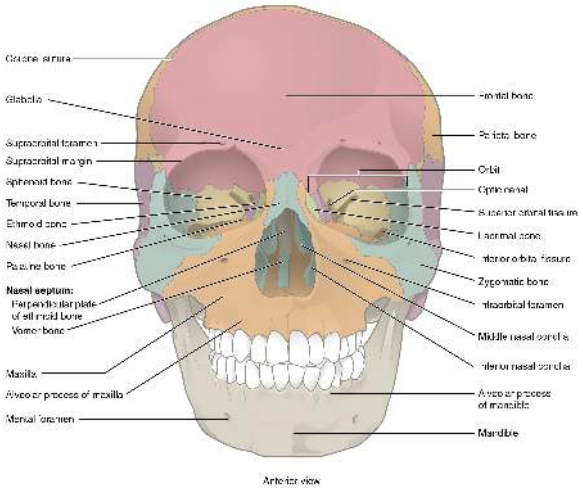



Figure **6.3.2**: Anterior View of Skull. An anterior view of the skull shows the bones that form the forehead, orbits (eye sockets), nasal cavity, nasal septum, and upper and lower jaws.

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 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. Located just above the inferior concha is the **middle nasal concha**, which is part of the ethmoid bone. A third bony plate, also part of the ethmoid bone, is the **superior nasal concha**. It is much smaller and out of sight, above the middle concha. The superior nasal concha is located just lateral to the perpendicular plate, in the upper nasal cavity.

## 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.

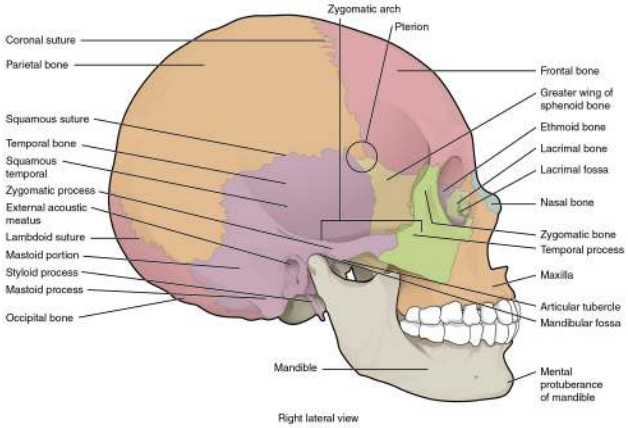



Figure **6.3.3**: Lateral View of Skull. The lateral skull shows the large rounded brain case, zygomatic arch, and the upper and lower jaws. The zygomatic arch is formed jointly by the zygomatic process of the temporal bone and the temporal process of the zygomatic bone. The shallow space above the zygomatic arch is the temporal fossa. The space inferior to the zygomatic arch and deep to the posterior mandible is the infratemporal fossa.

## 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 bounded superiorly by the rounded top of the skull, which is called the **calvaria** (skullcap), and the lateral and posterior sides of the skull. The bones that form the top and sides of the brain case are usually referred to as the "flat" bones of the skull.

The floor of the brain case 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 **6.3.4**). From anterior to posterior, the fossae increase in depth. The shape and depth of each fossa corresponds to the shape and size of the brain region that each houses. The boundaries and openings of the cranial fossae (singular = fossa) will be described in a later section.

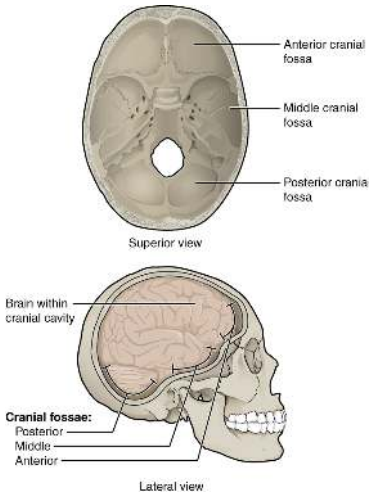



Figure **6.3.4**: Cranial Fossae. The bones of the brain case surround and protect the brain, which occupies the cranial cavity. The base of the brain case, which forms the floor of cranial cavity, is subdivided into the shallow anterior cranial fossa, the middle cranial fossa, and the deep posterior cranial fossa.

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 of the skull (see 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 bounded 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 (see 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 **6.3.5**). 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. Located inside each petrous ridge are small cavities that house the structures of the middle and inner ears.

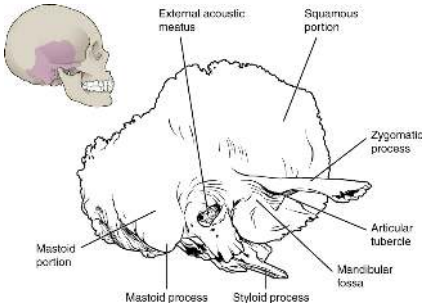



Figure **6.3.5**: Temporal Bone.A lateral view of the isolated temporal bone shows the squamous, mastoid, and zygomatic portions of the temporal bone.

Important landmarks of the temporal bone, as shown in Figure **6.3.6**, 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. (See also Figure **6.3.5**)
- **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.

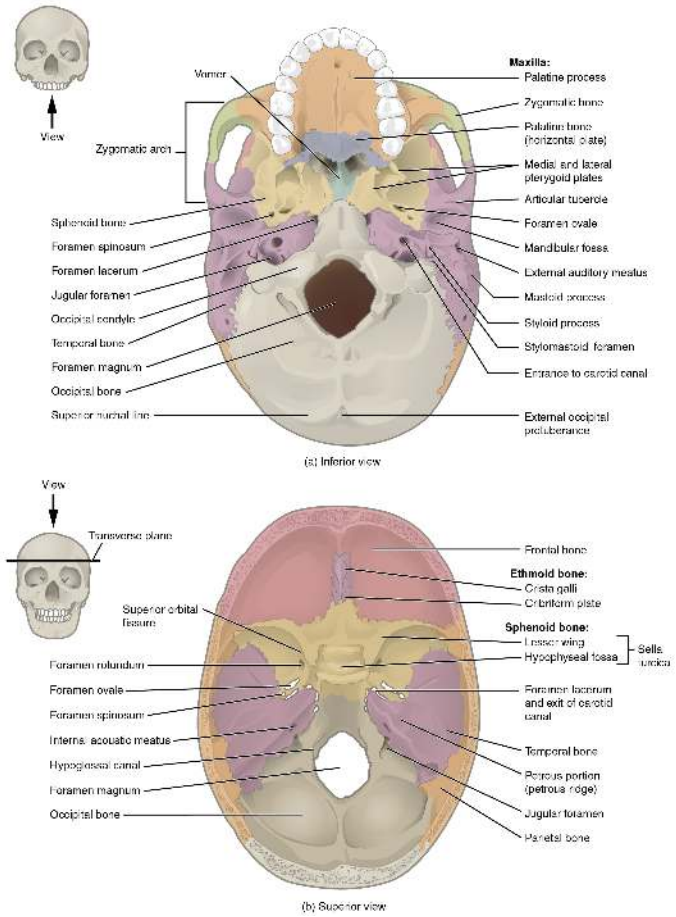



Figure **6.3.6**: External and Internal Views of Base of Skull. (a) The hard palate is formed anteriorly by the palatine processes of the maxilla bones and posteriorly by the horizontal plate of the palatine bones. (b) The complex floor of the cranial cavity is formed by the frontal, ethmoid, sphenoid, 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.

## Frontal Bone

The **frontal bone** is the single bone that forms the forehead. At its anterior midline, between the eyebrows, there is a slight depression called the **glabella** (see Figure **6.3.3**). 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. 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 the floor of the anterior cranial cavity above (see Figure **6.3.6.*b***).

## Occipital Bone

The **occipital bone** is the single bone that forms the posterior skull and posterior base of the cranial cavity (Figure **6.3.7**; see also Figure **6.3.6**). On its outside 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. 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.

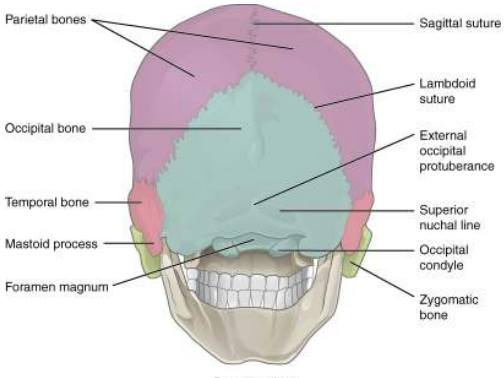



Figure **6.3.7**: Posterior View of Skull. This view of the posterior skull shows attachment sites for muscles and joints that support the skull.

## Sphenoid Bone

The **sphenoid bone** is a single, complex bone of the central skull (Figure **6.3.8**). 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 (see Figure **6.3.6**) and also extends laterally to contribute to the sides of the skull (see 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. The **sella turcica** ("Turkish saddle") is located at the midline of the middle cranial fossa. 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.

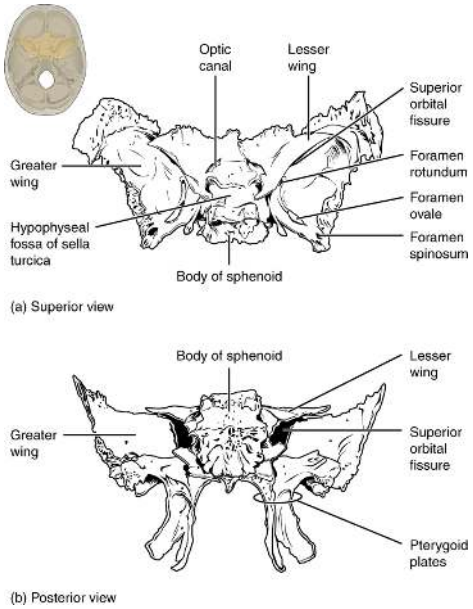



Figure **6.3.8**: Sphenoid Bone. Shown in isolation in (a) superior and (b) posterior views, the sphenoid bone is a single midline bone that forms the anterior walls and floor of the middle cranial fossa. It has a pair of lesser wings and a pair of greater wings. The sella turcica surrounds the hypophyseal 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.

## 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 **6.3.9** and Figure **6.3.10**). On the interior of the skull, the ethmoid also forms a portion of the floor of the anterior cranial cavity (see Figure **6.3.6*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 **6.3.11**).

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 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 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.

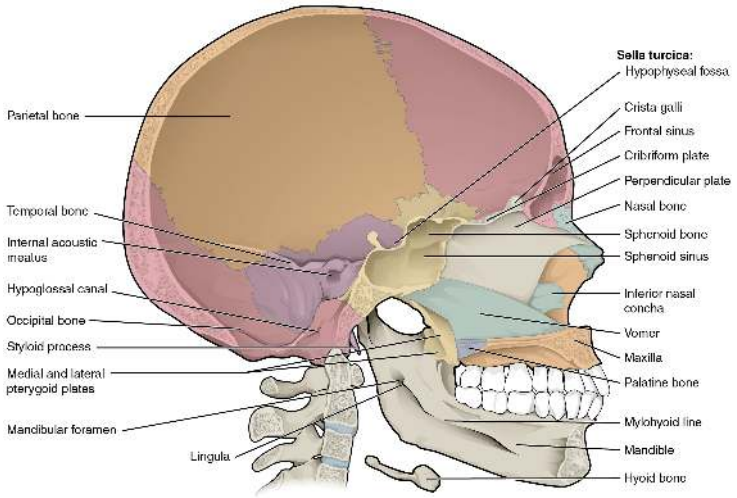



Figure **6.3.9**: Sagittal Section of Skull. This midline view of the sagittally sectioned skull shows the nasal septum.

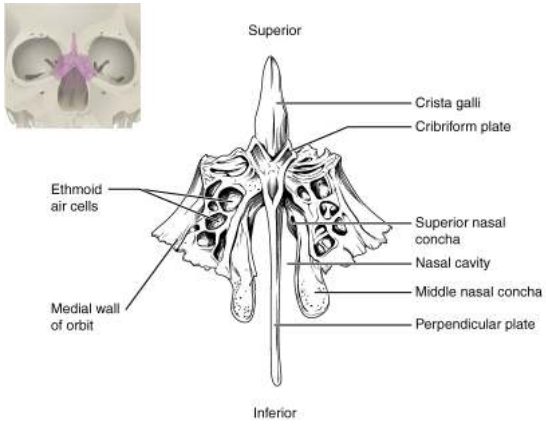



Figure **6.3.10**: Ethmoid Bone. The unpaired ethmoid bone is located at the midline within the central skull. It has an upward projection, the crista galli, and a downward projection, the perpendicular plate, which forms the upper nasal septum. The cribriform plates form both the roof of the nasal cavity 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.

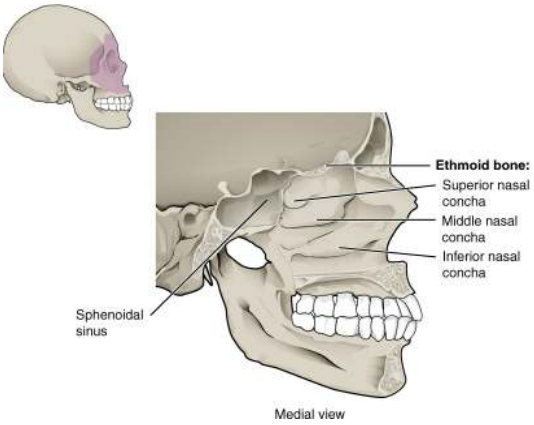



Figure **6.3.11**: Lateral Wall of Nasal Cavity. The three nasal conchae are curved bones that project from the lateral walls of the nasal cavity. The superior nasal concha and middle nasal concha are parts of the ethmoid bone. The inferior nasal concha is an independent bone of the skull.

## 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, fibrous 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.

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 (see Figure **6.3.3**). 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 (see Figure **6.3.7**). 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 (see Figure **6.3.3**). 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.

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. A strong blow to this region can fracture the bones around the pterion. 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.

QR Code representing a URL

*View this animation to see how a blow to the head may produce a contrecoup (counterblow) fracture of the basilar portion of the occipital bone on the base of the skull. Why may a basilar fracture be life threatening?*

## 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 **6.3.12**). 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 **6.3.6.*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.

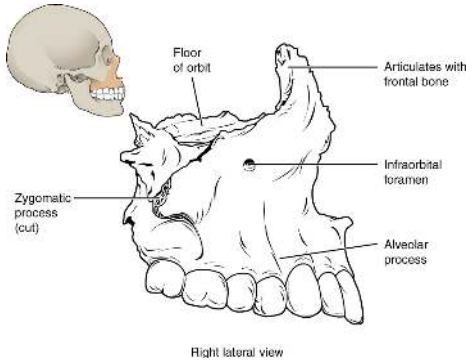



Figure **6.3.12**: Maxillary Bone. The maxillary bone forms the upper jaw and supports the upper teeth. Each maxilla also forms the lateral floor of each orbit and the majority of the hard palate.

### 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 **6.3.6.*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 (see Figure **6.3.2**). The short temporal process of the zygomatic bone projects posteriorly, where it forms the anterior portion of the zygomatic arch (see 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 (see 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 (see 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 (see 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 **6.3.6.*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 **6.3.13**).

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 for the mandible 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 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.

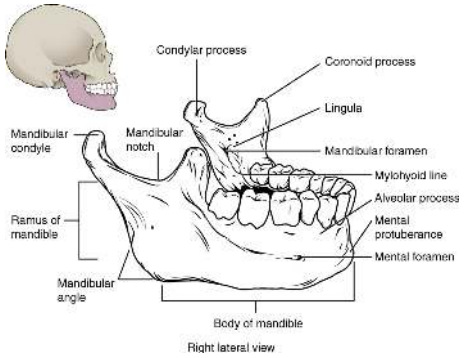



Figure **6.3.13**: Isolated Mandible. The mandible is the only moveable bone of the skull.

## 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 **6.3.14**). 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**, 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, which provides passage for the artery that supplies the eyeball, sensory nerves, and the nerves that supply the muscles involved in eye movements.

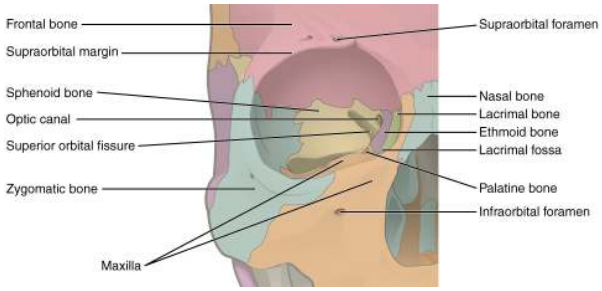



Figure **6.3.14**: Bones of the Orbit. Seven skull bones contribute to the walls of the orbit. Opening into the posterior orbit from the cranial cavity are the optic canal and superior orbital fissure.

## The Nasal Septum and Nasal Conchae

The **nasal septum** consists of both bone and cartilage components (Figure **6.3.15**; 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.

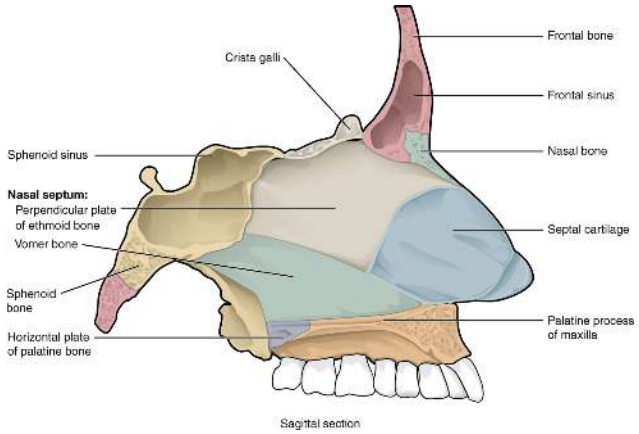



Figure **6.3.15**: Nasal Septum. The nasal septum is formed by the perpendicular plate of the ethmoid bone and the vomer bone. The septal cartilage fills the gap between these bones and extends into the nose.

## Cranial Fossae

Inside the skull, the floor of the cranial cavity is subdivided into three cranial fossae (spaces), which increase in depth from anterior to posterior (see Figure **6.3.4**, Figure **6.3.6*b***, and Figure **6.3.9**). 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.

### 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 (see Figure **6.3.6**).

Openings in the middle cranial fossa are as follows:

- **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.
- **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.

## Paranasal Sinuses

The **paranasal sinuses** are hollow, air-filled spaces located within certain bones of the skull (Figure **6.3.16**). 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 (see Figure **6.3.15**). 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.

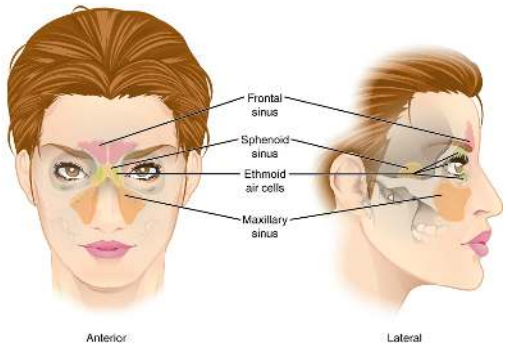



Figure **6.3.16**: Paranasal Sinuses. The paranasal sinuses are hollow, air-filled spaces named for the skull bone that each occupies. The most anterior is the frontal sinus, located in the frontal bone above the eyebrows. The largest are the maxillary sinuses, located in the right and left maxillary 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.

## Hyoid Bone

The hyoid bone is an independent bone that does not contact any other bone and thus is not part of the skull (Figure **6.3.17**). 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.

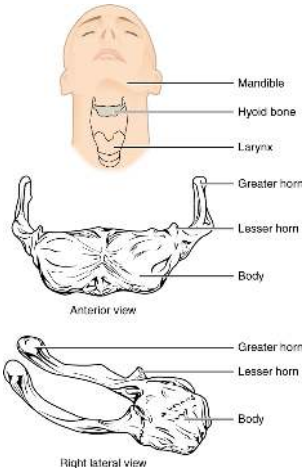



Figure **6.3.17**: Hyoid Bone. The hyoid bone is located in the upper neck and does not join with any other bone. It provides attachments for muscles that act on the tongue, larynx, and pharynx.

## Chapter 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.

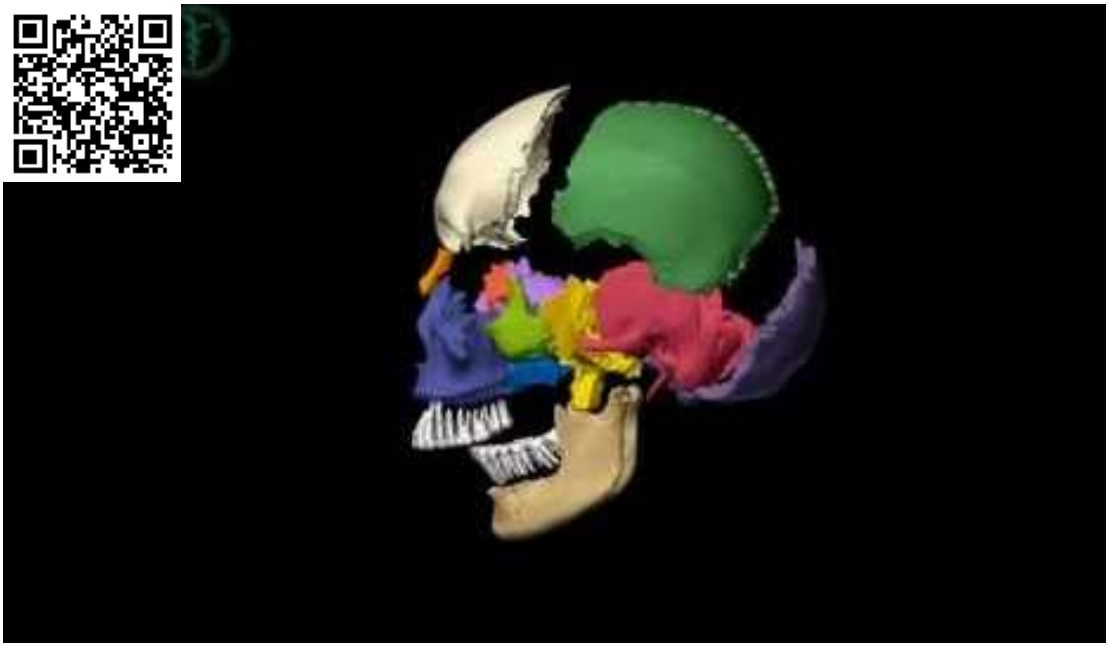
The anterior skull has the orbits that house the eyeballs and associated muscles. The walls of the orbit are formed by contributions from seven bones: the frontal, zygomatic, maxillary, palatine, ethmoid, lacrimal, and sphenoid. Located at the superior margin of the orbit is the supraorbital foramen, 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.

## Interactive Link Questions

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: 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.

View this animation to see how a blow to the head may produce a contrecoup (counterblow) fracture of the basilar portion of the occipital bone on the base of the skull. Why may a basilar fracture be life threatening?

Answer: A basilar fracture may damage an artery entering the skull, causing bleeding in the brain.

## 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: 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: 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: 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: A

Q. Parts of the sphenoid bone include the _____.

A. sella turcica

B. squamous portion

C. glabella

D. zygomatic process

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: D

## Critical Thinking Questions

Q. Define and list the bones that form the brain case or support the facial structures.

> 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.

> 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.

> 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.

> 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

Centers for Disease Control and Prevention (US). Injury prevention and control: traumatic brain injury [Internet]. Atlanta, GA; [cited 2013 Mar 18]. Available from: http://www.cdc.gov/traumaticbraininjury/statistics.html.

## 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

**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 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

**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

**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 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

**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 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 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

**Learning Objectives**

- 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**. 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.

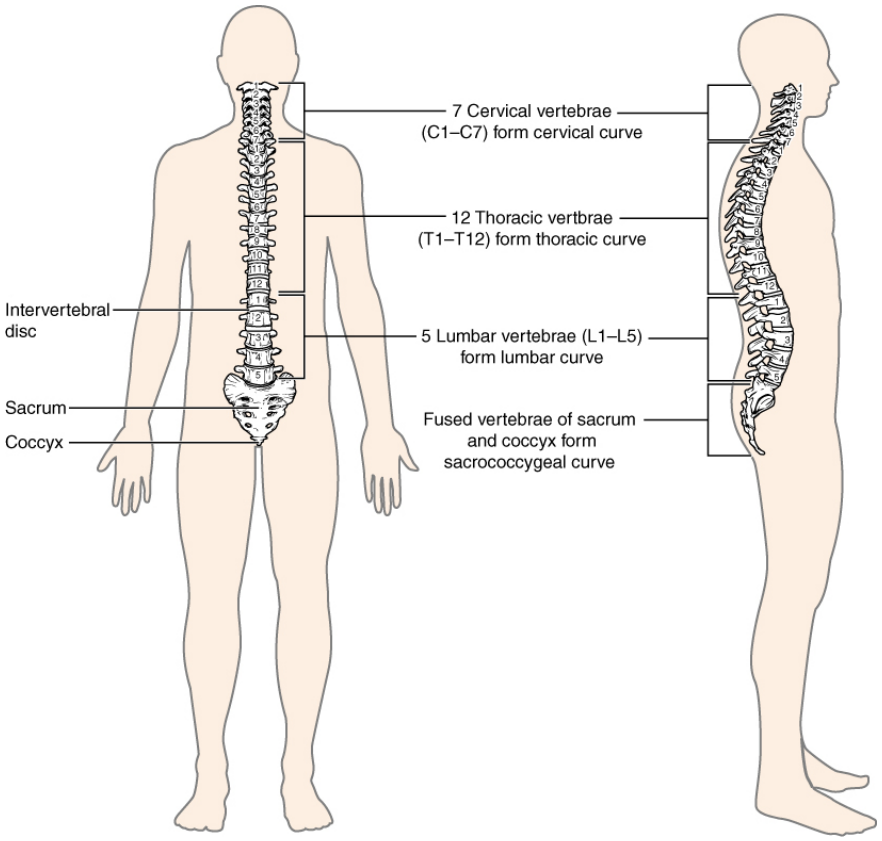



***Figure 6.4.1: Vertebral Column.*** *The adult vertebral column consists of 24 vertebrae, plus the sacrum and coccyx. The vertebrae are divided into three regions: cervical C1–C7 vertebrae, thoracic T1–T12 vertebrae, and lumbar L1–L5 vertebrae. The vertebral column is curved, with two primary curvatures (thoracic and sacrococcygeal curves) and two secondary curvatures (cervical and lumbar curves).*

## 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 skull. Inferiorly, C1 articulates with the C2 vertebra, and so on. Below these 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 not completed until middle age.

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.

Disorders associated with the curvature of the spine include **kyphosis** (an excessive posterior curvature of the thoracic region), **lordosis** (an excessive anterior curvature of the lumbar region), and **scoliosis** (an abnormal, lateral curvature, accompanied by twisting of the vertebral column).

### 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.

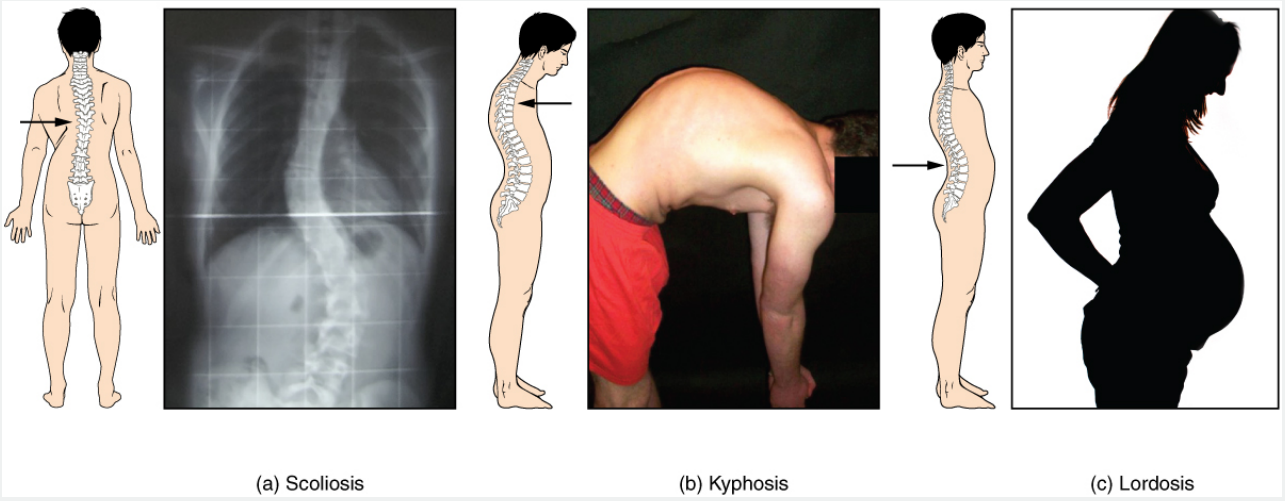



***Figure 6.4.2: Abnormal Curvatures of the Vertebral Column.*** *(a) Scoliosis is an abnormal lateral bending of the vertebral column. (b) An excessive curvature of the upper thoracic vertebral column is called kyphosis. (c) Lordosis is an excessive curvature in the lumbar region of the vertebral column.*

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.

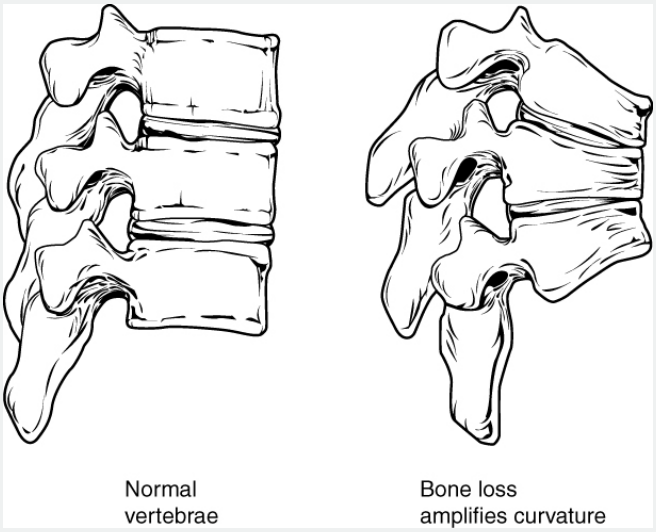



***Figure 6.4.3: Osteoporosis.*** *Osteoporosis is an age-related disorder that causes the gradual loss of bone density and strength. When the thoracic vertebrae are affected, there can be a gradual collapse of the vertebrae. This results in kyphosis, an excessive curvature of the thoracic region.*

*Osteoporosis is a common age-related bone disease in which bone density and strength is decreased. Watch this video to get a better understanding of how thoracic vertebrae may become weakened and may fracture due to this disease. How may vertebral osteoporosis contribute to kyphosis?*

## 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.

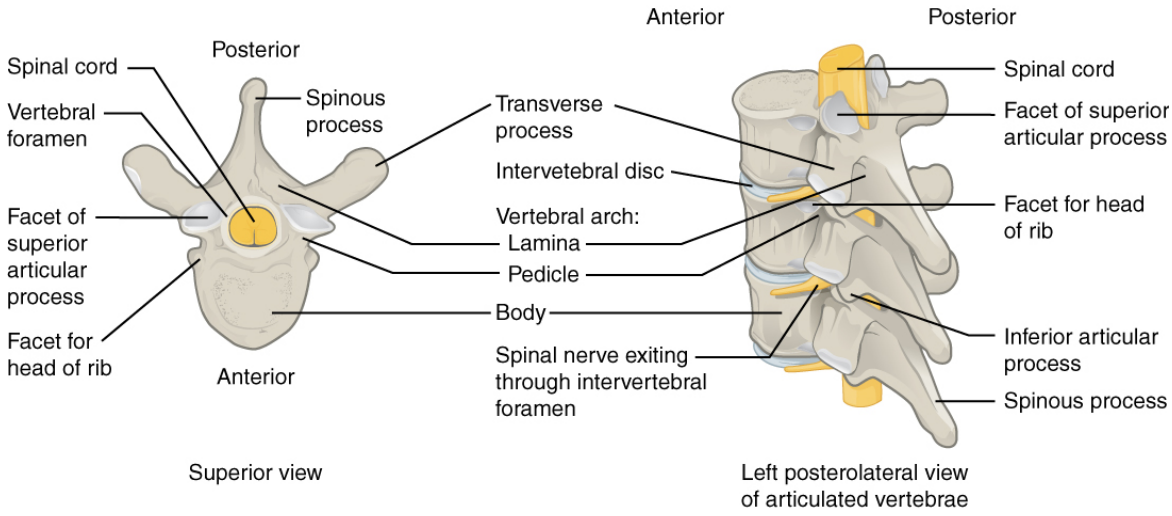



***Figure 6.4.4: Parts of a Typical Vertebra.*** *A typical vertebra consists of a body and a vertebral arch. The arch is formed by the paired pedicles and paired laminae. Arising from the vertebral arch are the transverse, spinous, superior articular, and inferior articular processes. The vertebral 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.*

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 (Figure **6.4.5**).

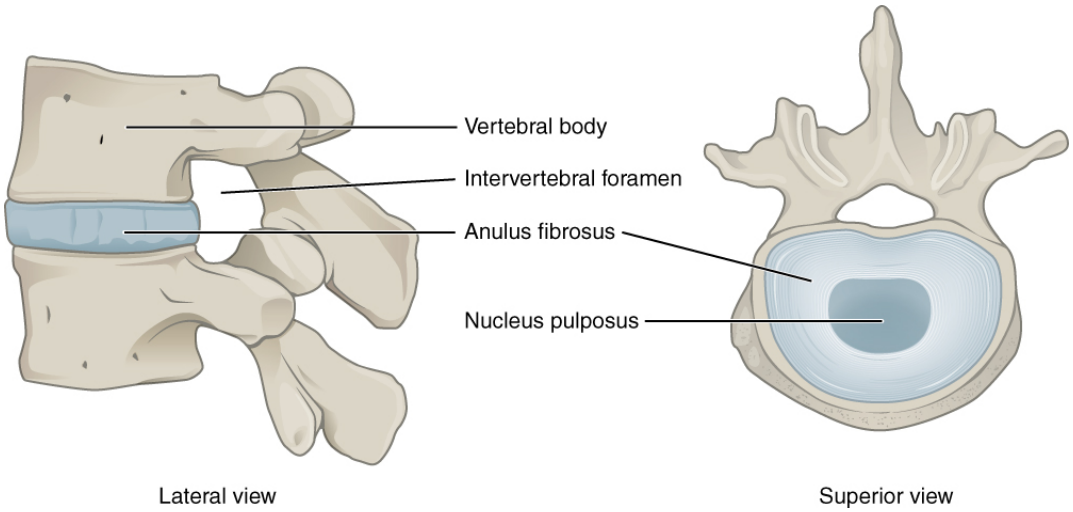



Figure **6.4.5**: Intervertebral Disc. The bodies of adjacent vertebrae are separated and united by an intervertebral disc, which provides padding and allows for movements between adjacent vertebrae. The disc consists of a fibrous outer layer called the anulus fibrosus and a gel-like center called the nucleus pulposus. The intervertebral foramen is the opening formed between adjacent vertebrae for the exit of a spinal nerve.

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. 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. Thus, cervical vertebrae are smaller than lumbar vertebrae due to differences in the proportion of body weight that each supports. 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 C4 or C5, have several characteristic features that differentiate them from thoracic or lumbar vertebrae (Figure **6.4.6**). 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. 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.

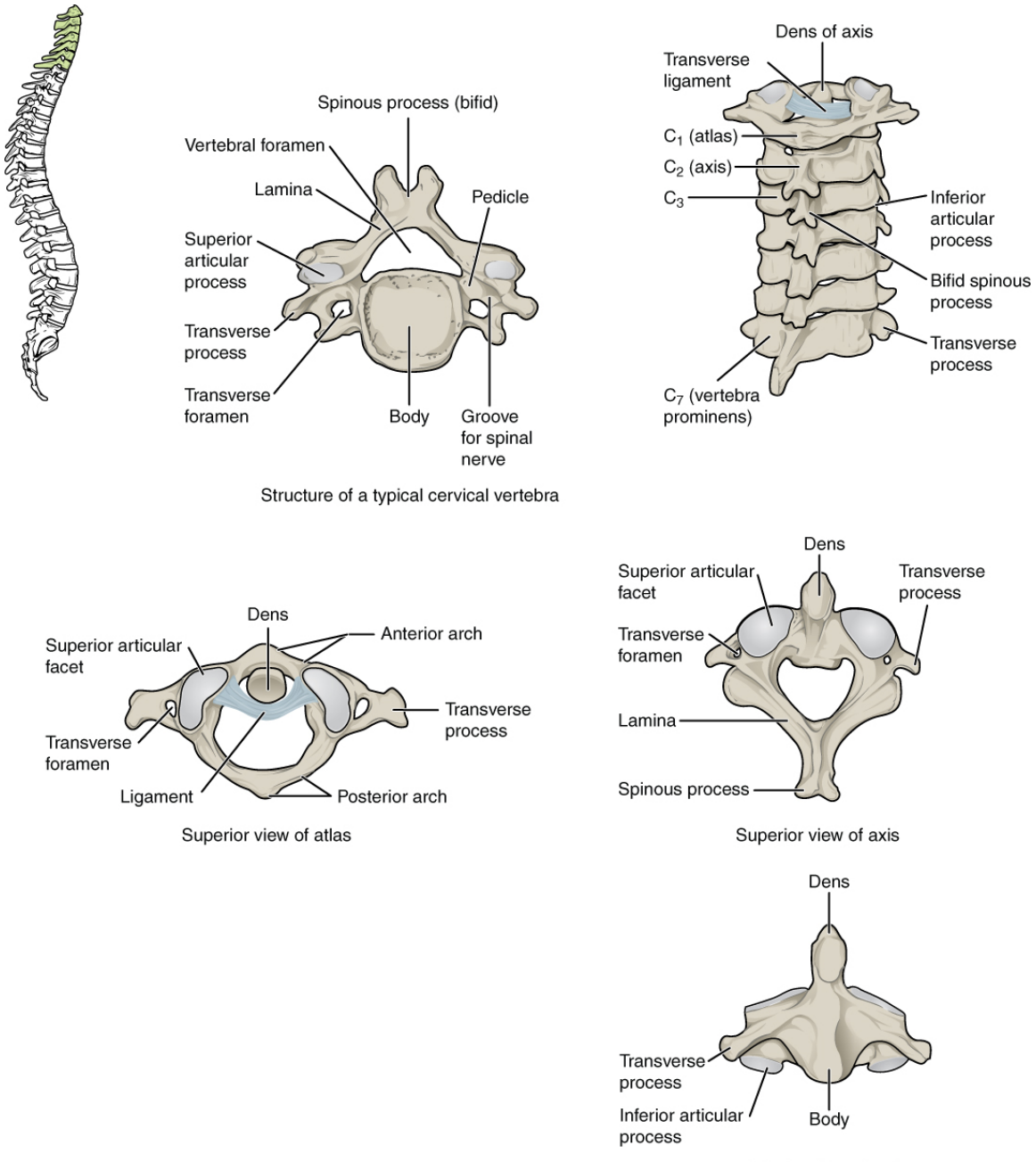



Figure **6.4.6**: Cervical Vertebrae. A typical cervical vertebra has a small body, a bifid spinous process, transverse processes that have a transverse foramen and are curved for spinal nerve passage. The atlas (C1 vertebra) does not have a body or spinous process. It consists of an anterior and a posterior arch and elongated transverse processes. The axis (C2 vertebra) has the upward projecting dens, which articulates with the anterior arch of the atlas.

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 **6.4.7**). 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.

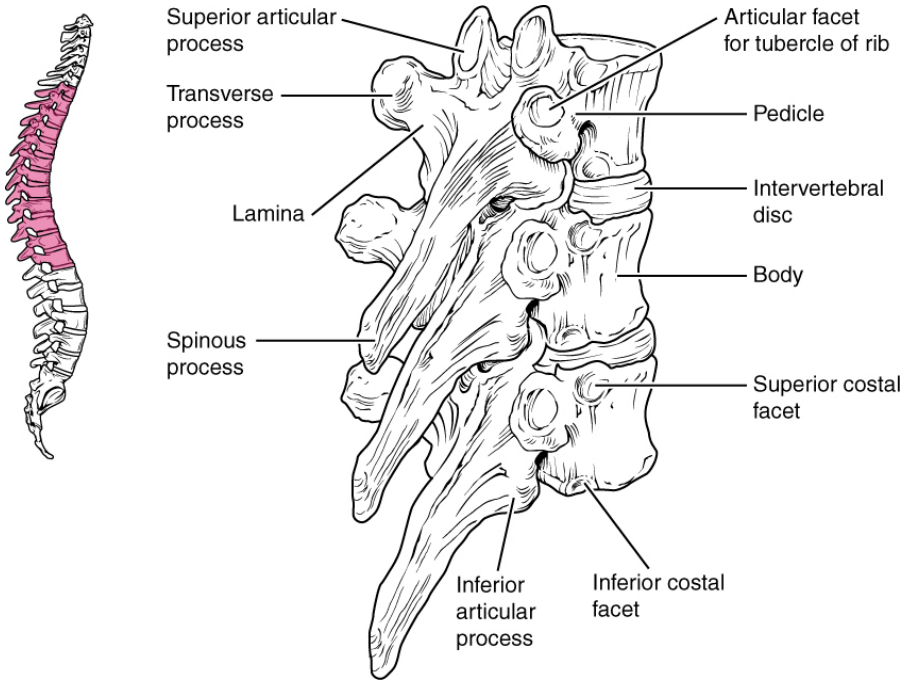



Figure **6.4.7**: Thoracic Vertebrae. A typical thoracic vertebra is distinguished by the spinous process, which is long and projects downward to overlap the next inferior vertebra. It also has articulation sites (facets) on the vertebral body and a transverse process for rib attachment.

Thoracic vertebrae have several additional articulation sites, each of which is called a **facet**, where a rib is attached. Most thoracic vertebrae have two facets 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.

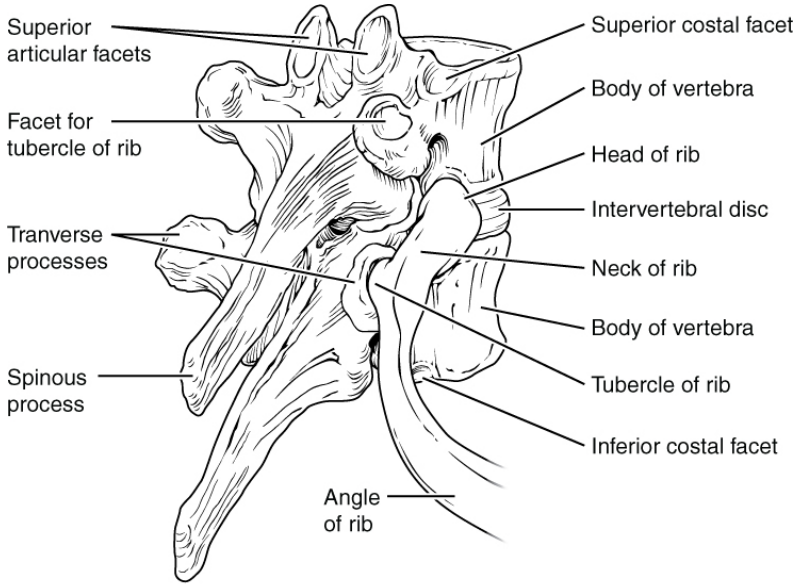



Figure **6.4.8**: Rib Articulation in Thoracic Vertebrae. Thoracic vertebrae have superior and inferior articular facets on the vertebral body for articulation with the head of a rib, and a transverse process facet for articulation with the rib tubercle.

## 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 **6.4.9**). 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.

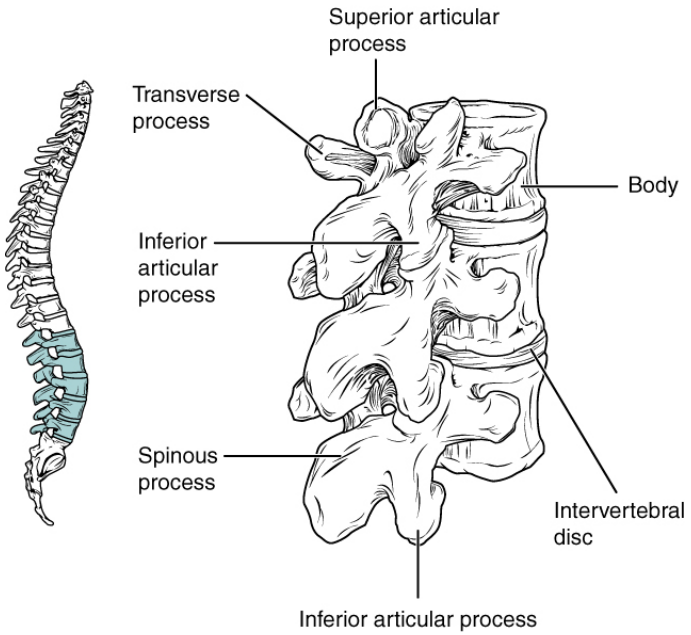



Figure **6.4.9**: Lumbar Vertebrae. Lumbar vertebrae are characterized by having a large, thick body and a short, rounded spinous process.

## 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 **6.4.10**). It is formed by the fusion of five sacral vertebrae, a process that does not begin until after the age of 20. 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 **6.4.10**). 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.

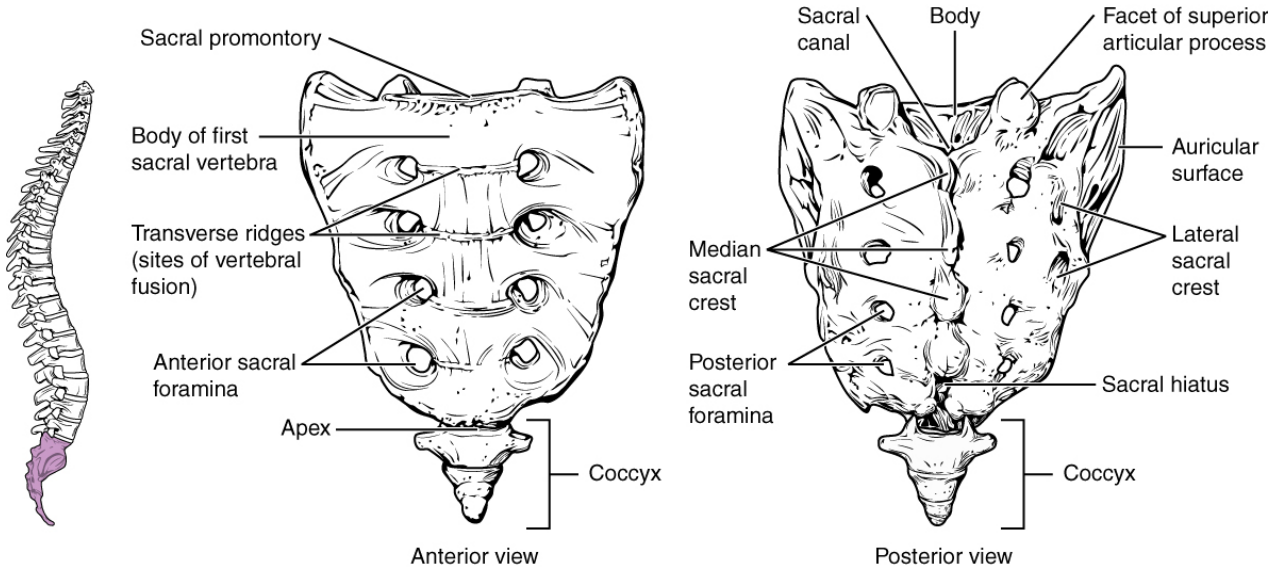



***Figure* 6.4.10*: Sacrum and Coccyx.*** *The sacrum is formed from the fusion of five sacral vertebrae, whose lines of fusion are indicated by the transverse ridges. The fused spinous processes form the median sacral crest, while the lateral sacral crest arises from the fused transverse processes. The coccyx is formed by the fusion of four small coccygeal vertebrae.*

## 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 during weight bearing, 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 (see Figure **6.4.5**). Each disc is anchored to the bodies of its adjacent vertebrae, thus strongly uniting these. 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.

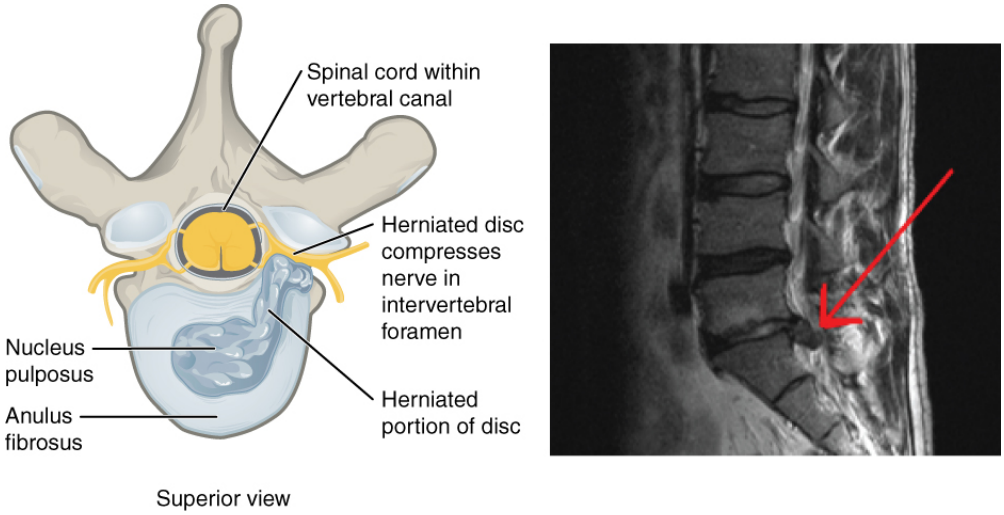



***Figure* 6.4.11*: Herniated Intervertebral Disc.*** *Weakening of the anulus fibrosus can result in herniation (protrusion) of the nucleus pulposus and compression of a spinal nerve, resulting in pain and/or muscle weakness in the body regions supplied by that nerve.*

Note

*Watch this animation to see what it means to "slip" a disk. Watch this second animation to see one possible treatment for a herniated disc, removing and replacing the damaged disc with an artificial one that allows for movement between the adjacent certebrae. How could lifting a heavy object produce pain in a lower limb?*

## 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.

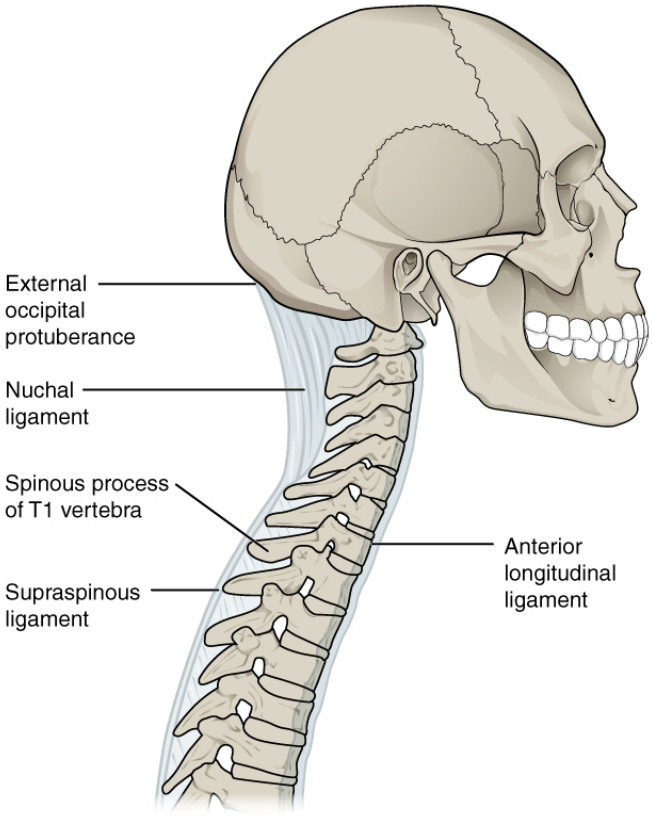



Figure **6.4.12**: Ligaments of Vertebral Column. The anterior longitudinal ligament runs the length of the vertebral column, uniting the anterior sides of the vertebral bodies. The supraspinous ligament connects the spinous processes of the thoracic and lumbar vertebrae. In the posterior neck, the supraspinous ligament enlarges to form the nuchal ligament, which attaches to the cervical spinous processes and to the base of the skull.

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.

*Use this tool 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?*

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.

## Chapter 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.

## Interactive Link Questions

Osteoporosis is a common age-related bone disease in which bone density and strength is decreased. Watch this video to get a better understanding of how thoracic vertebrae may become weakened and may fractured due to this disease. How may vertebral osteoporosis contribute to kyphosis?

Answer: Osteoporosis causes thinning and weakening of the vertebral bodies. When this occurs in thoracic vertebrae, the bodies may collapse producing kyphosis, an enhanced anterior curvature of the thoracic vertebral column.

Watch this animation to see what it means to “slip” a disk. Watch this second animation to see one possible treatment for a herniated disc, removing and replacing the damaged disc with an artificial one that allows for movement between the adjacent certebrae. How could lifting a heavy object produce pain in a lower limb?

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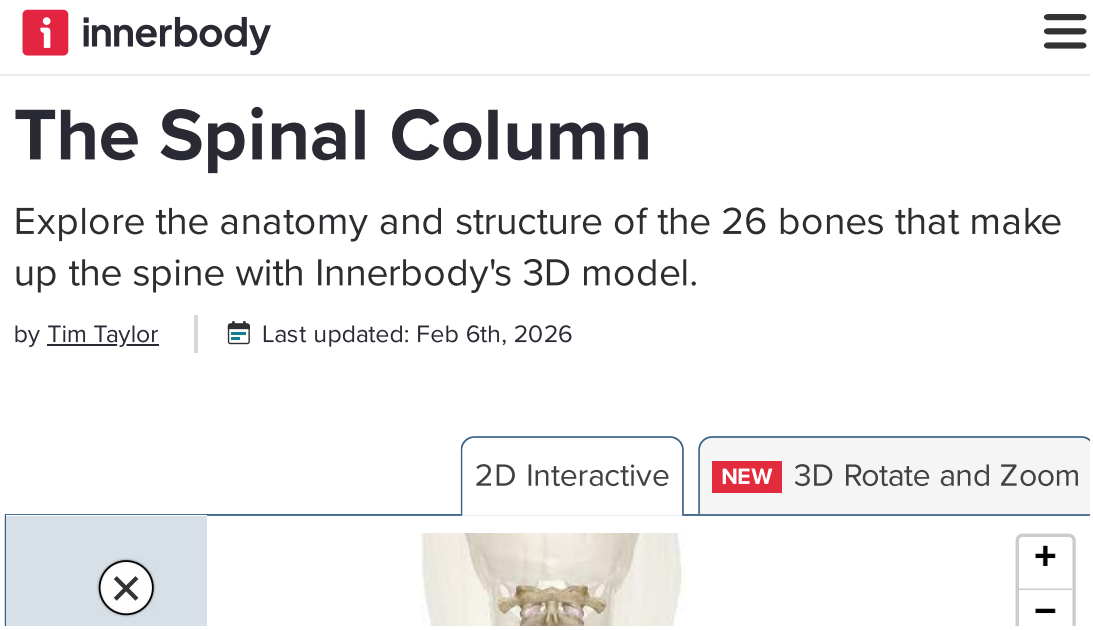
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Answer: Lifting a heavy object can cause an intervertebral disc in the lower back to bulge and compress a spinal nerve as it exits through the intervertebral foramen, thus producing pain in those regions of the lower limb supplied by that nerve.

Use this tool 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: The anterior longitudinal ligament is thickest in the thoracic region of the vertebral column, while the supraspinous ligament is thickest in the lumbar region.

## Review Questions

Q. The cervical region of the vertebral column consists of _____.

A. seven vertebrae

B. 12 vertebrae

C. five vertebrae

D. a single bone derived from the fusion of five vertebrae

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: 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: 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: 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: A

## Critical Thinking Questions

Q. Describe the vertebral column and define each region.

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: 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: 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: 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: 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.

## 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

**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

**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

**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 process**
paired bony processes that extends laterally from the vertebral arch of a 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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# 6.5: The Thoracic Cage

**Learning Objectives**

- 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.

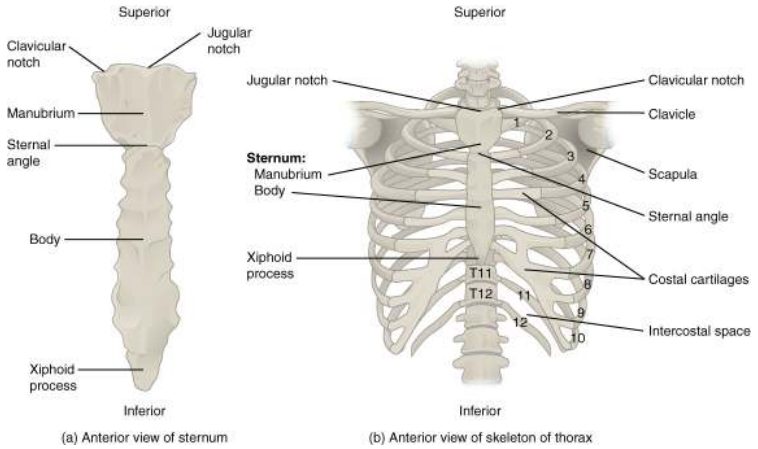



Figure **6.5.1**: Thoracic Cage. The thoracic cage is formed by the (a) sternum and (b) 12 pairs of ribs with their costal cartilages. The ribs are anchored posteriorly to the 12 thoracic vertebrae. The sternum consists of the manubrium, body, and xiphoid process. The ribs are classified as true ribs (1–7) and false ribs (8–12). The last two pairs of false ribs are also known as floating ribs (11–12).

## 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. 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

The posterior end of a typical rib is called the **head of the rib** (see [link]). 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. 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.

### 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.

## Chapter 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: B

Q. The sternal angle is the _____.

A. junction between the body and xiphoid process

B. site for attachment of the clavicle

C. site for attachment of the floating ribs

D. junction between the manubrium and body

Answer: D

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: 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: D

## Critical Thinking Questions

Q. Define the parts and functions of the thoracic cage.

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.

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.

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.

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

**sternal angle**
junction line between manubrium and body of the sternum and the site for attachment of the second rib to the sternum

**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

## Contributors and Attributions

**xiphoid process**
small process that forms the inferior tip of the sternum

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# 6.6: Embryonic Development of the Axial Skeleton

**Learning Objectives**

- 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 remained 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.

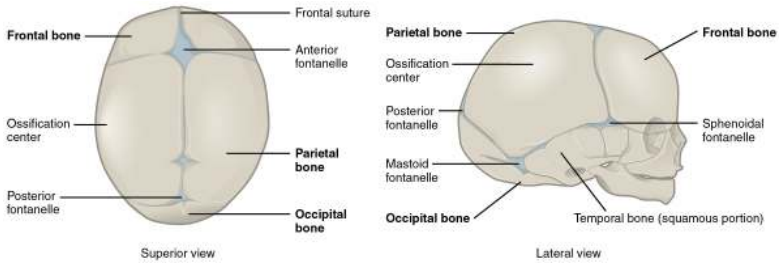



Figure **6.6.1**: Newborn Skull. The bones of the newborn skull are not fully ossified and are separated by large areas called fontanelles, which are filled with fibrous connective tissue. The fontanelles allow for continued growth of the skull after birth. At the time of birth, the facial bones are small and underdeveloped, and the mastoid process has not yet formed.

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.

## Chapter 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.

## Interactive Link Questions

View this video to review the two processes that give rise to the bones of the skull and body. What are the two mechanisms by which the bones of the body are formed and which bones are formed by each mechanism?

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Answer: Bones on the top and sides of the skull develop when fibrous membrane areas ossify (convert) into bone. The bones of the limbs, ribs, and vertebrae develop when cartilage models of the bones ossify 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: 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: D

## Critical Thinking Questions

Q. Discuss the processes by which the brain-case bones of the skull are formed and grow during skull enlargement.

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.

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.

## 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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# CHAPTER OVERVIEW

## 7: The Appendicular Skeleton

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.


7.1: Introduction

7.2: The Pectoral Girdle

7.3: Bones of the Upper Limb

7.4: The Pelvic Girdle and Pelvis

7.5: Bones of the Lower Limb


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# 7.1: Introduction

**Chapter Objectives**

- 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. (credit: Melissa Dooley/flickr)

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

**Learning Objectives**

- 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.

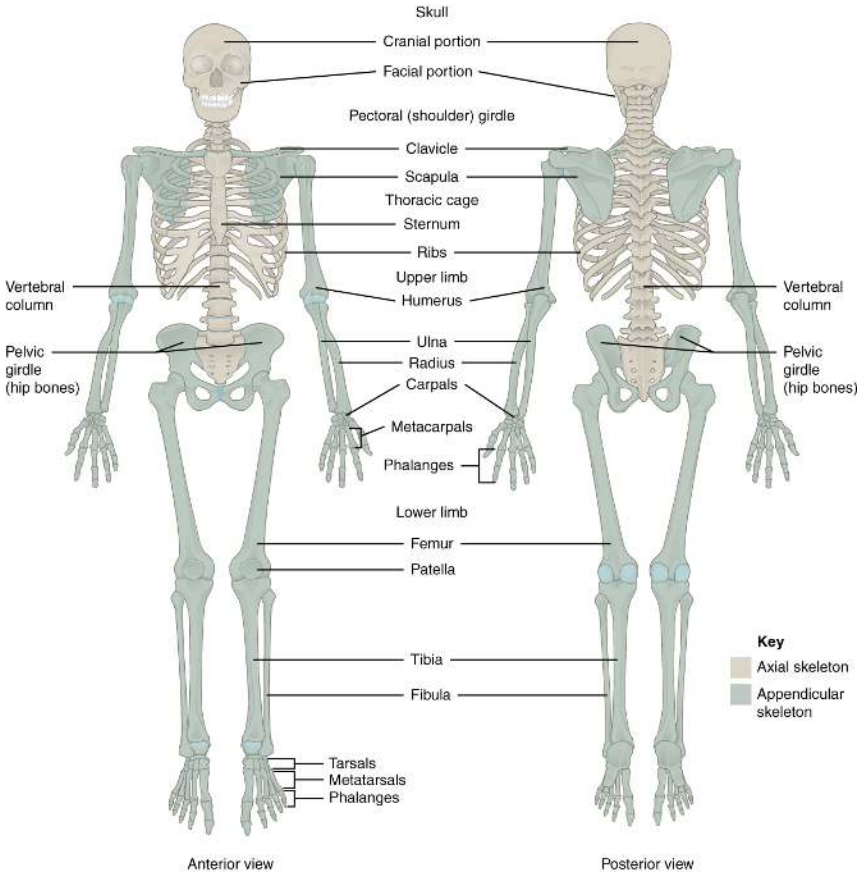



Figure **7.2.1**: Axial and Appendicular Skeletons. The axial skeleton forms the central axis of the body and consists of the skull, vertebral column, and thoracic cage. The appendicular skeleton consists of the pectoral and pelvic girdles, the limb bones, and the bones of the hands and feet.

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.

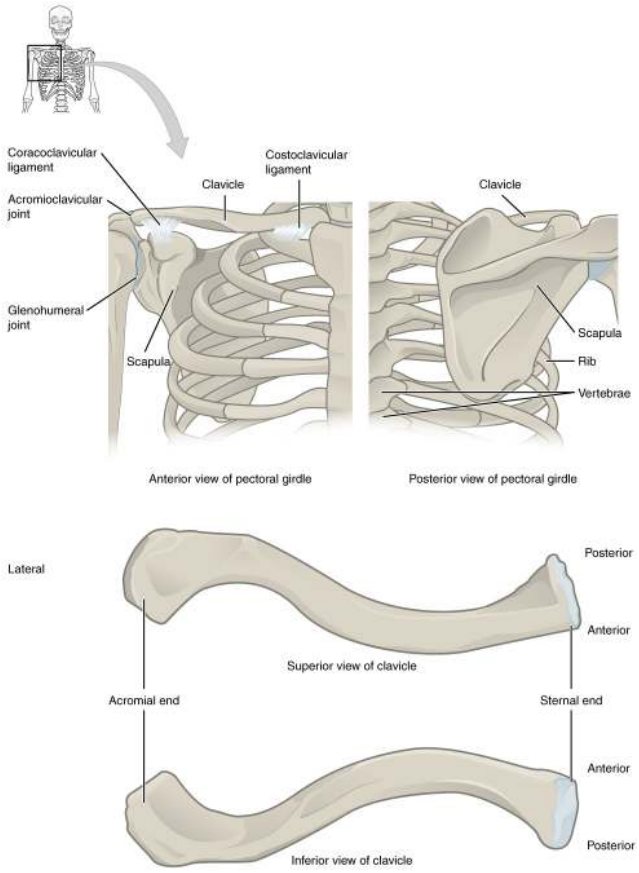



Figure **7.2.2**: Pectoral Girdle. The pectoral girdle consists of the clavicle and the scapula, which serve to attach the upper limb to the sternum of the axial skeleton.

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). 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.

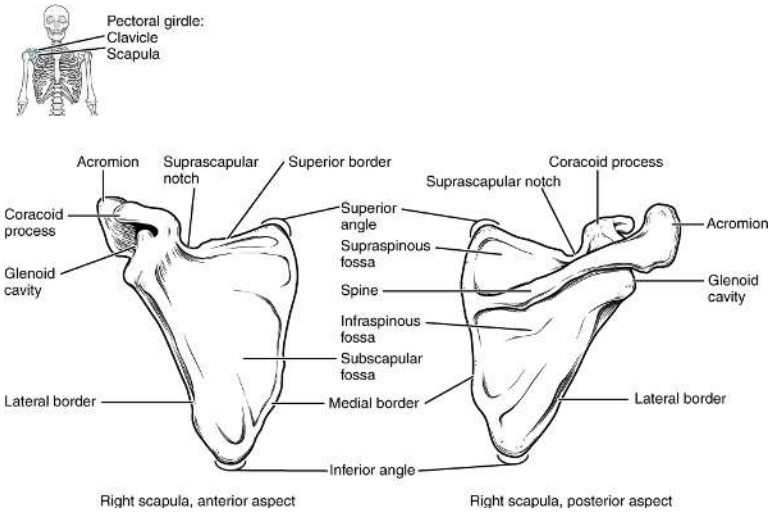



Figure **7.2.3**: Scapula. The isolated scapula is shown here from its anterior (deep) side and its posterior (superficial) side.

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.

## Chapter 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: B

Q. A shoulder separation results from injury to the _____.

A. glenohumeral joint

B. costoclavicular joint

C. acromioclavicular joint

D. sternoclavicular joint

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: 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: 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: C

## Critical Thinking Questions

Q. Describe the shape and palpable line formed by the clavicle and scapula.

> 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.

> 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

**acromial process**
acromion of the scapula

**acromioclavicular joint**
articulation between the acromion of the scapula and the acromial end of the clavicle

**acromion**
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

**Learning Objectives**

- 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 **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 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. 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 **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.

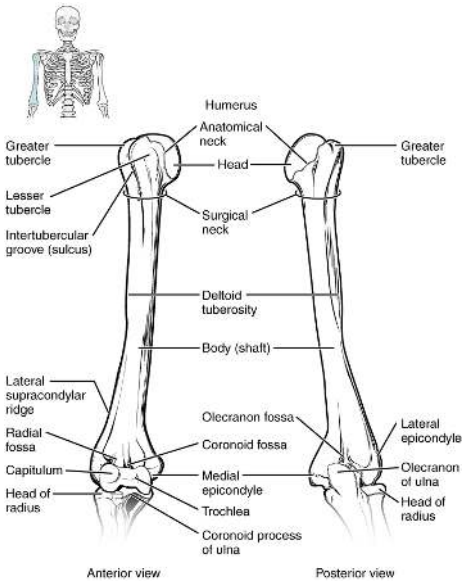



Figure 7.3.1: Humerus and Elbow Joint. The humerus is the single bone of the upper arm region. It articulates with the radius and ulna bones of the forearm to form the elbow joint.

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 and superior portions of the proximal ulna make up the **olecranon process**, which forms the bony tip of the elbow.

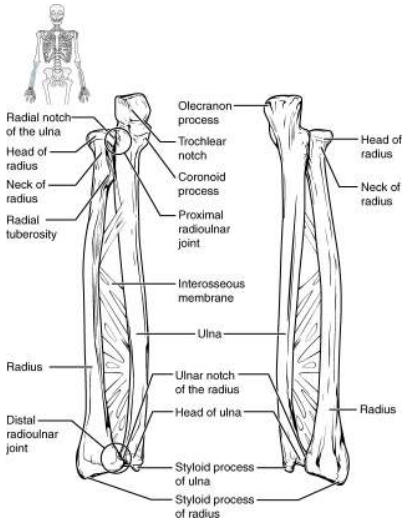



Figure **7.3.2**: Ulna and Radius.The ulna is located on the medial side of the forearm, and the radius is on the lateral side. These bones are attached to each other by an interosseous membrane.

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**, 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 **7.3.3** and 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.

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*Watch this video to see how fractures of the distal radius bone can affect the wrist joint. Explain the problems that may occur if a fracture of the distal radius involves the joint surface of the radiocarpal joint of the wrist.*

## 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.

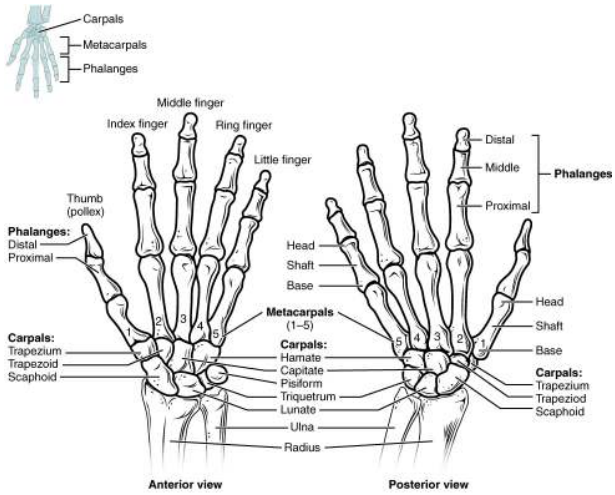



Figure **7.3.3**: Bones of the Wrist and Hand. The eight carpal bones form the base of the hand. These are arranged into proximal and distal rows of four bones each. The metacarpal bones form the palm of the hand. The thumb and fingers consist of the phalanx bones.

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.

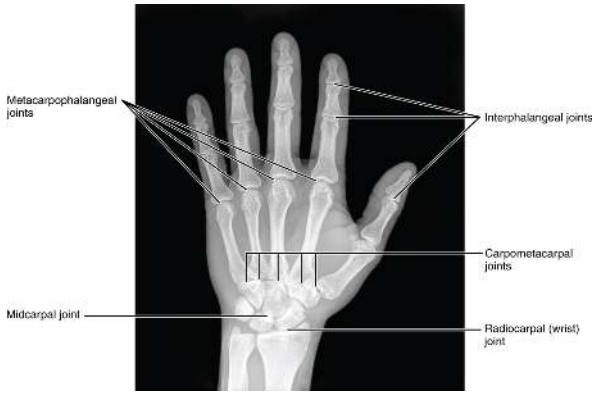



Figure **7.3.4**: Bones of the Hand. This radiograph shows the position of the bones within the hand. Note the carpal bones that form the base of the hand. (credit: modification of work by Trace Meek)

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. 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 (Figure **7.3.5**). 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.

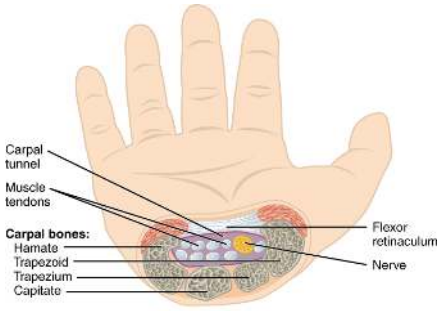



Figure **7.3.5**: Carpal Tunnel. The carpal tunnel is the passageway by which nine muscle tendons and a major nerve enter the hand from the anterior forearm. The walls and floor of the carpal tunnel are formed by the U-shaped grouping of the carpal bones, and the roof is formed by the flexor retinaculum, a strong ligament that anteriorly unites the bones.

## 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 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 expanded distal end 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.

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.

## Phalanx Bones

The fingers and thumb contain 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) through 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**).

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*Visit this site to explore the bones and joints of the hand. What are the three arches of the hand, and what is the importance of these during the gripping of an object?*

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). 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.

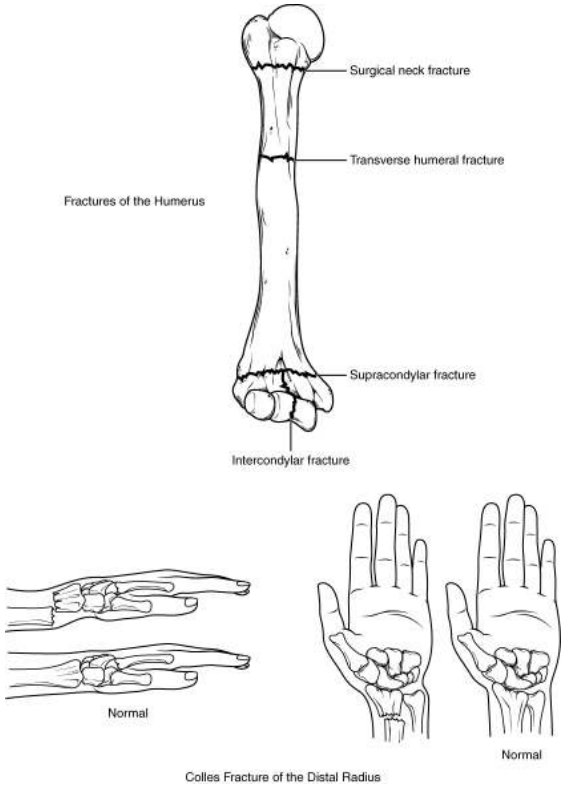



Figure **7.3.7**: Fractures of the Humerus and Radius. Falls or direct blows can result in fractures of the surgical neck or shaft of the humerus. Falls onto the elbow can fracture the distal humerus. A Colles fracture of the distal radius is the most common forearm fracture.

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*Watch this video to learn about a Colles fracture, 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?*

## Chapter 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.

## Interactive Link Questions

Watch this video to see how fractures of the distal radius bone can affect the wrist joint. Explain the problems that may occur if a fracture of the distal radius involves the joint surface of the radiocarpal joint of the wrist.

> Answer: A fracture through the joint surface of the distal radius may make the articulating surface of the radius rough or jagged. This can then cause painful movements involving this joint and the early development of arthritis. Surgery can return the joint surface to its original smoothness, thus allowing for the return of normal function.

Visit this site to explore the bones and joints of the hand. What are the three arches of the hand, and what is the importance of these during the gripping of an object?

Answer: The hand has a proximal transverse arch, a distal transverse arch, and a longitudinal arch. These allow the hand to conform to objects being held. These arches maximize the amount of surface contact between the hand and object, which enhances stability and increases sensory input.

Watch this video to learn about a Colles fracture, 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: 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.

## Review Questions

Q. How many bones are there in the upper limbs combined?

A. 20

B. 30

C. 40

D. 60

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: 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: C

Q. Which is the lateral-most carpal bone of the proximal row?

A. trapezium

B. hamate

C. pisiform

D. scaphoid

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: 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.

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.

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

**bicipital groove**
intertubercular groove; narrow groove located between the greater and lesser tubercles of the humerus

**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**
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)**
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

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# 7.4: The Pelvic Girdle and Pelvis

**Learning Objectives**

- 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.

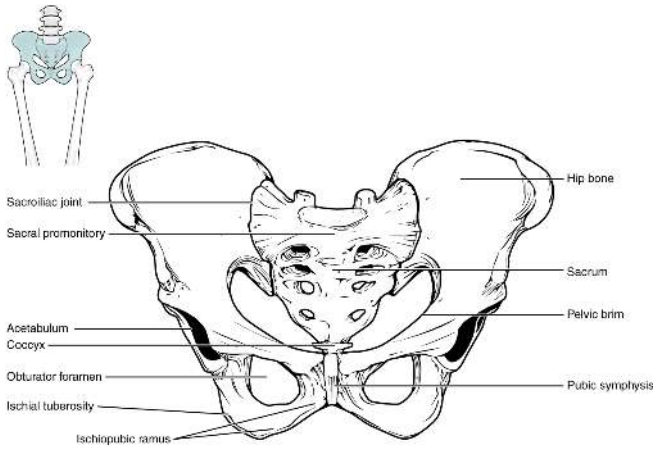



Figure 7.4.1: Pelvis.The pelvic girdle is formed by a single hip bone. The hip bone attaches the lower limb to the axial skeleton through its articulation with the sacrum. The right and left hip bones, plus the sacrum and the coccyx, together form the pelvis.

## 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.

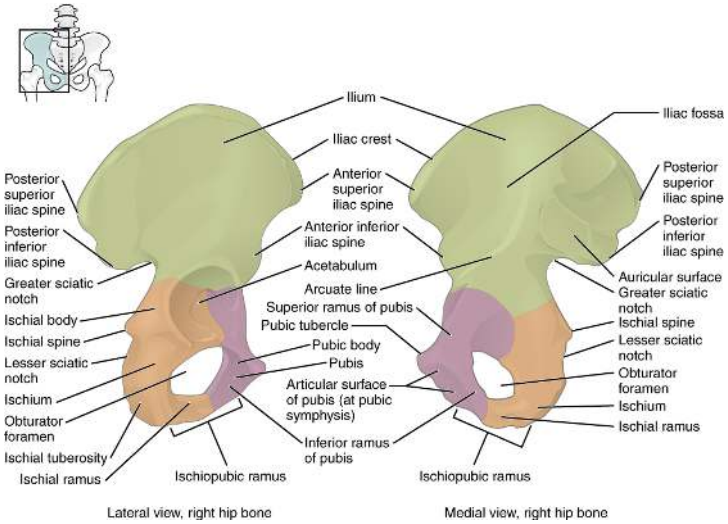



Figure 7.4.2: The Hip Bone. The adult hip bone consists of three regions. The ilium forms the large, fan-shaped superior portion, the ischium forms the posteroinferior portion, and the pubis forms the anteromedial portion.

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**.

### 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, 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. 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**.

## 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**. 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.

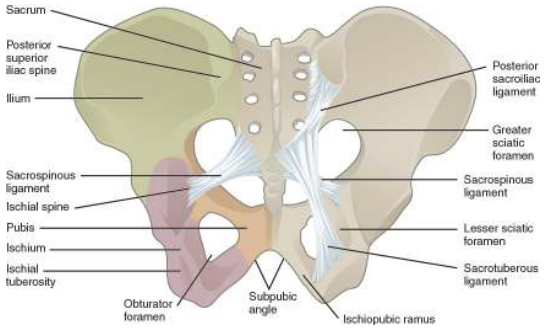
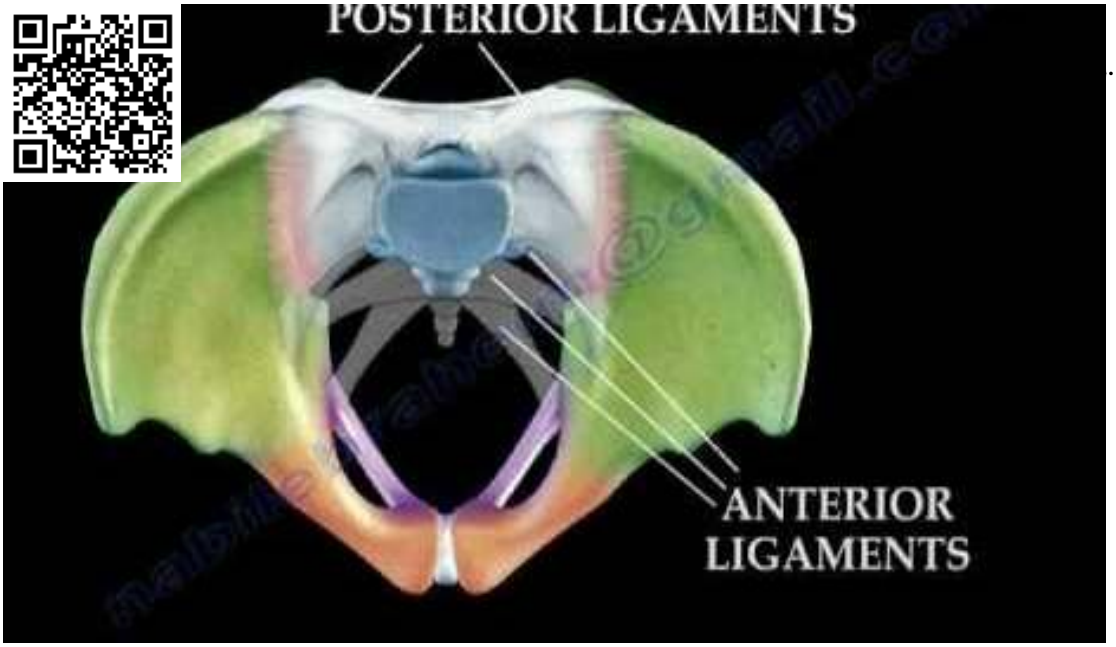



Figure **7.4.3**: Ligaments of the Pelvis. The posterior sacroiliac ligament supports the sacroiliac joint. The sacrospinous ligament spans the sacrum to the ischial spine, and the sacrotuberous ligament spans the sacrum to the ischial tuberosity. The sacrospinous and sacrotuberous ligaments contribute to the formation of the greater and lesser sciatic foramens.

*Watch this video for a 3-D view of the pelvis and its associated ligaments. What is the large opening in the bony pelvis, located between the ischium and pubic regions, and what two parts of the pubis contribute to the formation of this opening?*




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.

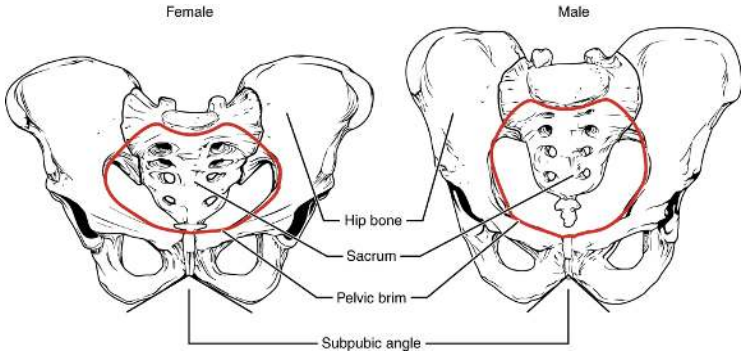



Figure **7.4.4**: Male and Female Pelvis. The female pelvis is adapted for childbirth and is broader, with a larger subpubic angle, a rounder pelvic brim, and a wider and more shallow lesser pelvic cavity than the male pelvis.

## 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.

Table **7.4.1**: Overview of Differences between the Female and Male Pelvis

| | Female pelvis | Male pelvis |
|---|---|---|
| **Pelvic weight** | Bones of the pelvis are lighter and thinner | Bones of the pelvis are thicker and heavier |
| **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.

## Chapter 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.

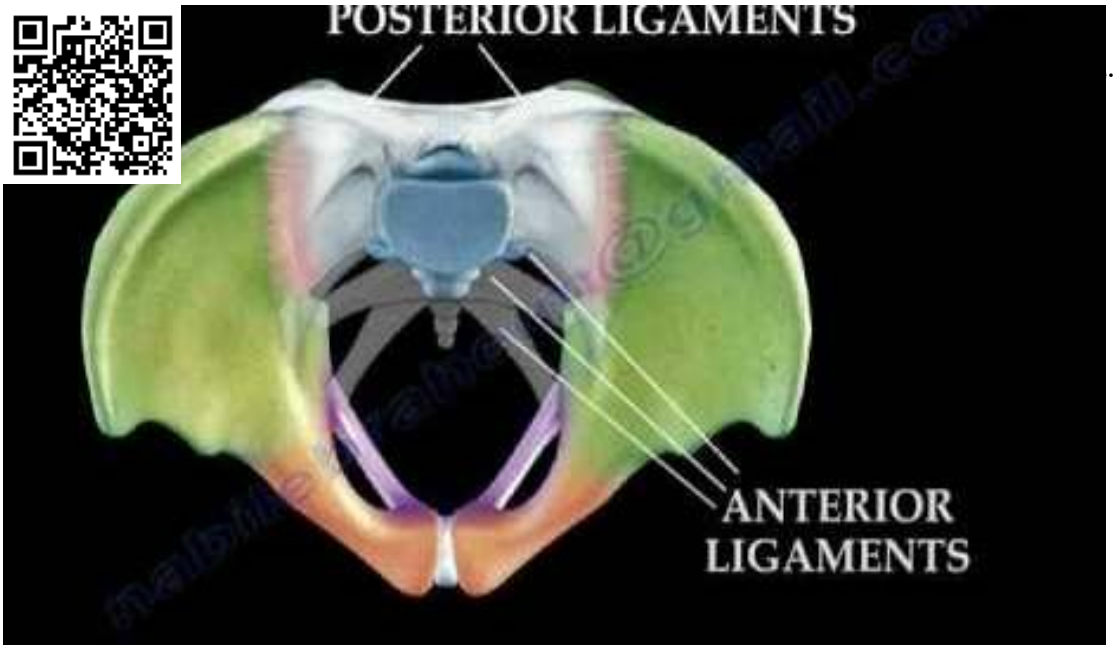
The pubis forms the anterior portion of the hip bone. The body of the pubis articulates with the pubis of the opposite hip bone at the pubic symphysis. The superior margin of the pubic body has the pubic tubercle. The pubis is joined to the ilium by the superior pubic ramus, the superior surface of which 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.

## Interactive Link Questions

Watch this video for a 3-D view of the pelvis and its associated ligaments. What is the large opening in the bony pelvis, located between the ischium and pubic regions, and what two parts of the pubis contribute to the formation of this opening?




Answer: The obturator foramen is located between the ischium and the pubis. The superior and inferior pubic rami contribute to the boundaries of the obturator foramen.

## Review Questions

Q. How many bones fuse in adulthood to form the hip bone?

A. 2

B. 3

C. 4

D. 5

Answer: B

Q. Which component forms the superior part of the hip bone?

A. ilium

B. pubis

C. ischium

D. sacrum

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: 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: 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: A

## Critical Thinking Questions

Q. Describe the articulations and ligaments that unite the four bones of the pelvis to each other.

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.

> 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 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

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# 7.5: Bones of the Lower Limb

**Learning Objectives**

- 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 (see [link]). 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.

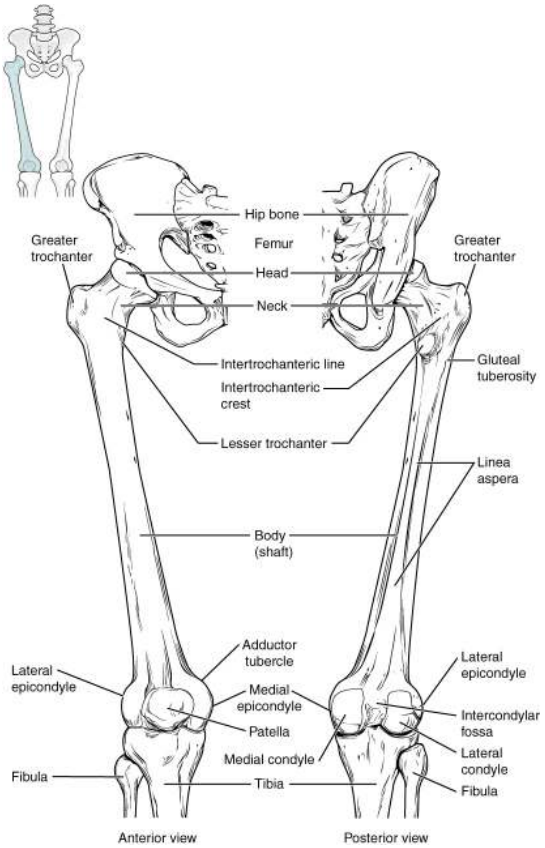


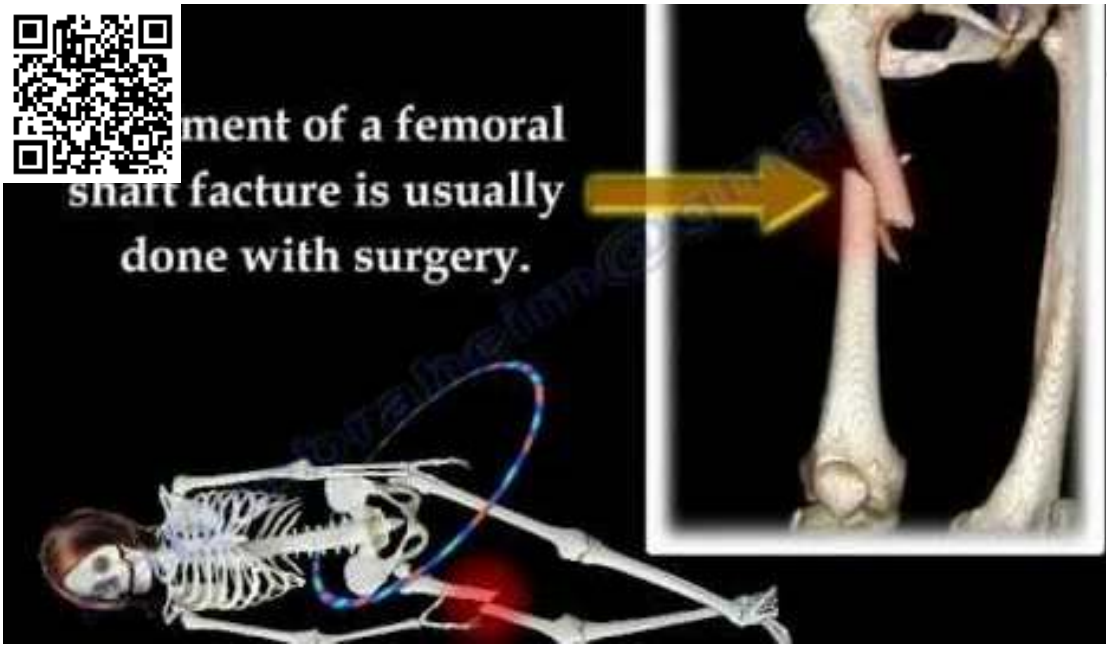

Figure **7.5.1**: Femur and Patella. The femur is the single bone of the thigh region. It articulates superiorly with the hip bone at the hip joint, and inferiorly with the tibia at the knee joint. The patella only articulates with the distal end of the femur.

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 **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.

*Watch this video to view how a fracture of the mid-femur is surgically repaired. How are the two portions of the broken femur stabilized during surgical repair of a fractured femur?*




## Patella

The patella (kneecap) is largest sesamoid bone of the body (see 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.

> *Visit this site to perform a virtual knee replacement surgery. The prosthetic knee components must be properly aligned to function properly. How is this alignment ensured?*

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HOMEOSTATIC IMBALANCES: 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 in 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.

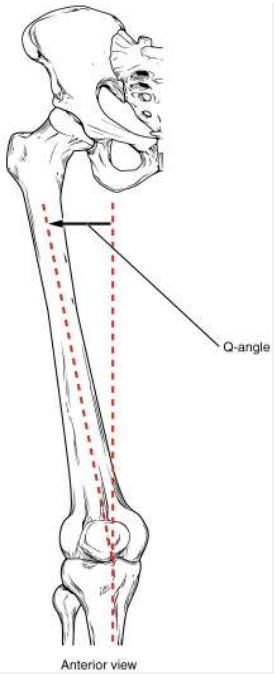



Figure **7.5.2**: The Q-Angle. The Q-angle is a measure of the amount of lateral deviation of the femur from the vertical line of the tibia. Adult females have a larger Q-angle due to their wider pelvis than adult males.

## 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.

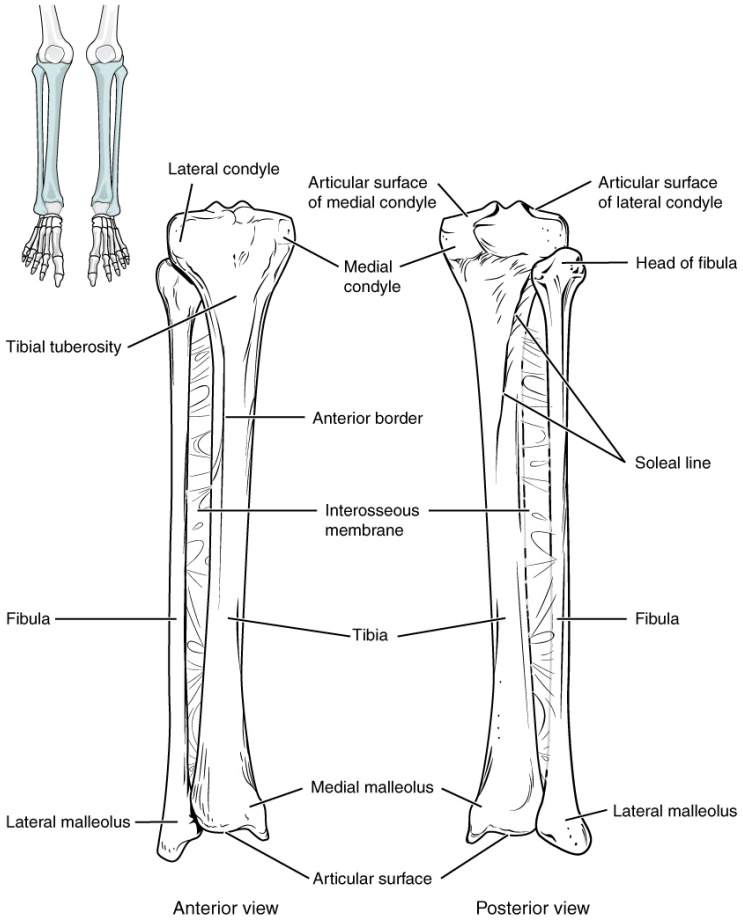



Figure **7.5.3**: Tibia and Fibula. The tibia is the larger, weight-bearing bone located on the medial side of the leg. The fibula is the slender bone of the lateral side of the leg and does not bear weight.

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. 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 **shaft of the tibia** becomes triangular in shape. The anterior apex of

MH 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 (see 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**. Three areas of articulation form the ankle joint: The superomedial surface of the talus bone articulates with the medial malleolus of the tibia, the top of the talus articulates with the distal end of the tibia, and the lateral side of the talus articulates with the lateral malleolus of the fibula. 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") that supports the medial side of the talus bone.

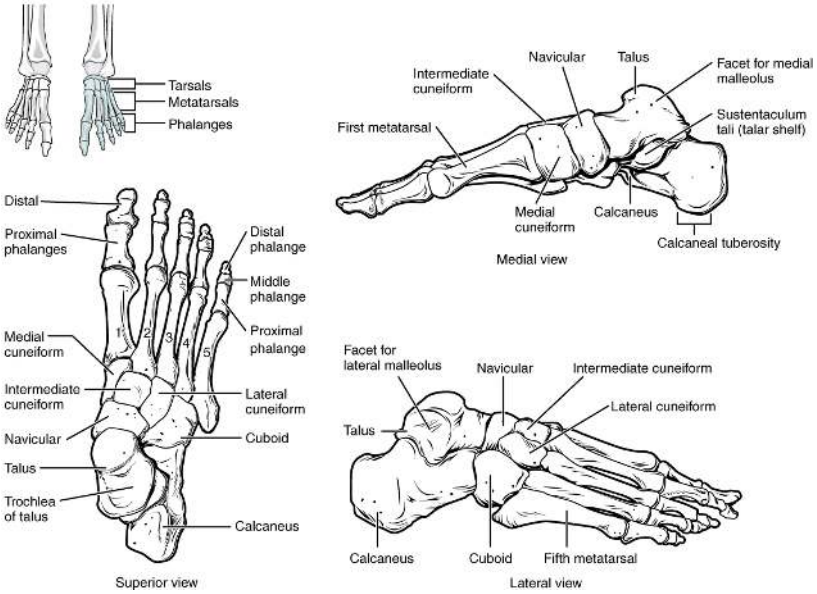



Figure 7.5.4: Bones of the Foot. The bones of the foot are divided into three groups. The posterior foot is formed by the seven tarsal bones. The mid-foot has the five metatarsal bones. The toes contain the phalanges.

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.

*Use this tutorial to review the bones of the foot. Which tarsal bones are in the proximal, intermediate, and distal groups?*



## 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 (see 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 (see Figure **7.5.4**). The toes are numbered 1–5, starting with the big toe (**hallux**). The big toe 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.

*View this link to learn about a bunion, a localized swelling on the medial side of the foot, next to the first metatarsophalangeal joint, at the base of the big toe. What is a bunion and what type of shoe is most likely to cause this to develop?* http://bones.emedtv.com/bunionectomy-with-fusion-video/what-are-bunions-video.html

## 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 (see 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").

## Chapter 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.

## Interactive Link Questions

Watch this video to view how a fracture of the mid-femur is surgically repaired. How are the two portions of the broken femur stabilized during surgical repair of a fractured femur?



Answer: A hole is drilled into the greater trochanter, the bone marrow (medullary) space inside the femur is enlarged, and finally an intramedullary rod is inserted into the femur. This rod is then anchored to the bone with screws.

Visit this site to perform a virtual knee replacement surgery. The prosthetic knee components must be properly aligned to function properly. How is this alignment ensured?

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Answer: Metal cutting jigs are attached to the bones to ensure that the bones are cut properly prior to the attachment of prosthetic components.

Use this tutorial to review the bones of the foot. Which tarsal bones are in the proximal, intermediate, and distal groups?



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Answer: The proximal group of tarsal bones includes the calcaneus and talus bones, the navicular bone is intermediate, and the distal group consists of the cuboid bone plus the medial, intermediate, and lateral cuneiform bones.

View this link to learn about a bunion, a localized swelling on the medial side of the foot, next to the first metatarsophalangeal joint, at the base of the big toe. What is a bunion and what type of shoe is most likely to cause this to develop?

Answer: A bunion results from the deviation of the big toe toward the second toe, which causes the distal end of the first metatarsal bone to stick out. A bunion may also be caused by prolonged pressure on the foot from pointed shoes with a narrow toe box that compresses the big toe and pushes it toward the second toe.

## 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: 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: C

Q. Which tarsal bone articulates with the tibia and fibula?

A. calcaneus

B. cuboid

C. navicular

D. talus

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: 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: 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.

> 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.

> 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

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

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

ligament of the head of the femur

ligament that spans the acetabulum of the hip bone and the fovea capitis of the femoral head

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

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

## Contributors and Attributions

tibial tuberosity

elevated area on the anterior surface of the proximal tibia

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# CHAPTER OVERVIEW

## 8: Joints


8.1: Introduction
8.2: Classification of Joints
8.3: Fibrous Joints
8.4: Cartilaginous Joints
8.5: Synovial Joints
8.6: Types of Body Movements
8.7: Anatomy of Selected Synovial Joints


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# 8.1: Introduction

Without joints, body movements would be impossible. (credit: Graham Richardson/flickr.com)

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# 8.2: Classification of Joints

**Learning Objectives**

- 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.

## 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 (immobile joint) or an amphiarthrosis (slightly mobile joint). 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 provide for a strong union between the articulating bones. This is important at locations where the bones provide protection for internal organs. Examples include sutures, the fibrous joints between the bones of the skull that surround and protect the brain (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.

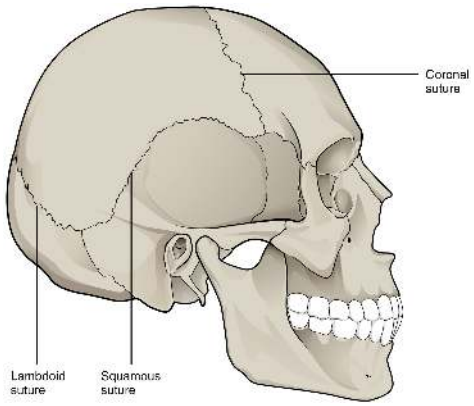



Figure 8.2.1: Suture Joints of Skull. The suture joints of the skull are an example of a synarthrosis, an immobile or essentially immobile joint.

## Amphiarthrosis

An **amphiarthrosis** is a joint that has limited mobility. 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.

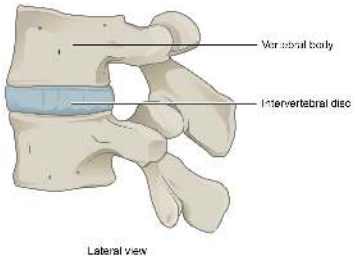



Figure 8.2.2: Intervertebral Disc. An intervertebral disc unites the bodies of adjacent vertebrae within the vertebral column. Each disc allows for limited movement between the vertebrae and thus functionally forms an amphiarthrosis type of joint. Intervertebral discs are made of fibrocartilage and thereby structurally form a symphysis type of cartilaginous joint.

## Diarthrosis

A freely mobile joint is classified as a **diarthrosis**. These types of joints include all synovial joints 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 the 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 shoulder and hip joints are multiaxial joints. 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.

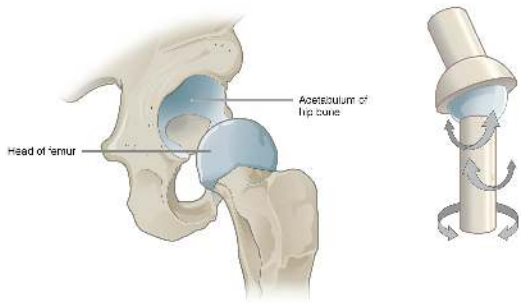



Figure **8.2.3**: Multiaxial Joint. A multiaxial joint, such as the hip joint, allows for three types of movement: anterior-posterior, medial-lateral, and rotational.

## Chapter 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: 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: 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: 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: D

## Critical Thinking Questions

Q. Define how joints are classified based on function. Describe and give an example for each functional type of joint.

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.

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

**Learning Objectives**

- 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 fibrous 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 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.

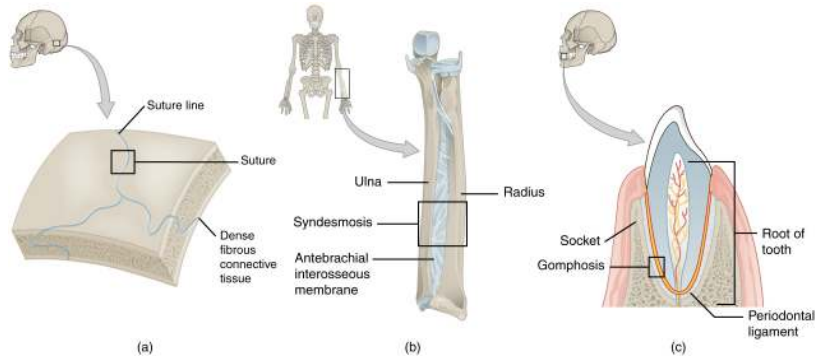



Figure 8.3.1: Fibrous Joints. Fibrous joints form strong connections between bones. (a) Sutures join most bones of the skull. (b) An interosseous membrane forms a syndesmosis between the radius and ulna bones of the forearm. (c) A gomphosis is a specialized fibrous joint that anchors a tooth to its socket in the jaw.

## Suture

All the bones of the skull, except for the mandible, are joined to each other by a fibrous joint called a **suture**. The 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 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. (See 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). 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 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.

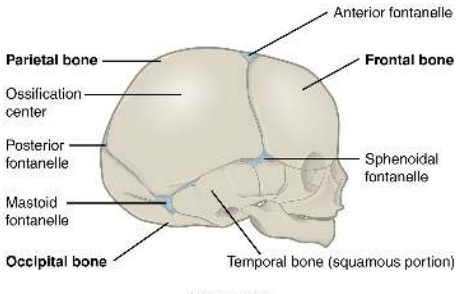



Figure **8.3.2**: The Newborn Skull. The fontanelles of a newborn's skull are broad areas of fibrous connective tissue that form fibrous joints between the bones of the skull.

## 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 an interosseous membrane (see Figure9.2.1.b). Similarly, in the leg, the shafts of the tibia and fibula are also united by an 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 maxillary bone (upper jaw) or mandible bone (lower jaw) 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 connective tissue, each of which is called a **periodontal ligament** (see Figure9.2.1.c). Due to the immobility of a gomphosis, this type of joint is functionally classified as a synarthrosis.

## Chapter 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 ligaments 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: 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: 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: 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: C

## Critical Thinking Questions

Q. Distinguish between a narrow and wide fibrous joint and give an example of each.

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.

> 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

**Learning Objectives**

- 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.

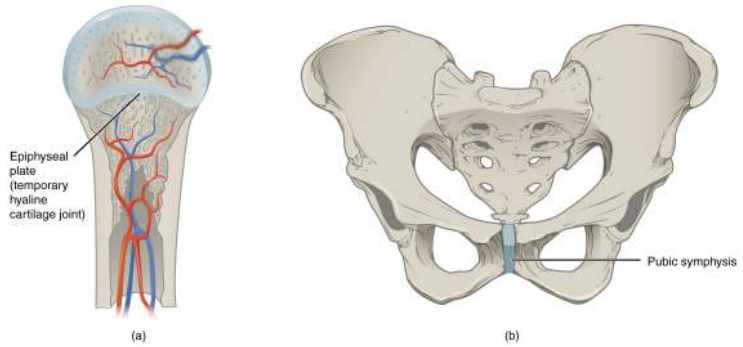



Figure **8.4.1**: Cartiliginous Joints. At cartilaginous joints, bones are united by hyaline cartilage to form a synchondrosis or by fibrocartilage to form a symphysis. (a) The hyaline cartilage of the epiphyseal plate (growth plate) forms a synchondrosis that unites the shaft (diaphysis) and end (epiphysis) 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.

## 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. 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 bone of the adult. Similarly, synostoses unite the sacral vertebrae that fuse together to form the adult sacrum.

QR Code representing a URL

*Visit this website to view a radiograph (X-ray image) of a child's hand and wrist. The growing bones of child have an epiphyseal plate that forms a synchondrosis between the shaft and end of a long bone. Being less dense than bone, the area of epiphyseal cartilage is seen on this radiograph as the dark epiphyseal*

*gaps located near the ends of the long bones, including the radius, ulna, metacarpal, and phalanx bones. Which of the bones in this image do not show an epiphyseal plate (epiphyseal gap)?*

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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, 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. 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.

## Chapter 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.

### Interactive Link Questions

Go to this website to view a radiograph (X-ray image) of a child's hand and wrist. The growing bones of child have an epiphyseal plate that forms a synchondrosis between the shaft and end of a long bone. Being less dense than bone, the area of epiphyseal cartilage is seen on this radiograph as the dark epiphyseal gaps located near the ends of the long bones, including the radius, ulna, metacarpal, and phalanx bones. Which of the bones in this image do not show an epiphyseal plate (epiphyseal gap)?

# Internal Server Error

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Answer: Although they are still growing, the carpal bones of the wrist area do not show an epiphyseal plate. Instead of elongating, these bones grow in diameter by adding new bone to their surfaces.

### 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: 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: 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: 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: A

## Critical Thinking Questions

Q. Describe the two types of cartilaginous joints and give examples of each.

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.

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

**Learning Objectives**

- 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.

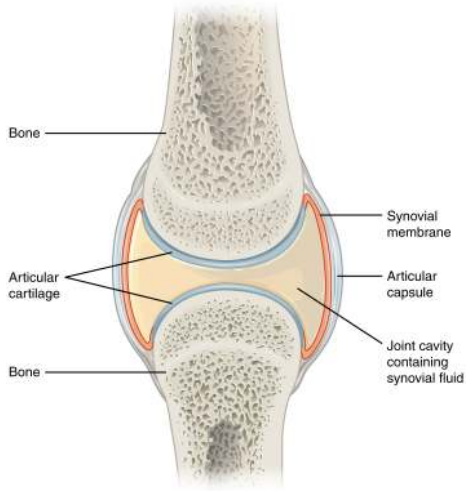



Figure 8.5.1: Synovial Joints. Synovial joints allow for smooth movements between the adjacent bones. The joint is surrounded by an articular capsule that defines a joint cavity filled with synovial fluid. The articulating surfaces of the bones are covered by a thin layer of articular cartilage. Ligaments support the joint by holding the bones together and resisting excess or abnormal joint motions.

## 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 Teflon® 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 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 body joint (Figure 8.5.2). 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 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 large anterior thigh muscle from the distal femur just above the knee.

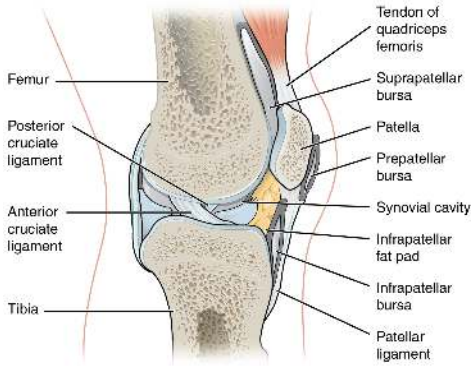



***Figure* 8.5.2*: Bursae.*** *Bursae are fluid-filled sacs that serve to prevent friction between skin, muscle, or tendon and an underlying bone. Three major bursae and a fat pad are part of the complex joint that unites the femur and tibia of the leg.*

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.

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**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, condyloid, saddle, plane, and ball-and socket-joints (Figure **8.5.3**).

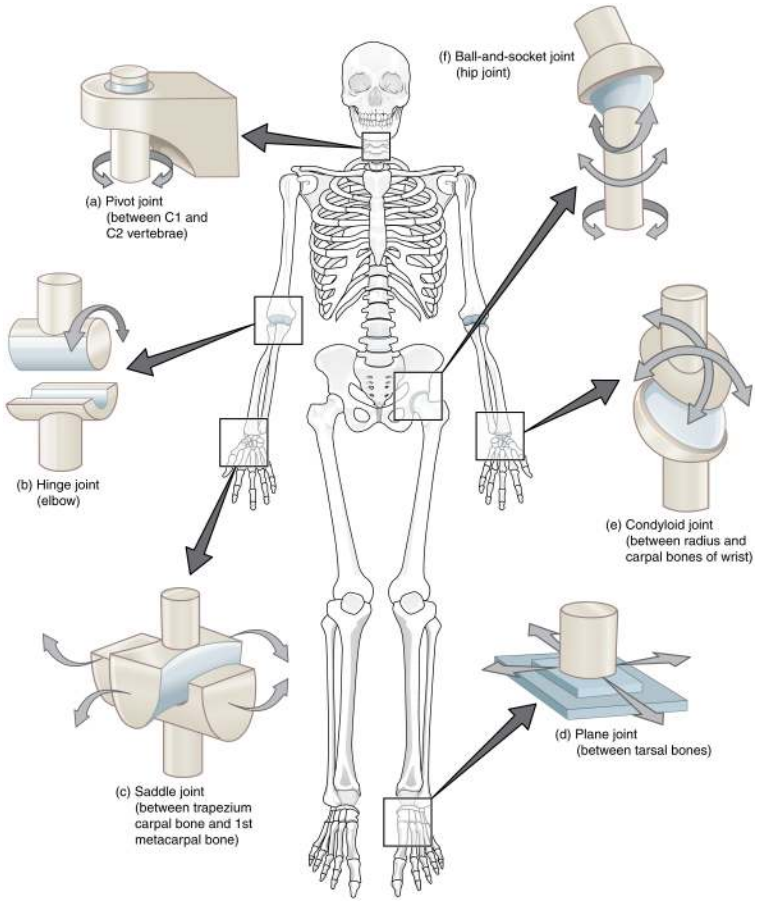



Figure **8.5.3**: Types of Synovial Joints. The six types of synovial joints allow the body to move in a variety of ways. (a) Pivot joints allow for rotation around an axis, such as between the first and second cervical vertebrae, which allows for side-to-side rotation of the head. (b) The hinge joint 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.

## 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 (see 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 diarthrosis 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 a 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 (see Figure9.4.3.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.

## Condyloid Joint

At a **condyloid joint** (ellipsoid joint), the shallow depression at the end of one bone articulates with a rounded structure from an adjacent bone or bones (see Figure9.4.3.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.

### 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 (see Figure9.4.3.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** (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 (see Figure9.4.3.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).

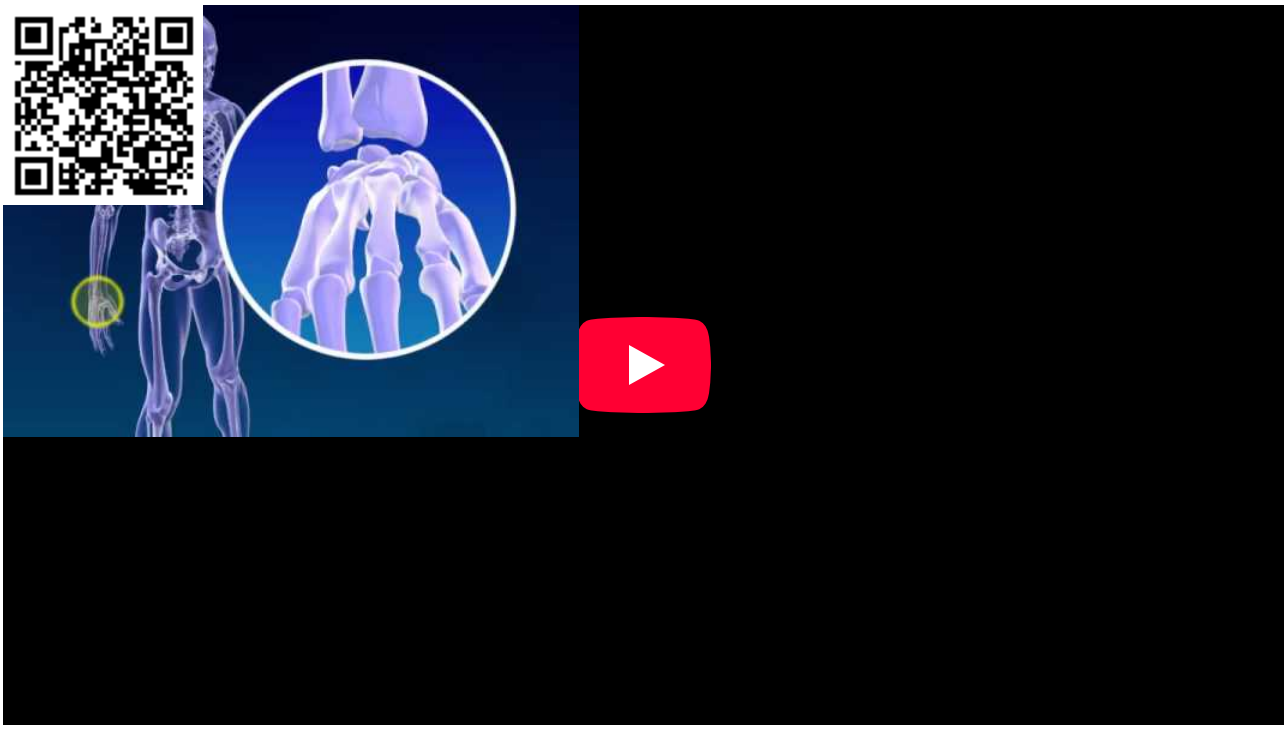
### Ball-and-Socket Joint

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 (see Figure9.4.3.f). The hip joint 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.

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*Watch this video to see an animation of synovial joints in action. Synovial joints are places where bones articulate with each other inside of a joint cavity. The different types of synovial joints are the ball-and-socket joint (shoulder joint), hinge joint (knee), pivot joint (atlantoaxial joint, between C1 and C2 vertebrae of the neck), condyloid joint (radiocarpal joint of the wrist), saddle joint (first carpometacarpal joint, between the trapezium carpal bone and the first metacarpal bone, at the base of the thumb), and plane joint (facet joints of vertebral column, between superior and inferior articular processes). Which type of synovial joint allows for the widest range of motion?*



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 prosthesis (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.

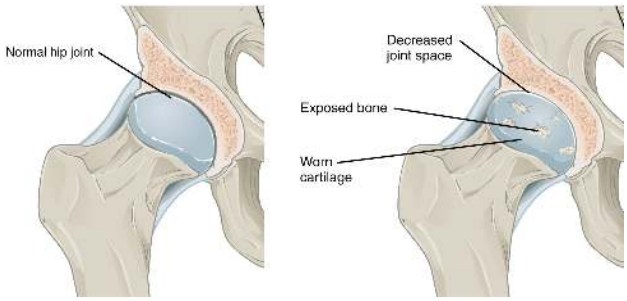



Figure **8.5.4**: Osteoarthritis. Osteoarthritis of a synovial joint results from aging or prolonged joint wear and tear. These cause erosion and loss of the articular cartilage covering the surfaces of the bones, resulting in inflammation that causes joint stiffness and pain.

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*Visit this website to learn about a patient who arrives at the hospital with joint pain and weakness in his legs. What caused this patient's weakness?*




*Watch this animation to observe hip replacement surgery (total hip arthroplasty), which can be used to alleviate the pain and loss of joint mobility associated with osteoarthritis of the hip joint. What is the most common cause of hip disability?*




*Watch this video to learn about the symptoms and treatments for rheumatoid arthritis. Which system of the body malfunctions in rheumatoid arthritis and what does this cause?*

## Chapter 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 strength 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.

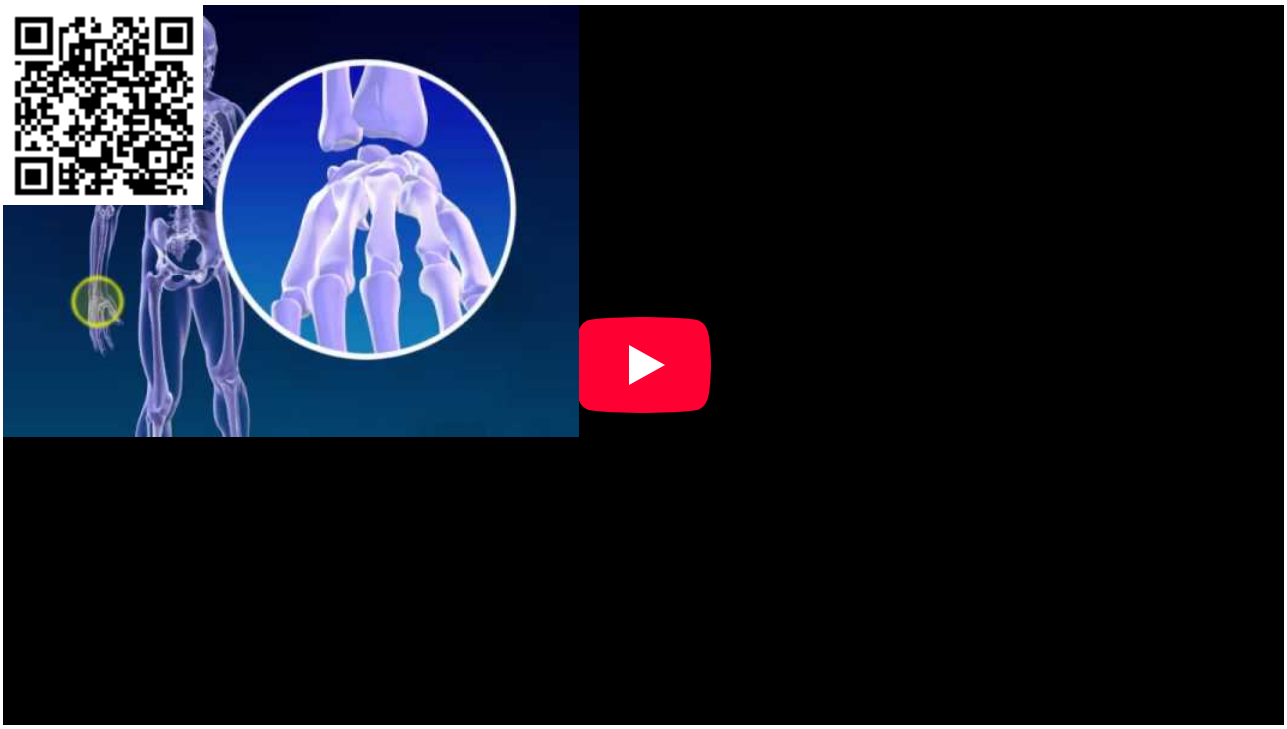
Based on the shape of the articulating bone surfaces and the types of movement allowed, synovial joints are classified into six types. At a pivot joint, one bone is held within a ring by a ligament and its articulation with a second bone. Pivot joints only allow for rotation around a single axis. These 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.

## Interactive Link Questions

Watch this video to see an animation of synovial joints in action. Synovial joints are places where bones articulate with each other inside of a joint cavity. The different types of synovial joints are the ball-and-socket joint (shoulder joint), hinge joint (knee), pivot joint (atlantoaxial joint, between C1 and C2 vertebrae of the neck), condyloid joint (radiocarpal joint of the wrist), saddle joint (first carpometacarpal joint, between the trapezium carpal bone and the first metacarpal bone, at the base of the thumb), and plane joint (facet joints of vertebral column, between superior and inferior articular processes). Which type of synovial joint allows for the widest ranges of motion?



Answer: Ball-and-socket joint.

Visit this website to read about a patient who arrives at the hospital with joint pain and weakness in his legs. What caused this patient's weakness?

Answer: Gout is due to the accumulation of uric acid crystals in the body. Usually these accumulate within joints, causing joint pain. This patient also had crystals that accumulated in the space next to his spinal cord, thus compressing the spinal cord and causing muscle weakness.

Watch this animation to observe hip replacement surgery (total hip arthroplasty), which can be used to alleviate the pain and loss of joint mobility associated with osteoarthritis of the hip joint. What is the most common cause of hip disability?

> Answer: The most common cause of hip disability is osteoarthritis, a chronic disease in which the articular cartilage of the joint wears away, resulting in severe hip pain and stiffness.

Watch this video to learn about the symptoms and treatments for rheumatoid arthritis. Which system of the body malfunctions in rheumatoid arthritis and what does this cause?

Answer: The immune system malfunctions and attacks healthy cells in the lining of your joints. This causes inflammation and pain in the joints and surrounding tissues.

## Review Questions

Q. Which type of joint provides the greatest range of motion?

A. ball-and-socket

B. hinge

C. condyloid

D. plane

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: 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: 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: 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: 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: 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: 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: A

## Critical Thinking Questions

Q. Describe the characteristic structures found at all synovial joints.

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.

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

**Learning Objectives**

- 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). 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** as you go through this section.

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*Watch this video to learn about anatomical motions. What motions involve increasing or decreasing the angle of the foot at the ankle?*



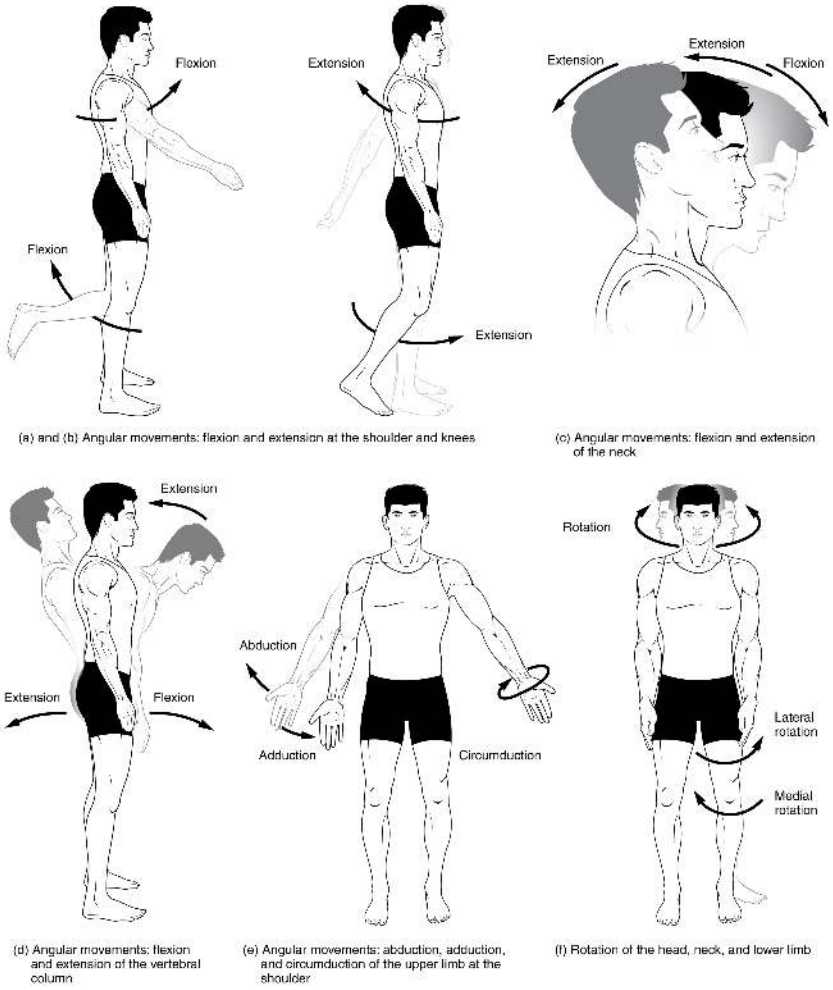



***Figure* 8.6.1*: Movements of the Body, Part 1.*** *Synovial joints give the body many ways in which to move. (a)–(b) Flexion and extension motions are in the sagittal (anterior–posterior) plane of motion. These movements take place at the shoulder, hip, elbow, knee, wrist, metacarpophalangeal, metatarsophalangeal, 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).*

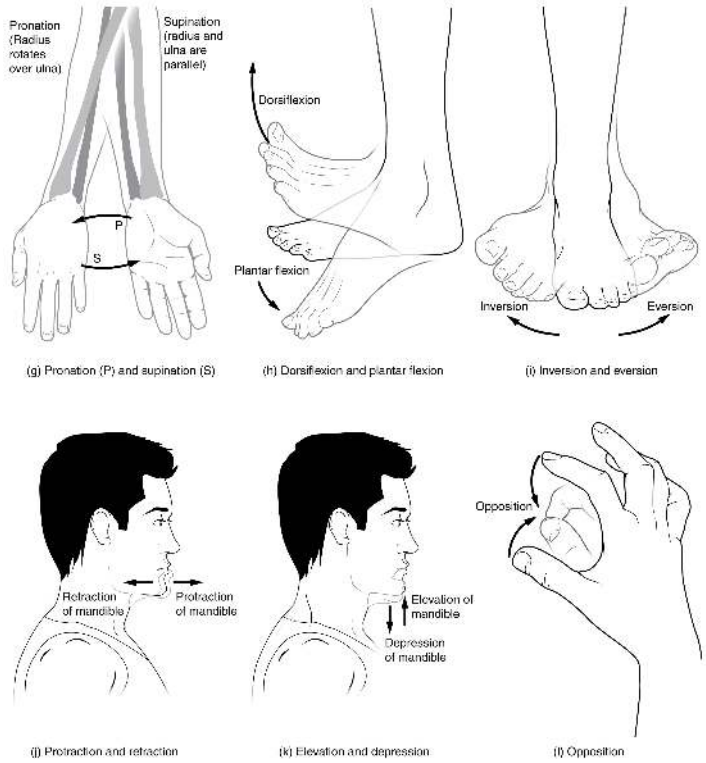



***Figure* 8.6.2*: Movements of the Body, Part 2.*** *(g) Supination of the forearm turns the hand to the palm forward position in which the radius and ulna are parallel, while forearm pronation turns the hand to the palm backward position in which the radius crosses over the ulna to form an "X." (h) 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.*

## 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. 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. **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.

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 (see Figure **8.6.1**.a-d).

**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 (see Figure9.5.1.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 (see Figure9.5.1.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.

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** (see Figure9.5.1.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. It helps to remember that supination is the motion you use when scooping up soup with a spoon (see Figure 8.6.2.g).

## 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 (see 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 (see 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. (See 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 (see 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** (see Figure **8.6.2**.l).

***Table* 8.6.1**

| Movements of the Joints | | |
|---|---|---|
| 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 |

## Chapter 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.

## Interactive Link Questions

Watch this video to learn about anatomical motions. What motions involve increasing or decreasing the angle of the foot at the ankle?




Answer: Dorsiflexion of the foot at the ankle decreases the angle of the ankle joint, while plantar flexion increases the angle of the ankle joint.

## Chapter Review

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: 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: 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: 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: 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: C

## Critical Thinking Questions

Q. Briefly define the types of joint movements available at a ball-and-socket joint.

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.

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

**Learning Objectives**

- 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) (see [link]). 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 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**). A strong 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.”

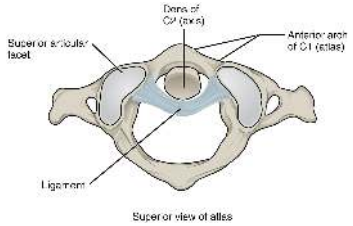



Figure **8.7.1**: Atlantoaxial Joint. The atlantoaxial joint is a pivot type of joint between the dens portion of the axis (C2 vertebra) and the anterior arch of the atlas (C1 vertebra), with the dens held in place by a ligament.

## 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 side-to-side 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, 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 his or her 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.

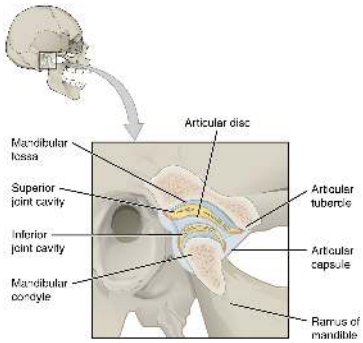
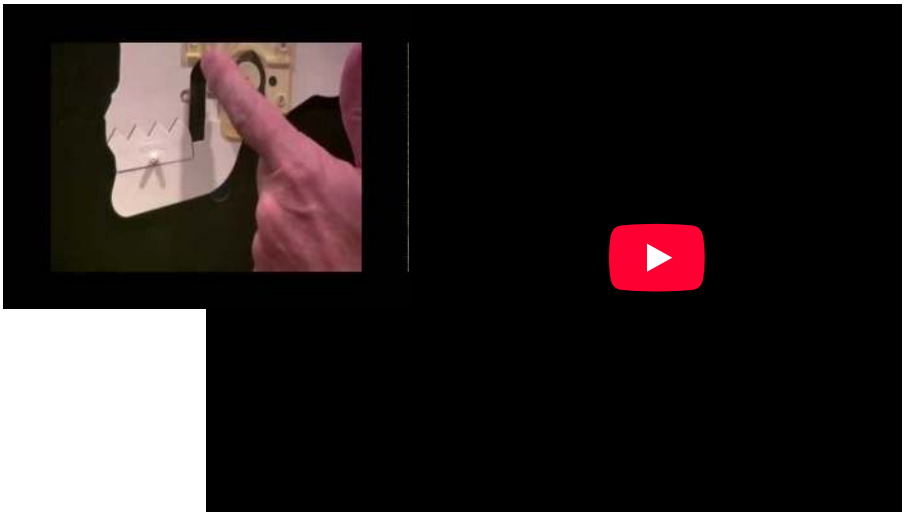



Figure **8.7.2**: Temporomandibular Joint. The temporomandibular joint is the articulation between the temporal bone of the skull and the condyle of the mandible, with an articular disc located between these bones. During depression of the mandible (opening of the mouth), the mandibular condyle moves both forward and hinges downward as it travels from the mandibular fossa onto the articular tubercle.

*Watch this video to learn about TMJ. Opening of the mouth requires the combination of two motions at the temporomandibular joint, an anterior gliding motion of the articular disc and mandible and the downward hinging of the mandible. What is the initial movement of the mandible during opening and how much mouth opening does this produce?*



## 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.

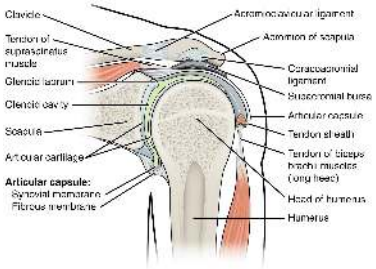



Figure **8.7.3**: Glenohumeral Joint. The glenohumeral (shoulder) joint is a ball-and-socket joint that provides the widest range of motions. It has a loose articular capsule and is supported by ligaments and the rotator cuff muscles.

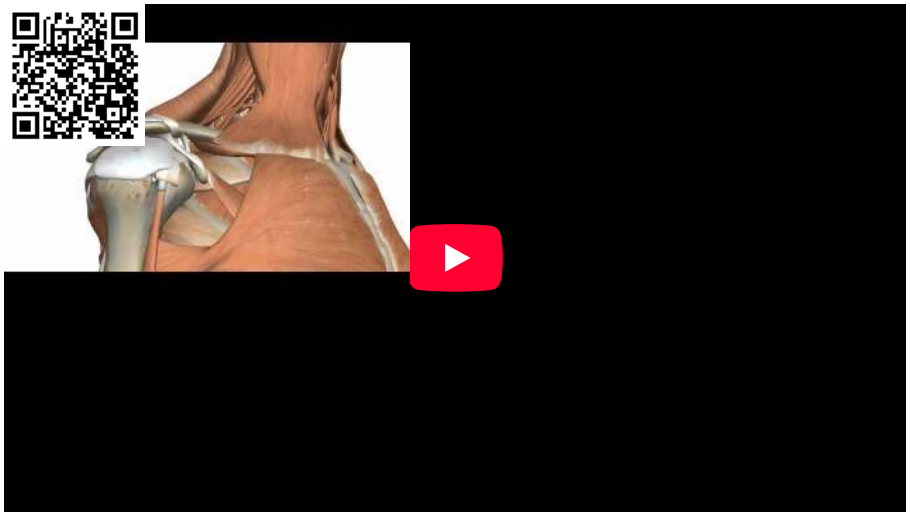
The large range of motions at the shoulder joint is provided by the articulation of the large, rounded humeral head with the small and shallow glenoid cavity, which is only about one third of the size of the humeral head. The socket formed by the glenoid cavity is deepened slightly by a small lip of fibrocartilage called the **glenoid labrum**, which extends around the outer margin of the cavity. The articular capsule that surrounds the glenohumeral joint is 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.

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**. 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").

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*Watch this video for a tutorial on the anatomy of the shoulder joint. What movements are available at the shoulder joint?*



QR Code representing a URL

*Watch this video to learn more about the anatomy of the shoulder joint, including bones, joints, muscles, nerves, and blood vessels. What is the shape of the glenoid labrum in cross-section, and what is the importance of this shape?*

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## 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 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.

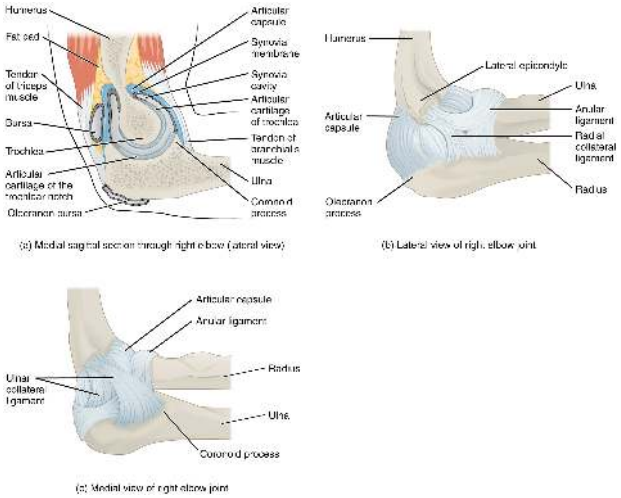



Figure 8.7.4: Elbow Joint. (a) The elbow is a hinge joint that allows only for flexion and extension of the forearm. (b) It is supported by the ulnar and radial collateral ligaments. (c) The annular ligament supports the head of the radius at the proximal radioulnar joint, the pivot joint that allows for rotation of the radius.

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Watch this animation to learn more about the anatomy of the elbow joint. Which structures provide the main stability for the elbow?




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*Watch this video to learn more about the anatomy of the elbow joint, including bones, joints, muscles, nerves, and blood vessels. What are the functions of the articular cartilage?*

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### Hip Joint

The hip 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 at 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).

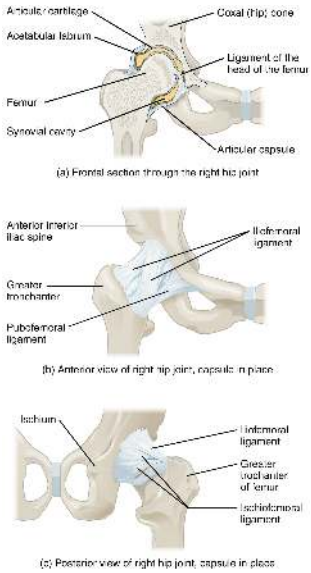
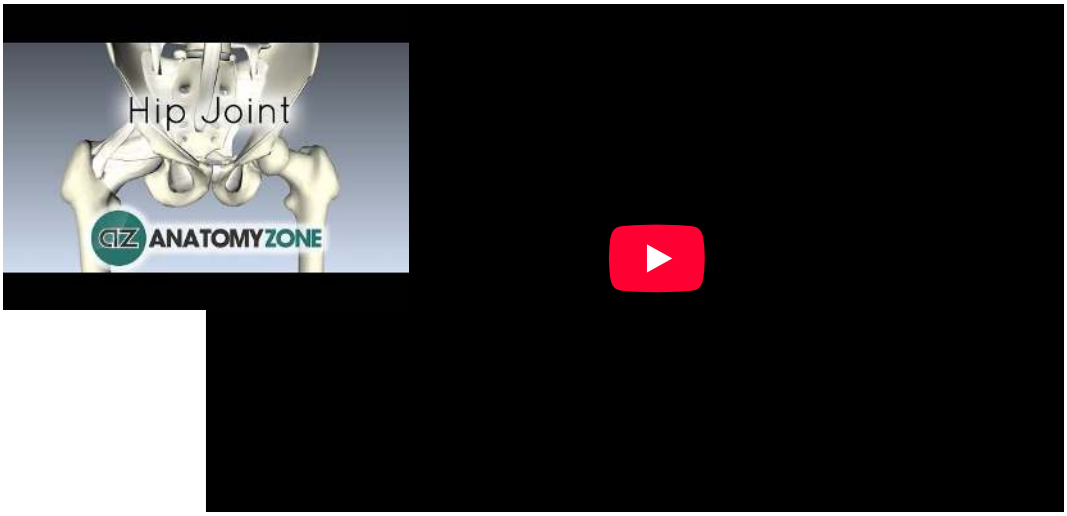



Figure **8.7.5**: Hip Joint. (a) The ball-and-socket joint of the hip is a multiaxial joint that provides both stability and a wide range of motion. (b–c) When standing, the supporting ligaments are tight, pulling the head of the femur into the acetabulum.

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Watch this video for a tutorial 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?




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*Watch this video to learn more about the anatomy of the hip joint, including bones, joints, muscles, nerves, and blood vessels. Where is the articular cartilage thickest within the hip joint?*

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## 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.

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** (see Figure9.6.6.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 (see Figure9.6.6.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.

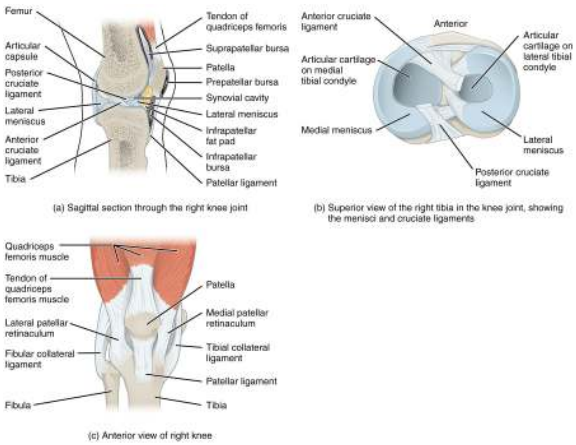
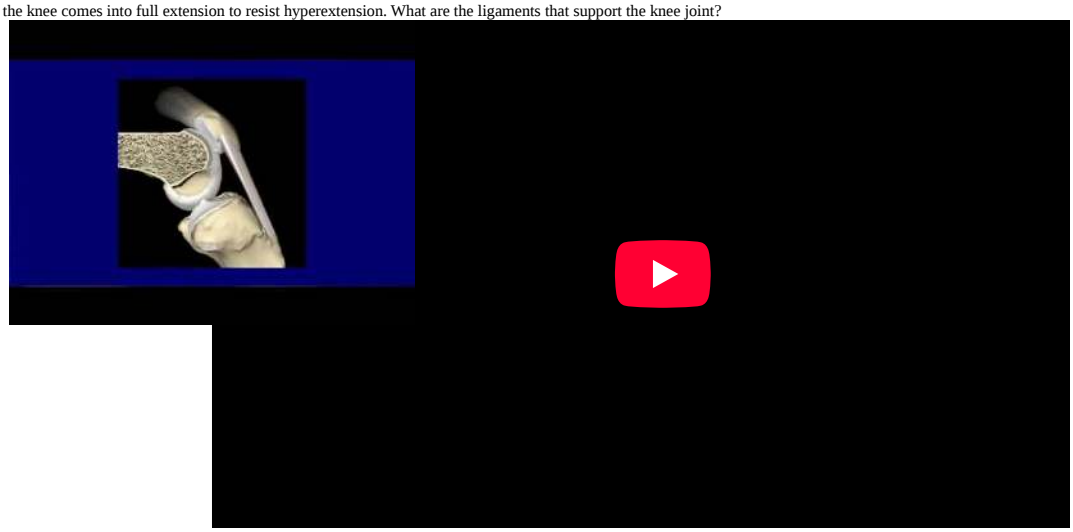



Figure **8.7.6**: Knee Joint. (a) The knee joint is the largest joint of the body. (b)–(c) It is supported by the tibial and fibular collateral ligaments located on the sides of the knee outside of the articular capsule, and the anterior and posterior cruciate ligaments found inside the capsule. The medial and lateral menisci provide padding and support between the femoral condyles and tibial condyles.

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Watch this video to learn more about the flexion and extension of the knee, as the femur both rolls and glides on the tibia to maintain stable contact between the bones in all knee positions. The patella glides along a groove on the anterior side of the distal femur. The collateral ligaments on the sides of the knee become tight in the fully extended position to help stabilize the knee. The posterior cruciate ligament supports the knee when flexed and the anterior cruciate ligament becomes tight when the knee comes into full extension to resist hyperextension. What are the ligaments that support the knee joint?



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*Watch this video to learn more about the anatomy of the knee joint, including bones, joints, muscles, nerves, and blood vessels. Which ligament of the knee keeps the tibia from sliding too far forward in relation to the femur and which ligament keeps the tibia from sliding too far backward?*


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**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.

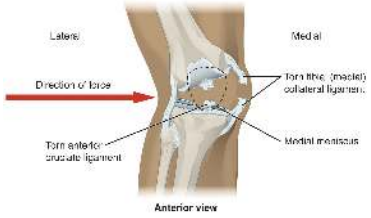
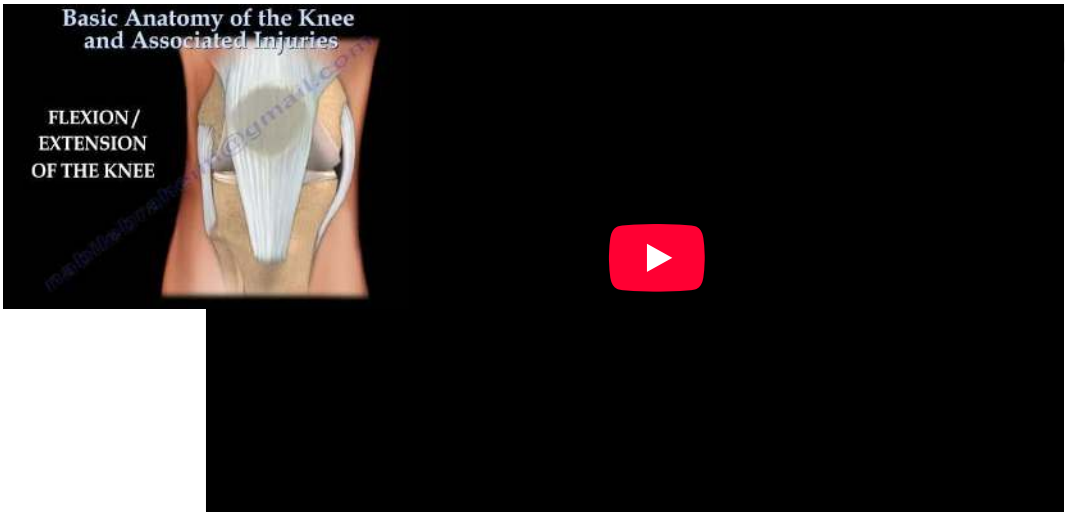



Figure **8.7.7**: Knee Injury. A strong blow to the lateral side of the extended knee will cause three injuries, in sequence: tearing of the tibial collateral ligament, damage to the medial meniscus, and rupture of the anterior cruciate ligament.

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Watch this video to learn more about different knee injuries and diagnostic testing of the knee. What are the most common causes of anterior cruciate ligament injury?




## 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.

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**. 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.

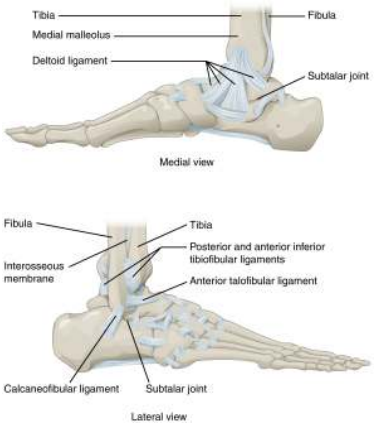
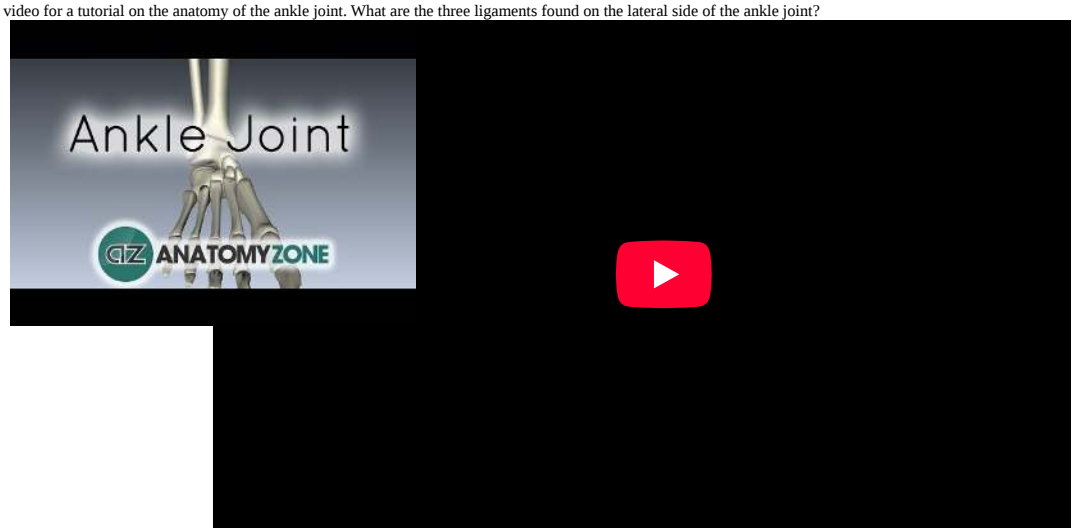



Figure **8.7.8**: Ankle Joint. The talocrural (ankle) joint is a uniaxial hinge joint that only allows for dorsiflexion or plantar flexion of the foot. Movements at the subtalar joint, between the talus and calcaneus bones, combined with motions at other intertarsal joints, enables eversion/inversion 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.

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Watch this video for a tutorial on the anatomy of the ankle joint. What are the three ligaments found on the lateral side of the ankle joint?




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*Watch this video to learn more about the anatomy of the ankle joint, including bones, joints, muscles, nerves, and blood vessels. Which type of joint used in woodworking does the ankle joint resemble?*

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**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.

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*Watch this video to learn more about the ligaments of the ankle joint, ankle sprains, and treatment. During an inversion ankle sprain injury, all three ligaments that resist excessive inversion of the foot may be injured. What is the sequence in which these three ligaments are injured?*




## Chapter 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 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.

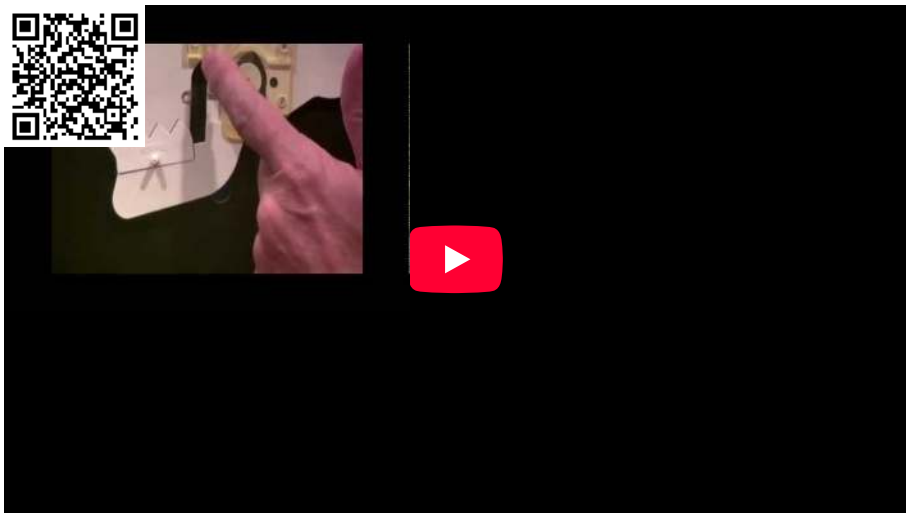
The knee includes three articulations. The femoropatellar joint is between the patella and distal femur. The patella, a sesamoid bone incorporated into the tendon of the quadriceps femoris muscle of the anterior thigh, serves to protect this tendon from rubbing against the distal femur during knee movements. 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.

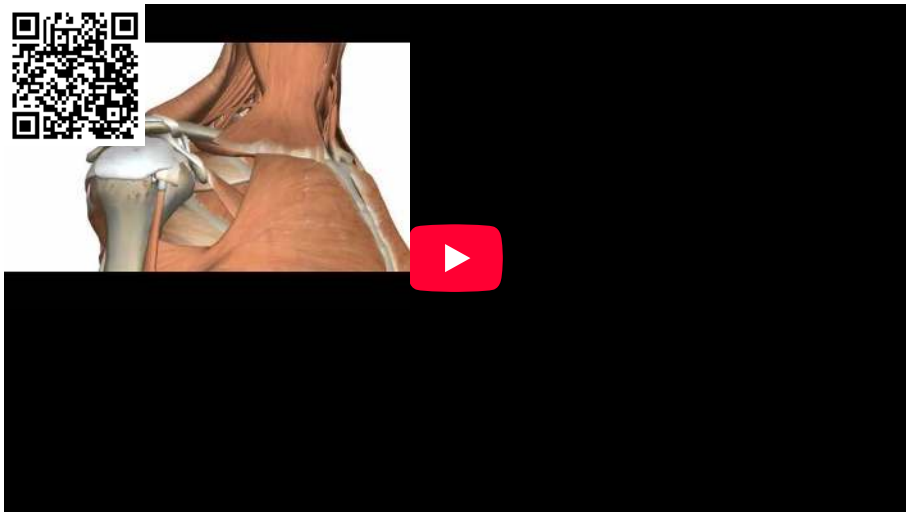
## Interactive Link Questions

Watch this video to learn about TMJ. Opening of the mouth requires the combination of two motions at the temporomandibular joint, an anterior gliding motion of the articular disc and mandible and the downward hinging of the mandible. What is the initial movement of the mandible during opening and how much mouth opening does this produce?



Answer: The first motion is rotation (hinging) of the mandible, but this only produces about 20 mm (0.78 in) of mouth opening.

Watch this video for a tutorial on the anatomy of the shoulder joint. What movements are available at the shoulder joint?



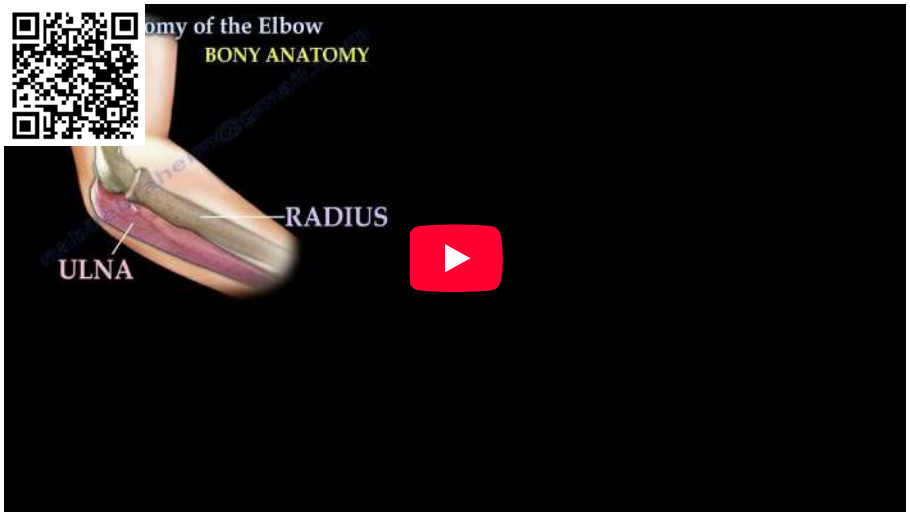
Answer: The shoulder joint is a ball-and-socket joint that allows for flexion-extension, abduction-adduction, medial rotation, lateral rotation, and circumduction of the humerus.

Watch this video to learn about the anatomy of the shoulder joint, including bones, joints, muscles, nerves, and blood vessels. What is the shape of the glenoid labrum in cross-section, and what is the importance of this shape?

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Answer: The glenoid labrum is wedge-shaped in cross-section. This is important because it creates an elevated rim around the glenoid cavity, which creates a deeper socket for the head of the humerus to fit into.

Watch this animation to learn more about the anatomy of the elbow joint. What structures provide the main stability for the elbow?




Answer: The structures that stabilize the elbow include the coronoid process, the radial (lateral) collateral ligament, and the anterior portion of the ulnar (medial) collateral ligament.

Watch this video to learn more about the anatomy of the elbow joint, including bones, joints, muscles, nerves, and blood vessels. What are the functions of the articular cartilage?

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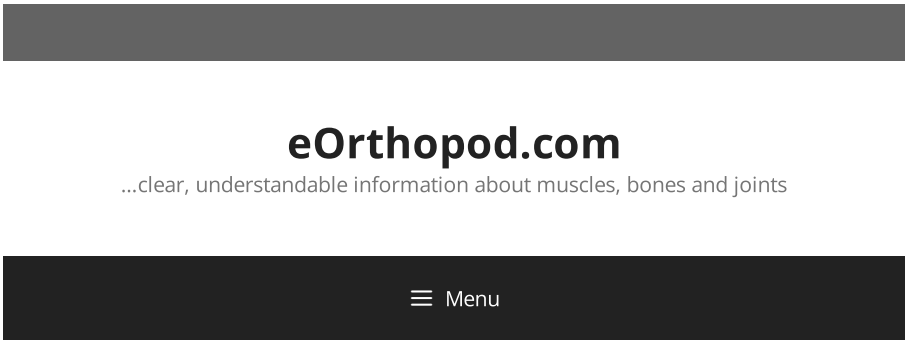
Answer: The articular cartilage functions to absorb shock and to provide an extremely smooth surface that makes movement between bones easy, without damaging the bones.

Watch this video for a tutorial 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: 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.

Watch this video to learn more about the anatomy of the hip joint, including bones, joints, muscles, nerves, and blood vessels. Where is the articular cartilage thickest within the hip joint?




Answer: The articular cartilage is thickest in the upper and back part of the acetabulum, the socket portion of the hip joint. These regions receive most of the force from the head of the femur during walking and running.

Watch this video to learn more about the flexion and extension of the knee, as the femur both rolls and glides on the tibia to maintain stable contact between the bones in all knee positions. The patella glides along a groove on the anterior side of the distal femur. The collateral ligaments on the sides of the knee become tight in the fully extended position to help stabilize the knee. The posterior cruciate ligament supports the knee when flexed and the anterior cruciate ligament becomes tight when the knee comes into full extension to resist hyperextension. What are the ligaments that support the knee joint?



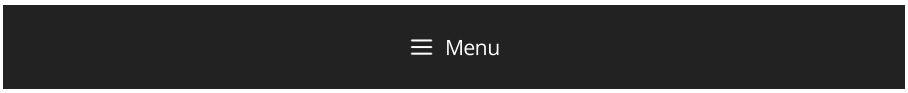
Answer: There are five ligaments associated with the knee joint. The tibial collateral ligament is located on the medial side of the knee and the fibular collateral ligament is located on the lateral side. The anterior and posterior cruciate ligaments are located inside the knee joint.

Watch this video to learn more about the anatomy of the knee joint, including bones, joints, muscles, nerves, and blood vessels. Which ligament of the knee keeps the tibia from sliding too far forward in relation to the femur and which ligament keeps the tibia from sliding too far backward?



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Answer: The anterior cruciate ligament prevents the tibia from sliding too far forward in relation to the femur and the posterior cruciate ligament keeps the tibia from sliding too far backward.

Watch this video to learn more about different knee injuries and diagnostic testing of the knee. What are the most causes of anterior cruciate ligament injury?




Answer: The anterior cruciate ligament (ACL) is most commonly injured when traumatic force is applied to the knee during a twisting motion or when side standing or landing from a jump.

Watch this video for a tutorial on the anatomy of the ankle joint. What are the three ligaments found on the lateral side of the ankle joint?




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.

Watch this video to learn more about the anatomy of the ankle joint, including bones, joints, muscles, nerves, and blood vessels. The ankle joint resembles what type of joint used in woodworking?

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Answer: Because of the square shape of the ankle joint, it has been compared to a mortise-and-tendon type of joint.

Watch this video to learn about the ligaments of the ankle joint, ankle sprains, and treatment. During an inversion ankle sprain injury, all three ligaments that resist excessive inversion of the foot may be injured. What is the sequence in which these three ligaments are injured?




Answer: QAn inversion ankle sprain may injure all three ligaments located on the lateral side of the ankle. The sequence of injury would be the anterior talofibular ligament first, followed by the calcaneofibular ligament second, and finally, the posterior talofibular ligament third.

## 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: 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: 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: 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: 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: B

## Critical Thinking Questions

Q. Discuss the structures that contribute to support of the shoulder joint.

> 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.

> 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

**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

**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 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 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

**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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# CHAPTER OVERVIEW

## 9: Muscle Tissue

Muscle tissue is a soft tissue that composes muscles in animal bodies, and gives rise to muscles' ability to contract. This is opposed to other components or tissues in muscle such as tendons or perimysium. Muscle tissue varies with function and location in the body. In mammals the three types are: **skeletal** or striated muscle; **smooth** or non-striated muscle; and **cardiac** muscle, which is sometimes known as semi-striated.


9.1: Prelude 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: Cardiac Muscle Tissue
9.7: Smooth Muscle


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# 9.1: Prelude to Muscle Tissue

Athletes rely on toned skeletal muscles to supply the force required for movement. (credit: Emmanuel Huybrechts/flickr)

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# 9.2: Overview of Muscle Tissues

**Learning Objectives**

- Describe the different types of muscle
- Explain contractibility 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 three muscle tissues have some properties in common; 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 length of the membrane. 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.

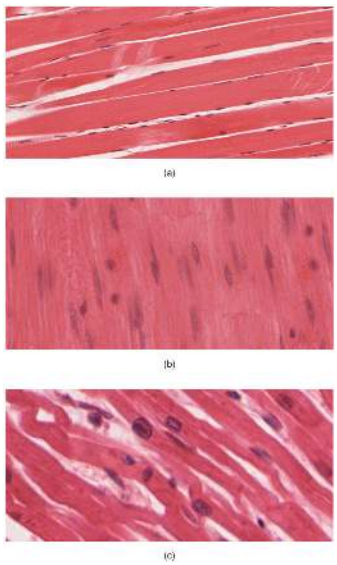


***Figure 9.2.1: The Three Types of Muscle Tissue.*** *The body contains three types of muscle tissue: (a) skeletal muscle, (b) smooth muscle, and (c) cardiac muscle. From top, LM × 1600, LM × 1600, LM × 1600. (Micrographs provided by the Regents of University of Michigan Medical School © 2012)*

The muscles all begin the actual process of contracting (shortening) when a protein called actin is pulled by a protein called myosin. This occurs in striated muscle (skeletal and cardiac) after specific binding sites on the actin have been exposed in response to the interaction between calcium ions ($Ca^{++}$) and proteins (troponin and tropomyosin) that "shield" the actin-binding sites. $Ca^{++}$ 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 and the actin-binding sites are re-shielded.

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 fibers. Muscle tissue also has the quality of **extensibility**; it can stretch or extend. **Contractility** allows muscle tissue to pull on its attachment points and shorten with force.

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.c). **Skeletal muscle** fibers are multinucleated structures 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.

## Chapter 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: D

Q. Which element is important in directly triggering contraction?

A. sodium ($Na^+$)

B. calcium ($Ca^{++}$)

C. potassium ($K^+$)

D. chloride ($Cl^-$)

Answer: B

Q. Which of the following properties is *not* common to all three muscle tissues?

A. excitability

B. the need for ATP

C. at rest, uses shielding proteins to cover actin-binding sites

D. elasticity

Answer: C

## Critical Thinking Questions

Q. Why is elasticity an important quality of muscle tissue?

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


- Whitney Menefee, Julie Jenks, Chiara Mazzasette, & Kim-Leiloni Nguyen
- Reedley College, Butte College, Pasadena City College, & Mt. San Antonio College via ASCCC Open Educational Resources Initiative


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 9.3.19.3.1). 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.

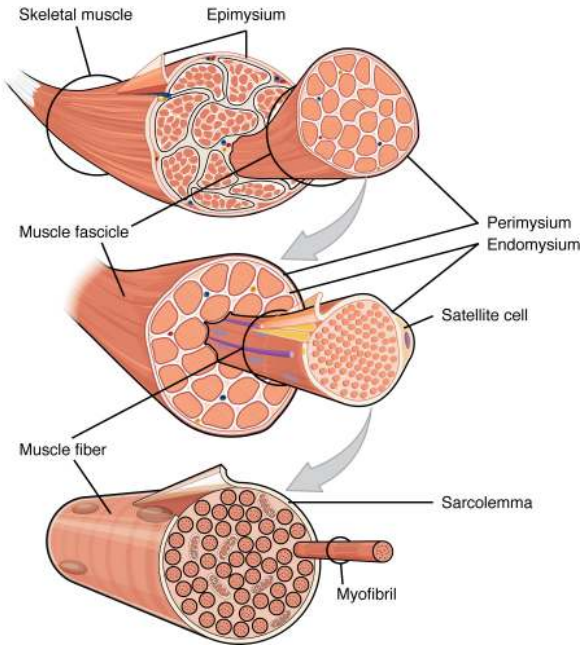



Figure 9.3.1: The Three Connective Tissue Layers. Bundles of muscle fibers, called fascicles, are covered by the perimysium. Muscle fibers are covered by the endomysium. (Image credit: "The Three Connective Tissue Layers" by Openstax is licensed under CC BY 4.0)

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.

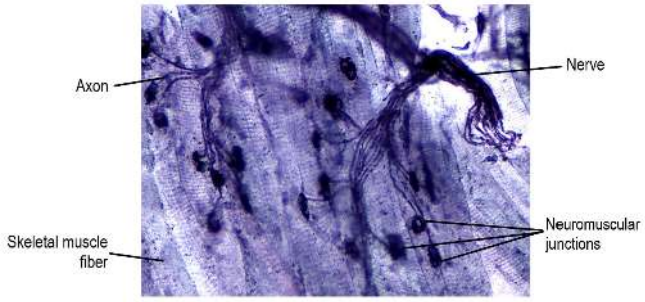



Figure 9.3.2: Neuromuscular Junctions. Every skeletal muscle fiber is innervated by a motor neuron at the neuromuscular junction. Signals from motor neurons initiate the process of muscle contraction. (Image credit: "Motor End Plate - Labeled" by Whitney Menefee is licensed under CC BY-SA 4.0 / A derivative 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 $\mu$m 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 $\mu$m 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 $\mu$m, 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.

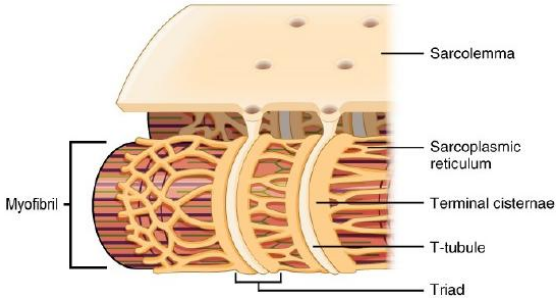



Figure 9.3.3: The Triad. Narrow T-tubules permit the conduction of electrical impulses. The SR functions to regulate intracellular levels of calcium. Two terminal cisternae (where enlarged SR connects to the T-tubule) and one T-tubule comprise a triad—a "threesome" of membranes, with those of SR on two 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 $\mu$m 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.

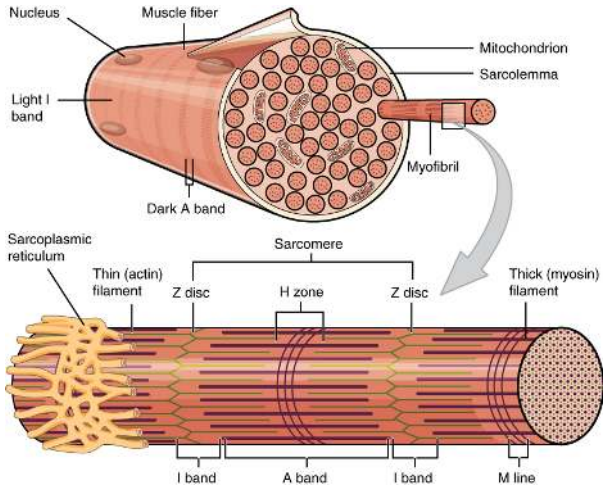



Figure 9.3.4: The Sarcomere. Myofibrils within the sarcoplasm are composed of chains of thousands of repeating sarcomeres. (Image credit: "Muscle Fibers" by Openstax is licensed under CC BY 4.0)

## 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.

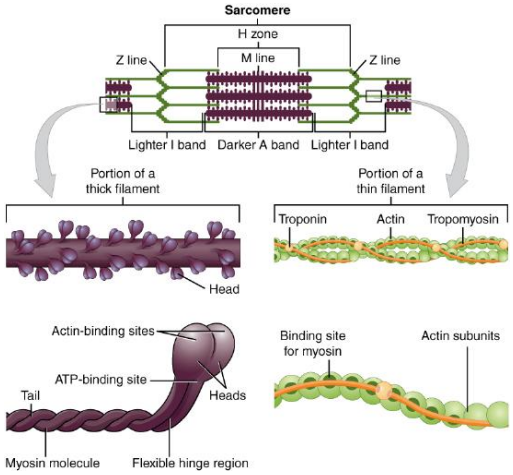



Figure 9.3.5: Myofilaments. The sarcomere, the region from one Z-line to the next Z-line, is the functional unit of a skeletal muscle fiber and is composed of a repeating arrangements of actin and myosin, along with other proteins. (Image credit: "Thick and Thin Filaments" by Openstax is licensed under CC BY 4.0)

## Chapter 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 in the cell. Muscles attach to bones directly or through tendons or aponeuroses. Skeletal muscles maintain posture, stabilize bones and joints, 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. Muscle fibers are composed of myofibrils. The striations are created by the organization of actin and myosin resulting in the banding pattern of myofibrils.

## Interactive Link Questions

Watch this video to learn more about macro- and microstructures of skeletal muscles. (a) What are the names of the “junction points” between sarcomeres? (b) What are the names of the “subunits” within the myofibrils that run the length of skeletal muscle fibers? (c) What is the “double strand of pearls” described in the video? (d) What gives a skeletal muscle fiber its striated appearance?



Answer: (a) Z-lines. (b) Sarcomeres. (c) This is the arrangement of the actin and myosin filaments in a sarcomere. (d) The alternating strands of actin and myosin filaments.

Every skeletal muscle fiber is supplied by a motor neuron at the NMJ. Watch this video to learn more about what happens at the neuromuscular junction. (a) What is the definition of a motor unit? (b) What is the structural and functional difference between a large motor unit and a small motor unit? Can you give an example of each? (c) Why is the neurotransmitter acetylcholine degraded after binding to its receptor?



Answer: (a) It is the number of skeletal muscle fibers supplied by a single motor neuron. (b) A large motor unit has one neuron supplying many skeletal muscle fibers for gross movements, like the Temporalis muscle, where 1000 fibers are supplied by one neuron. A small motor has one neuron supplying few skeletal muscle fibers for very fine movements, like the extraocular eye muscles, where six fibers are supplied by one neuron. (c) To avoid prolongation of muscle contraction.

## Review Questions

Q. The correct order for the smallest to the largest unit of organization in muscle tissue is _____.

A. fascicle, filament, muscle fiber, myofibril

B. filament, myofibril, muscle fiber, fascicle

C. muscle fiber, fascicle, filament, myofibril

D. myofibril, muscle fiber, filament, fascicle

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: A

## Critical Thinking Questions

Q. What would happen to skeletal muscle if the epimysium were destroyed?

A. Muscles would lose their integrity during powerful movements, resulting in muscle damage.

Q. Describe how tendons facilitate body movement.

> 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?

> 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?

> 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

**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

**motor end-plate**
sarcolemma of muscle fiber at the neuromuscular junction, with receptors for the neurotransmitter acetylcholine

**myofibril**
long, cylindrical organelle that runs parallel within the muscle fiber and contains the sarcomeres

**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 $Ca^{++}$

**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

**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

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# 9.4: Muscle Fiber Contraction and Relaxation

**Learning Objectives**

- 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, ACh—from the motor neuron innervating that fiber. The local membrane of the fiber will depolarize as positively charged sodium ions ($Na^{+}$) enter, triggering an action potential that spreads to the rest of the membrane will depolarize, including the T-tubules. This triggers the release of calcium ions ($Ca^{++}$) from storage in the sarcoplasmic reticulum (SR). The $Ca^{++}$ then initiates contraction, which is sustained by ATP (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.

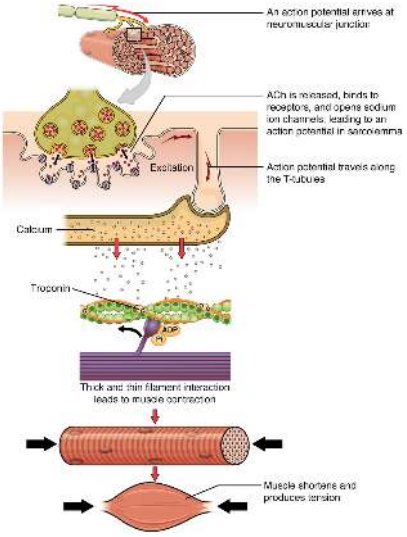



Figure **9.4.1**: Contraction of a Muscle Fiber. A cross-bridge forms between actin and the myosin heads triggering contraction. As long as $Ca^{++}$ ions remain in the sarcoplasm to bind to troponin, and as long as ATP is available, the muscle fiber will continue to shorten.

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, which causes the tropomyosin to reshield (or re-cover) the binding sites on the actin strands. A muscle also can stop contracting when it runs out of ATP and becomes fatigued (Figure **9.4.2**).

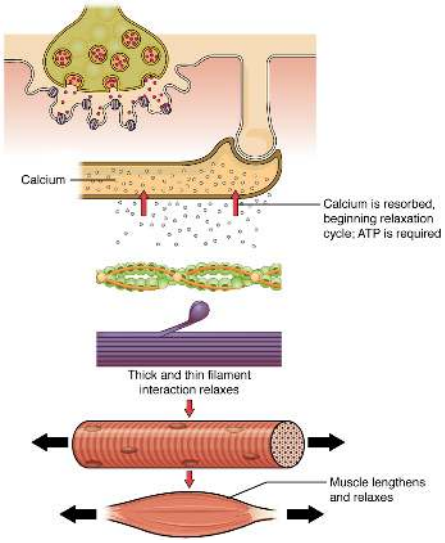
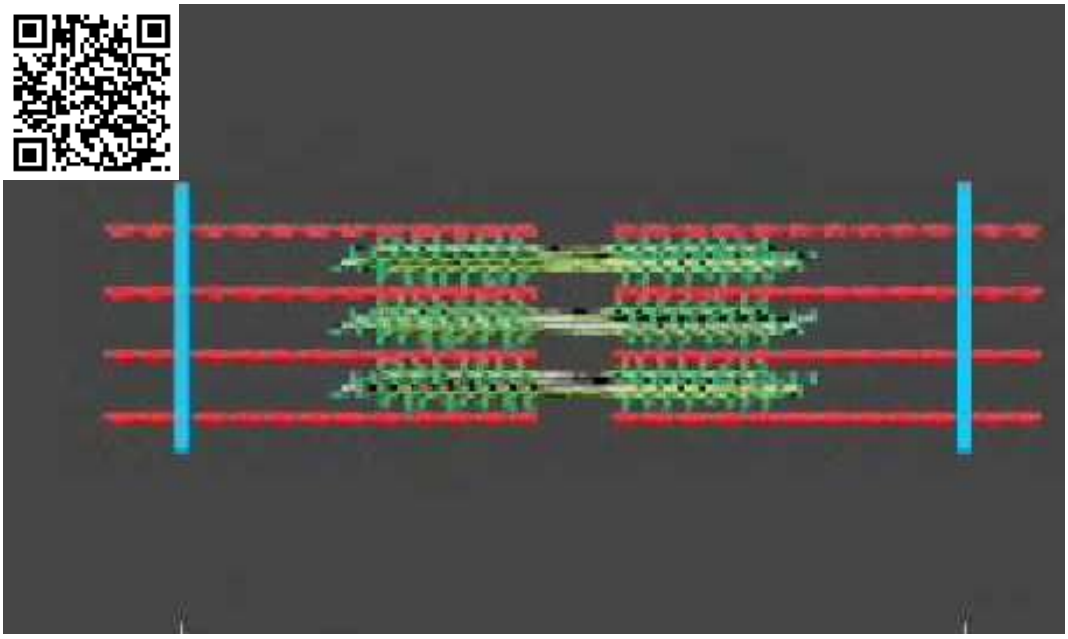



Figure **9.4.2**: Relaxation of a Muscle Fiber. $Ca^{++}$ ions are pumped back into the SR, which causes the tropomyosin to reshield the binding sites on the actin strands. A muscle may also stop contracting when it runs out of ATP and becomes fatigued.

The release of calcium ions initiates muscle contractions. Watch this video to learn more about the role of calcium. (a) What are "T-tubules" and what is their role? (b) Please describe how actin-binding sites are made available for cross-bridging with myosin heads during contraction.



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, anchored at their bases at a spot called the M-line. A myofibril is composed of many sarcomeres running along its length; thus, myofibrils and muscle cells contract as the sarcomeres contract.

## Muscle Strength

The number 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 the increased mass and

bulk in a skeletal muscle. Likewise, decreased use of a skeletal muscle results in atrophy, where the number of sarcomeres and myofibrils disappear (but not the number of muscle fibers). It is common for a limb in a cast to show atrophied muscles when the cast is removed, and certain diseases, such as polio, show atrophied muscles.

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 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.

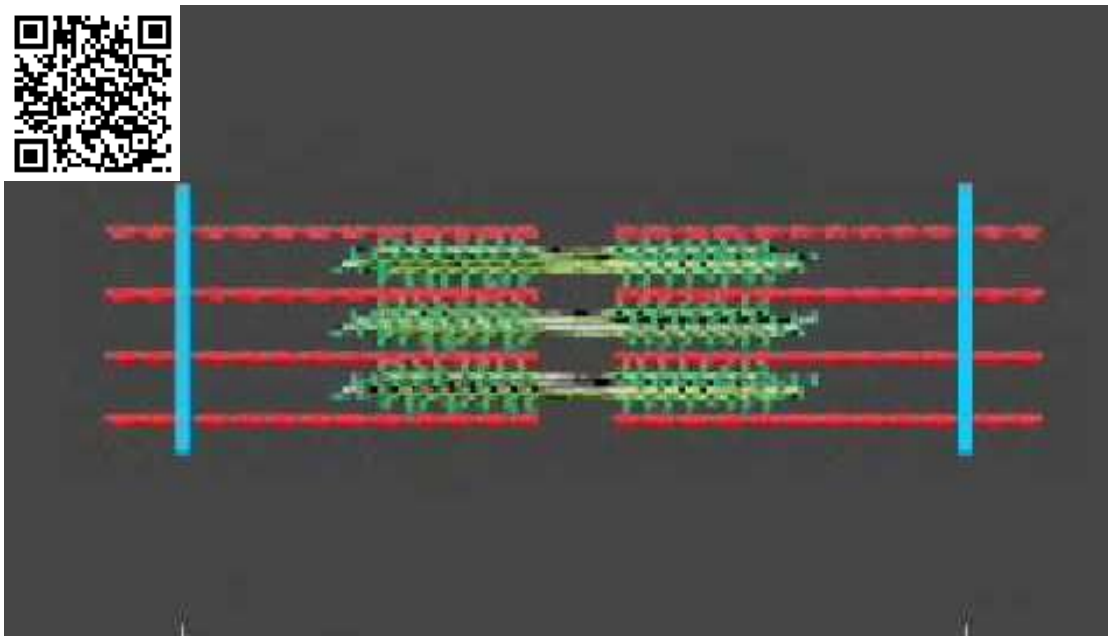
## Chapter Review

A sarcomere is 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.

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 SR. The actin sites are exposed after $Ca^{++}$ enters the sarcoplasm from its SR storage to activate the troponin-tropomyosin complex so that the tropomyosin shifts away from the sites. The cross-bridging of myposin heads docking into actin-binding sites is followed by the "power stroke"—the sliding of the thin filaments by thick filaments. The power strokes are powered by ATP. Ultimately, the sarcomeres, myofibrils, and muscle fibers shorten to produce movement.

## Interactive Link Questions

The release of calcium ions initiates muscle contractions. Watch this video to learn more about the role of calcium. (a) What are "T-tubules" and what is their role? (b) Please also describe how actin-binding sites are made available for cross-bridging with myosin heads during contraction.



Answer: (a) The T-tubules are inward extensions of the sarcolemma that trigger the release of $Ca^{++}$ from SR during an Action Potential. (b) $Ca^{++}$ binds to tropomyosin, and this slides the tropomyosin rods away from the binding sites.

## Review Questions

Q. In relaxed muscle, the myosin-binding site on actin is blocked by _____.

A. titin

B. troponin

C. myoglobin

D. tropomyosin

Answer: D

Q. The cell membrane of a muscle fiber is called _____.

A. myofibril

B. sarcolemma

C. sarcoplasm

D. myofilament

Answer: B

Q. Thin and thick filaments are organized into functional units called _____.

A. myofibrils

B. myofilaments

C. T-tubules

D. sarcomeres

Answer: D

## Critical Thinking Questions

Q. What causes the striated appearance of skeletal muscle tissue?

A. Dark A bands and light I bands repeat along myofibrils, and the alignment of myofibrils in the cell cause the entire cell to appear striated.

## 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

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## 9.5: Types of Muscle Fibers

**Learning Objectives**

- 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 (oxygen and glucose) to produce ATP. **Fast oxidative (FO)** fibers have fast contractions and primarily use aerobic respiration, but because they may switch to anaerobic respiration (glycolysis), 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.

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 and do not produce a large amount of tension. 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.

FO fibers are sometimes called intermediate fibers because they possess characteristics that are intermediate between fast fibers and slow fibers. They produce 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.

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.

# Exercise and Muscle Performance

Physical training alters the appearance of skeletal muscles and can produce changes in muscle performance. Conversely, a lack of use can result in decreased performance and muscle appearance. Although muscle cells can change in size, new cells are not formed when muscles grow. Instead, structural proteins are added to muscle fibers in a process called **hypertrophy**, so cell diameter increases. The reverse, when structural proteins are lost and muscle mass decreases, is called **atrophy**. Age-related muscle atrophy is called **sarcopenia**. Cellular components of muscles can also undergo changes in response to changes in muscle use.

## Endurance Exercise

Slow fibers are predominantly used in endurance exercises that require little force but involve numerous repetitions. The aerobic metabolism used by slow-twitch fibers allows them to maintain contractions over long periods. Endurance training modifies these slow fibers to make them even more efficient by producing more mitochondria to enable more aerobic metabolism and more ATP production. Endurance exercise can also increase the amount of myoglobin in a cell, as increased aerobic respiration increases the need for oxygen. Myoglobin is found in the sarcoplasm and acts as an oxygen storage supply for the mitochondria.

The training can trigger the formation of more extensive capillary networks around the fiber, a process called **angiogenesis**, to supply oxygen and remove metabolic waste. To allow these capillary networks to supply the deep portions of the muscle, muscle mass does not greatly increase in order to maintain a smaller area for the diffusion of nutrients and gases. All of these cellular changes result in the ability to sustain low levels of muscle contractions for greater periods without fatiguing.

The proportion of SO muscle fibers in muscle determines the suitability of that muscle for endurance, and may benefit those participating in endurance activities. Postural muscles have a large number of SO fibers and relatively few FO and FG fibers, to keep the back straight (**Figure 5.1**). Endurance athletes, like marathon-runners also would benefit from a larger proportion of SO fibers, but it is unclear if the most-successful marathoners are those with naturally high numbers of SO fibers, or whether the most successful marathon runners develop high numbers of SO fibers with repetitive training. Endurance training can result in overuse injuries such as stress fractures and joint and tendon inflammation.




**Figure 5.1 Marathoners** Long-distance runners have a large number of SO fibers and relatively few FO and FG fibers. (credit: “Tseo2”/Wikimedia Commons)

## Resistance Exercise

Resistance exercises, as opposed to endurance exercise, require large amounts of FG fibers to produce short, powerful movements that are not repeated over long periods. The high rates of ATP hydrolysis and cross-bridge formation in FG fibers result in powerful muscle contractions. Muscles used for power have a higher ratio of FG to SO/FO fibers, and trained athletes possess even higher levels of FG fibers in their muscles. Resistance exercise affects muscles by increasing the formation of myofibrils, thereby increasing the thickness of muscle fibers. This added structure causes hypertrophy, or the enlargement of muscles, exemplified by the large skeletal muscles seen in body builders and other athletes (**Figure 5.2**). Because this muscular enlargement is achieved by the addition of structural proteins, athletes trying to build muscle mass often ingest large amounts of protein.



**Figure 5.2 Hypertrophy** Body builders have a large number of FG fibers and relatively few FO and SO fibers. (credit: Lin Mei/flickr)

Except for the hypertrophy that follows an increase in the number of sarcomeres and myofibrils in a skeletal muscle, the cellular changes observed during endurance training do not usually occur with resistance training. There is usually no significant increase in mitochondria or capillary density. However, resistance training does increase the development of connective tissue, which adds to the overall mass of the muscle and helps to contain muscles as they produce increasingly powerful contractions. Tendons also become stronger to prevent tendon damage, as the force produced by muscles is transferred to tendons that attach the muscle to bone.

For effective strength training, the intensity of the exercise must continually be increased. For instance, continued weight lifting without increasing the weight of the load does not increase muscle size. To produce ever-greater results, the weights lifted must become increasingly heavier, making it more difficult for muscles to move the load. The muscle then adapts to this heavier load, and an even heavier load must be used if even greater muscle mass is desired.

If done improperly, resistance training can lead to overuse injuries of the muscle, tendon, or bone. These injuries can occur if the load is too heavy or if the muscles are not given sufficient time between workouts to recover or if joints are not aligned properly during the exercises. Cellular damage to muscle fibers that occurs after intense exercise includes damage to the sarcolemma and myofibrils. This muscle damage contributes to the feeling of soreness after strenuous exercise, but muscles gain mass as this damage is repaired, and additional structural proteins are added to replace the damaged ones. Overworking skeletal muscles can also lead to tendon damage and even skeletal damage if the load is too great for the muscles to bear.

## Chapter Review

ATP provides the energy for muscle contraction. The three mechanisms for ATP regeneration are creatine phosphate, anaerobic glycolysis, and aerobic metabolism. Creatine phosphate provides about the first 15 seconds of ATP at the beginning of muscle contraction. Anaerobic glycolysis produces small amounts of ATP in the absence of oxygen for a short period. Aerobic metabolism utilizes oxygen to produce much more ATP, allowing a muscle to work for longer periods. Muscle fatigue, which has many contributing factors, occurs when muscle can no longer contract. An oxygen debt is created as a result of muscle use. 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. Muscle fatigue is caused by _____.

A. buildup of ATP and lactic acid levels

B. exhaustion of energy reserves and buildup of lactic acid levels

C. buildup of ATP and pyruvic acid levels

D. exhaustion of energy reserves and buildup of pyruvic acid levels

Answer: B

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: A

Q. What aspect of creatine phosphate allows it to supply energy to muscles?

A. ATPase activity

B. phosphate bonds

C. carbon bonds

D. hydrogen bonds

Answer: B

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: D

## Critical Thinking Questions

Q. Why do muscle cells use creatine phosphate instead of glycolysis to supply ATP for the first few seconds of muscle contraction?

A. Creatine phosphate is used because creatine phosphate and ADP are converted very quickly into ATP by creatine kinase. Glycolysis cannot generate ATP as quickly as creatine phosphate.

Q. Is aerobic respiration more or less efficient than glycolysis? Explain your answer.

A. Aerobic respiration is much more efficient than anaerobic glycolysis, yielding 36 ATP per molecule of glucose, as opposed to two ATP produced by glycolysis.

## 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: Cardiac Muscle Tissue

**Learning Objectives**

- Describe intercalated discs and gap junctions
- Describe a desmosome

Cardiac muscle tissue is only found in the heart. Highly coordinated contractions of cardiac muscle pump blood into the vessels of the circulatory system. Similar to skeletal muscle, cardiac muscle is striated and organized into sarcomeres, possessing the same banding organization as skeletal muscle (Figure **9.6.1**). However, cardiac muscle fibers are shorter than skeletal muscle fibers and usually contain only one nucleus, which is located in the central region of the cell. Cardiac muscle fibers also possess many mitochondria and myoglobin, as ATP is produced primarily through aerobic metabolism. Cardiac muscle fibers cells also are extensively branched and are connected to one another at their ends by intercalated discs. An **intercalated disc** allows the cardiac muscle cells to contract in a wave-like pattern so that the heart can work as a pump.

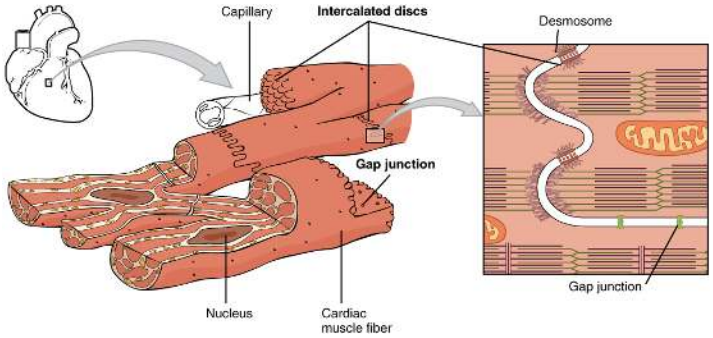



Figure **9.6.2**: Cardiac Muscle. Intercalated discs are part of the cardiac muscle sarcolemma and they contain gap junctions and desmosomes.

Contractions of the heart (heartbeats) are controlled by specialized cardiac muscle cells called pacemaker cells that directly control heart rate. Although cardiac muscle cannot be consciously controlled, the pacemaker cells respond to signals from the autonomic nervous system (ANS) to speed up or slow down the heart rate. The pacemaker cells can also respond to various hormones that modulate heart rate to control blood pressure.

The wave of contraction that allows the heart to work as a unit, called a functional syncytium, begins with the pacemaker cells. This group of cells is self-excitable and able to depolarize to threshold and fire action potentials on their own, a feature called **autorhythmicity**; they do this at set intervals which determine heart rate. Because they are connected with gap junctions to surrounding muscle fibers and the specialized fibers of the heart's conduction system, the pacemaker cells are able to transfer the depolarization to the other cardiac muscle fibers in a manner that allows the heart to contract in a coordinated manner.

Another feature of cardiac muscle is its relatively long action potentials in its fibers, having a sustained depolarization "plateau." The plateau is produced by $Ca^{++}$ entry though voltage-gated calcium channels in the sarcolemma of cardiac muscle fibers. This sustained depolarization (and $Ca^{++}$ entry) provides for a longer contraction than is produced by an action potential in skeletal muscle. Unlike skeletal muscle, a large percentage of the $Ca^{++}$ that initiates contraction in cardiac muscles comes from outside the cell rather than from the SR.

## Chapter Review

Cardiac muscle is striated muscle that is present only in the heart. Cardiac muscle fibers have a single nucleus, are branched, and joined to one another by intercalated discs that contain gap junctions for depolarization between cells and desmosomes to hold the fibers together when the heart contracts. Contraction in each cardiac muscle fiber is triggered by $Ca^{++}$ ions in a similar manner as skeletal muscle, but here the $Ca^{++}$ ions come from SR and through voltage-gated calcium channels in the sarcolemma. Pacemaker cells stimulate the spontaneous contraction of cardiac muscle as a functional unit, called a syncytium.

## Review Questions

Q. Cardiac muscles differ from skeletal muscles in that they _____.

A. are striated

B. utilize aerobic metabolism

C. contain myofibrils

D. contain intercalated discs

Answer: D

Q. If cardiac muscle cells were prevented from undergoing aerobic metabolism, they ultimately would _____.

A. undergo glycolysis

B. synthesize ATP

C. stop contracting

D. start contracting

Answer: C

## Critical Thinking Questions

Q. What would be the drawback of cardiac contractions being the same duration as skeletal muscle contractions?

A. An action potential could reach a cardiac muscle cell before it has entered the relaxation phase, resulting in the sustained contractions of tetanus. If this happened, the heart would not beat regularly.

Q. How are cardiac muscle cells similar to and different from skeletal muscle cells?

A. Cardiac and skeletal muscle cells both contain ordered myofibrils and are striated. Cardiac muscle cells are branched and contain intercalated discs, which skeletal muscles do not have.

## Glossary

**autorhythmicity**
heart's ability to control its own contractions

**desmosome**
cell structure that anchors the ends of cardiac muscle fibers to allow contraction to occur

**intercalated disc**
part of the sarcolemma that connects cardiac tissue, and contains gap junctions and desmosomes

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# 9.7: Smooth Muscle

**Learning Objectives**

- Describe a dense body
- Explain how smooth muscle works with internal organs and passageways through the body
- Explain how smooth muscles differ from skeletal and cardiac muscles
- Explain the difference between single-unit and multi-unit smooth muscle

Smooth muscle (so-named because the cells do not have striations) is present in the walls of hollow organs like the urinary bladder, uterus, stomach, intestines, and in the walls of passageways, such as the arteries and veins of the circulatory system, and the tracts of the respiratory, urinary, and reproductive systems (Figure **9.7.1**.a,b). 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.

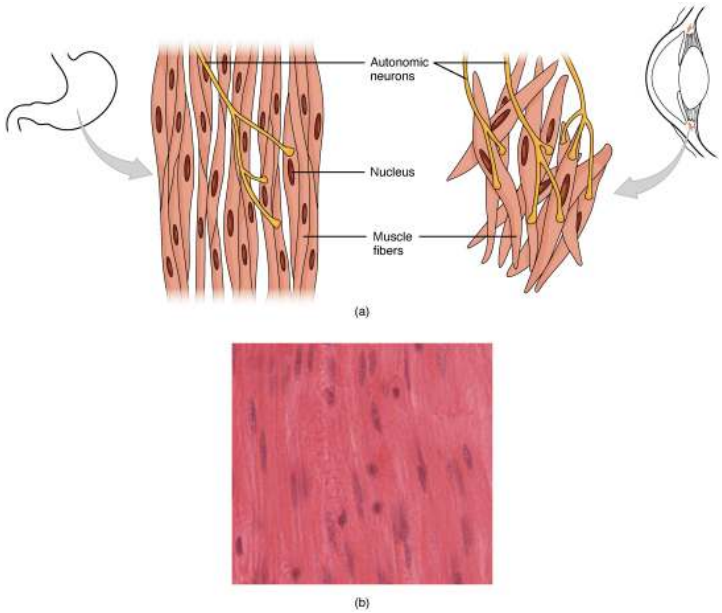



Figure **9.7.1**: Smooth Muscle Tissue. Smooth muscle tissue is found around organs in the digestive, respiratory, reproductive tracts and the iris of the eye. LM × 1600. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

QR Code representing a URL

View the University of Michigan WebScope at virtualslides.med.umich.edu/H....svs/view.apml to explore the tissue sample in greater detail.

Smooth muscle fibers are spindle-shaped (wide in the middle and tapered at both ends, somewhat like a football) and have a single nucleus; they range from about 30 to 200 $\mu$m (thousands of times shorter than skeletal muscle fibers), and they produce their own connective tissue, endomysium. Although they do not have striations and sarcomeres, smooth muscle fibers do have actin and myosin contractile proteins, and thick and thin filaments. These thin filaments are anchored by dense bodies. A **dense body** is analogous to the Z-discs of skeletal and cardiac muscle fibers and is fastened to the sarcolemma. Calcium ions are supplied by the SR in the fibers and by sequestration from the extracellular fluid through membrane indentations called calveoli.

Because smooth muscle cells do not contain troponin, cross-bridge formation is not regulated by the troponin-tropomyosin complex but instead by the regulatory protein **calmodulin**. In a smooth muscle fiber, external $Ca^{++}$ ions passing through opened calcium channels in the sarcolemma, and additional $Ca^{++}$ released from SR, bind to calmodulin. The $Ca^{++}$-calmodulin complex then activates an enzyme called myosin (light chain) kinase, which, in turn, activates the myosin heads by phosphorylating them (converting ATP to ADP and $P_i$, with the $P_i$ attaching to the head). The heads can then attach to actin-binding sites and pull on the thin filaments. The thin filaments also are anchored to the dense bodies; the structures invested in the inner membrane of the sarcolemma (at adherens junctions) that also have cord-like intermediate filaments attached to them. When the thin filaments slide

past the thick filaments, they pull on the dense bodies, structures tethered to the sarcolemma, which then pull on the intermediate filaments networks throughout the sarcoplasm. This arrangement causes the entire muscle fiber to contract in a manner whereby the ends are pulled toward the center, causing the midsection to bulge in a corkscrew motion (Figure **9.7.2**).

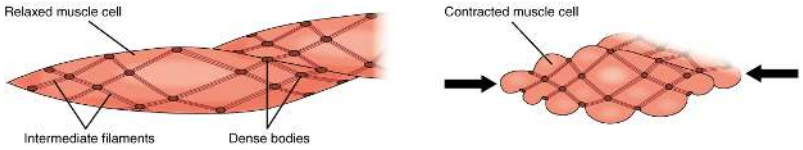



Figure **9.7.2**: Muscle Contraction. The dense bodies and intermediate filaments are networked through the sarcoplasm, which cause the muscle fiber to contract.

Although smooth muscle contraction relies on the presence of $Ca^{++}$ ions, smooth muscle fibers have a much smaller diameter than skeletal muscle cells. T-tubules are not required to reach the interior of the cell and therefore not necessary to transmit an action potential deep into the fiber. Smooth muscle fibers have a limited calcium-storing SR but have calcium channels in the sarcolemma (similar to cardiac muscle fibers) that open during the action potential along the sarcolemma. The influx of extracellular $Ca^{++}$ ions, which diffuse into the sarcoplasm to reach the calmodulin, accounts for most of the $Ca^{++}$ that triggers contraction of a smooth muscle cell.

Muscle contraction continues until ATP-dependent calcium pumps actively transport $Ca^{++}$ ions back into the SR and out of the cell. However, a low concentration of calcium remains in the sarcoplasm to maintain muscle tone. This remaining calcium keeps the muscle slightly contracted, which is important in certain tracts and around blood vessels.

Because most smooth muscles must function for long periods without rest, their power output is relatively low, but contractions can continue without using large amounts of energy. Some smooth muscle can also maintain contractions even as $Ca^{++}$ is removed and myosin kinase is inactivated/dephosphorylated. This can happen as a subset of cross-bridges between myosin heads and actin, called **latch-bridges**, keep the thick and thin filaments linked together for a prolonged period, and without the need for ATP. This allows for the maintaining of muscle “tone” in smooth muscle that lines arterioles and other visceral organs with very little energy expenditure.

Smooth muscle is not under voluntary control; thus, it is called involuntary muscle. The triggers for smooth muscle contraction include hormones, neural stimulation by the ANS, and local factors. In certain locations, such as the walls of visceral organs, stretching the muscle can trigger its contraction (the stretch-relaxation response).

Axons of neurons in the ANS do not form the highly organized NMJs with smooth muscle, as seen between motor neurons and skeletal muscle fibers. Instead, there is a series of neurotransmitter-filled bulges called varicosities as an axon courses through smooth muscle, loosely forming motor units (Figure **9.7.3**). A **varicosity** releases neurotransmitters into the synaptic cleft. Also, visceral muscle in the walls of the hollow organs (except the heart) contains pacesetter cells. A **pacesetter cell** can spontaneously trigger action potentials and contractions in the muscle.

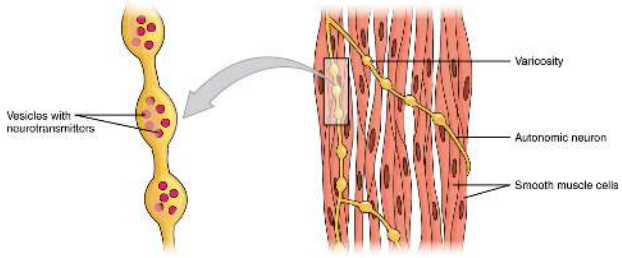



Figure **9.7.3**: Motor Units. A series of axon-like swelling, called varicosities or “boutons,” from autonomic neurons form motor units through the smooth muscle.

Smooth muscle is organized in two ways: as single-unit smooth muscle, which is much more common; and as multiunit smooth muscle. The two types have different locations in the body and have different characteristics. Single-unit muscle has its muscle fibers joined by gap junctions so that the muscle contracts as a single unit. This type of smooth muscle is found in the walls of all visceral organs except the heart (which has cardiac muscle in its walls), and so it is commonly called **visceral muscle**. Because the muscle fibers are not constrained by the organization and stretchability limits of sarcomeres, visceral smooth muscle has a **stress-**

**relaxation response**. This means that as the muscle of a hollow organ is stretched when it fills, the mechanical stress of the stretching will trigger contraction, but this is immediately followed by relaxation so that the organ does not empty its contents prematurely. This is important for hollow organs, such as the stomach or urinary bladder, which continuously expand as they fill. The smooth muscle around these organs also can maintain a muscle tone when the organ empties and shrinks, a feature that prevents "flabbiness" in the empty organ. In general, visceral smooth muscle produces slow, steady contractions that allow substances, such as food in the digestive tract, to move through the body.

Multiunit smooth muscle cells rarely possess gap junctions, and thus are not electrically coupled. As a result, contraction does not spread from one cell to the next, but is instead confined to the cell that was originally stimulated. Stimuli for multiunit smooth muscles come from autonomic nerves or hormones but not from stretching. This type of tissue is found around large blood vessels, in the respiratory airways, and in the eyes.

## Hyperplasia in Smooth Muscle

Similar to skeletal and cardiac muscle cells, smooth muscle can undergo hypertrophy to increase in size. Unlike other muscle, smooth muscle can also divide to produce more cells, a process called **hyperplasia**. This can most evidently be observed in the uterus at puberty, which responds to increased estrogen levels by producing more uterine smooth muscle fibers, and greatly increases the size of the myometrium.

## Sections Summary

Smooth muscle is found throughout the body around various organs and tracts. Smooth muscle cells have a single nucleus, and are spindle-shaped. Smooth muscle cells can undergo hyperplasia, mitotically dividing to produce new cells. The smooth cells are nonstriated, but their sarcoplasm is filled with actin and myosin, along with dense bodies in the sarcolemma to anchor the thin filaments and a network of intermediate filaments involved in pulling the sarcolemma toward the fiber's middle, shortening it in the process. $Ca^{++}$ ions trigger contraction when they are released from SR and enter through opened voltage-gated calcium channels. Smooth muscle contraction is initiated when the $Ca^{++}$ binds to intracellular calmodulin, which then activates an enzyme called myosin kinase that phosphorylates myosin heads so they can form the cross-bridges with actin and then pull on the thin filaments. Smooth muscle can be stimulated by pacesetter cells, by the autonomic nervous system, by hormones, spontaneously, or by stretching. The fibers in some smooth muscle have latch-bridges, cross-bridges that cycle slowly without the need for ATP; these muscles can maintain low-level contractions for long periods. Single-unit smooth muscle tissue contains gap junctions to synchronize membrane depolarization and contractions so that the muscle contracts as a single unit. Single-unit smooth muscle in the walls of the viscera, called visceral muscle, has a stress-relaxation response that permits muscle to stretch, contract, and relax as the organ expands. Multiunit smooth muscle cells do not possess gap junctions, and contraction does not spread from one cell to the next.

## Multiple Choice

Q. Smooth muscles differ from skeletal and cardiac muscles in that they _____.

A. lack myofibrils

B. are under voluntary control

C. lack myosin

D. lack actin

Answer: A

Q. Which of the following statements describes smooth muscle cells?

A. They are resistant to fatigue.

B. They have a rapid onset of contractions.

C. They cannot exhibit tetanus.

D. They primarily use anaerobic metabolism.

Answer: A

## Free Response

Q. Why can smooth muscles contract over a wider range of resting lengths than skeletal and cardiac muscle?

A. Smooth muscles can contract over a wider range of resting lengths because the actin and myosin filaments in smooth muscle are not as rigidly organized as those in skeletal and cardiac muscle.

Q. Describe the differences between single-unit smooth muscle and multiunit smooth muscle.

A. Single-unit smooth muscle is found in the walls of hollow organs; multiunit smooth muscle is found in airways to the lungs and large arteries. Single-unit smooth muscle cells contract synchronously, they are coupled by gap junctions, and they exhibit spontaneous action potential. Multiunit smooth cells lack gap junctions, and their contractions are not synchronous.

## Glossary

**calmodulin**
regulatory protein that facilitates contraction in smooth muscles

**dense body**
sarcoplasmic structure that attaches to the sarcolemma and shortens the muscle as thin filaments slide past thick filaments

**hyperplasia**
process in which one cell splits to produce new cells

**latch-bridges**
subset of a cross-bridge in which actin and myosin remain locked together

**pacesetter cell**
cell that triggers action potentials in smooth muscle

**stress-relaxation response**
relaxation of smooth muscle tissue after being stretched

**varicosity**
enlargement of neurons that release neurotransmitters into synaptic clefts

**visceral muscle**
smooth muscle found in the walls of visceral organs

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# CHAPTER OVERVIEW

## 10: The Muscular System

The muscular system is an organ system consisting of skeletal, smooth and cardiac muscles. It permits movement of the body, maintains posture, and circulates blood throughout the body.


10.1: Prelude 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: 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: Prelude to the Muscular System

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

**Learning Objectives**

- 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 moveable 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 (stabilized) bone is called the **origin**. During forearm **flexion**—bending the elbow—the brachioradialis assists the brachialis.

Although a number of muscles may be involved in an action, the principal muscle involved is called the **prime mover**, or **agonist**. To lift 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). A synergist can also be a **fixator** that stabilizes the bone that is the attachment for the prime mover's origin.

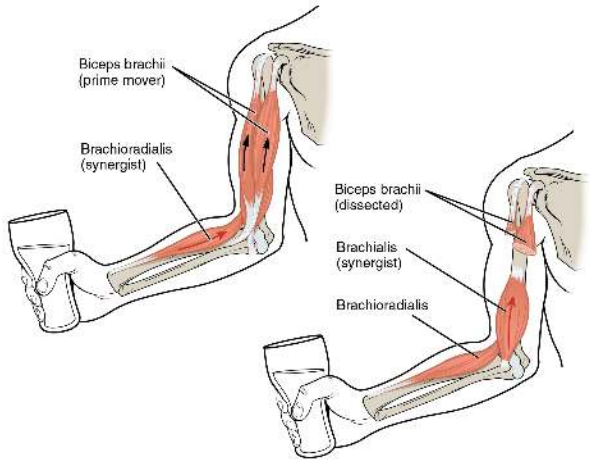



Figure 10.2.1: Prime Movers and Synergists. The biceps brachii flex the lower arm. The brachoradialis, in the forearm, and brachialis, located deep to the biceps in the upper arm, are both synergists that aid in this motion.

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. What follows are the most common fascicle arrangements.

**Parallel** muscles have fascicles that are arranged in the same direction as the long axis of the muscle (Figure **10.2.2**). 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. A more common name for this muscle is **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**.



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 connect to the upper arm and the forearm. (credit: Victoria Garcia)

**Circular** muscles are also called sphincters (see 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.

There are other muscles throughout the body named by their shape or location. 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. The rectus abdomis (rector = "straight") is the straight muscle in the anterior wall of the abdomen, while the rectus femoris is the straight muscle in the anterior compartment of the thigh.

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. 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 fascicles, 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 fascicle is 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.

## Chapter 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, pennate, fusiform, or triangular. 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; D

Q. Which of the following helps an agonist work?

A. a synergist

B. a fixator

C. an insertion

D. an antagonist

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: B

Q. Which is moved the *least* during muscle contraction?

A. the origin

B. the insertion

C. the ligaments

D. the joints

Answer: A

Q. Which muscle has a convergent pattern of fascicles?

A. biceps brachii

B. gluteus maximus

C. pectoralis major

D. rectus femoris

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: 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: A

## Critical Thinking Questions

Q. What effect does fascicle arrangement have on a muscle's action?

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.

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.

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

**Learning Objectives**

- 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, Figure 10.3.2, and Table 10.3.1). 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.

| 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 towards | A muscle that moves the little finger or toe toward |
| | digiti | digitus = digit | | refers to a finger or toe | |
| | minimi | minimus = mini, tiny | | little | |

Figure 10.3.2: Understanding a Muscle Name from the Latin.

Table 10.3.1: 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. 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).

## Chapter 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: 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: C

Q. Which muscle name does *not* make sense?

A. extensor digitorum

B. gluteus minimus

C. biceps femoris

D. extensor minimus longus

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: D

## Critical Thinking Questions

Q. Describe the different criteria that contribute to how skeletal muscles are named.

> 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

**Learning Objectives**

- 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).

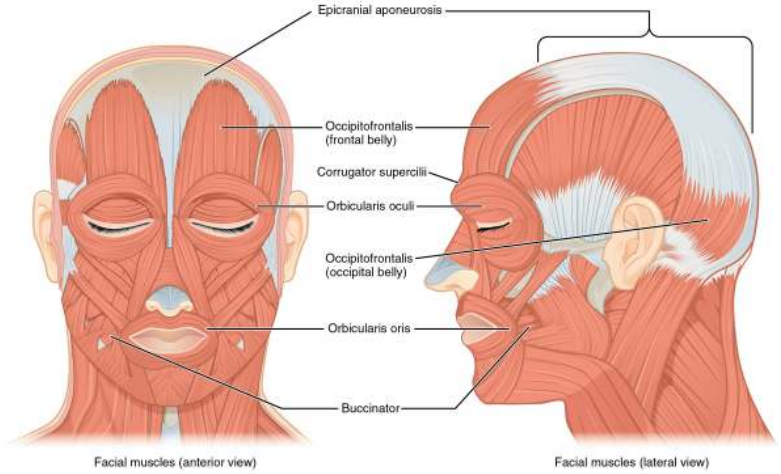



Figure 10.4.1: Muscles of Facial Expression. Many of the muscles of facial expression insert into the skin surrounding the eyelids, nose and mouth, producing facial expressions by moving the skin rather than bones.

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 Figure 10.4.2.

| Movement | Target | Target motion direction | Prime mover | Origin | Insertion |
|---|---|---|---|---|---|
| **Brow** | | | | | |
| Furrowing brow | Skin of scalp | Anterior | Occipito-frontalis, frontal belly | Epicraneal aponeurosis | Underneath skin of forehead |
| Unfurrowing brow | Skin of scalp | Posterior | Occipito-frontalis, occipital belly | Occipital bone; mastoid process (temporal bone) | Epicraneal aponeurosis |
| Lowering eyebrows (e.g., scowling, frowning) | Skin underneath eyebrows | Inferior | Corrugator supercilii | Frontal bone | Skin underneath eyebrow |
| **Nose** | | | | | |
| Flaring nostrils | Nasal cartilage (pushes nostrils open when cartilage is compressed) | Inferior compression; posterior compression | Nasalis | Maxilla | Nasal bone |
| **Mouth** | | | | | |
| Raising upper lip | Upper lip | Elevation | Levator labii superioris | Maxilla | Underneath skin at corners of the mouth; orbicularis oris |
| Lowering lower lip | Lower lip | Depression | Depressor labii inferioris | Mandible | Underneath skin of lower lip |
| Opening mouth and sliding lower jaw left and right | Lower jaw | Depression, lateral | Depressor angulus oris | Mandible | Underneath skin at corners of mouth |
| Smiling | Corners of mouth | Lateral elevation | Zygomaticus major | Zygomatic bone | Underneath skin at corners of mouth (dimple area); orbicularis oris |
| Shaping of lips (as during speech) | Lips | Multiple | Orbicularis oris | Tissue surrounding lips | Underneath skin at corners of the mouth |
| Lateral movement of cheeks (e.g., sucking on a straw; also used to compress air in mouth while blowing) | Cheeks | Lateral | Buccinator | Maxilla, mandible; sphenoid bone (via pterygomandibular raphae) | Orbicularis oris |
| Pursing of lips by straightening them laterally | Corners of mouth | Lateral | Risorius | Fascia of parotid salivary gland | Underneath skin at corners of the mouth |
| Protrusion of lower lip (e.g., pouting expression) | Lower lip and skin of chin | Protraction | Mentalis | Mandible | Underneath skin of chin |

Figure **10.4.2**: Muscles in Facial Expression.

## 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 **10.4.3** and Table **10.4.1**). 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.

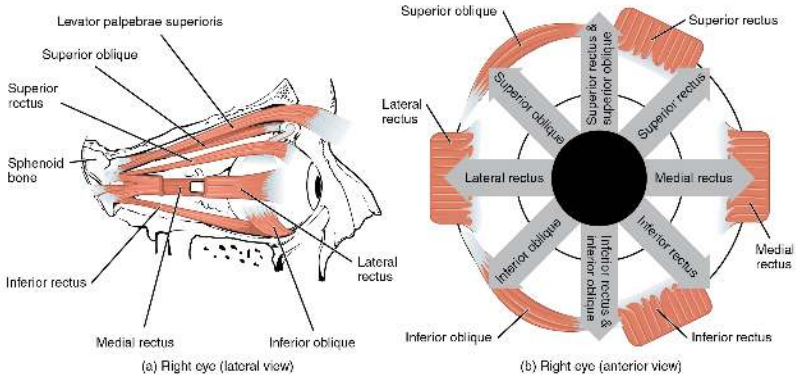



Figure **10.4.3**: Muscles of the Eyes. (a) The extrinsic eye muscles originate outside of the eye on the skull. (b) Each muscle inserts onto the eyeball.

Table **10.4.1**: Muscles of the Eyes

| Movement | Target | Target motion direction | Prime mover | Origin | Insertion |
|---|---|---|---|---|---|
| Moves eyes up and toward nose; rotates eyes from 1 o’clock to 3 o’clock | Eyeballs | Superior (elevates); medial (adducts) | Superior rectus | Common tendinous ring (ring attaches to optic foramen) | Superior surface of eyeball |
| Moves eyes down and toward nose; rotates eyes from 6 o’clock to 3 o’clock | Eyeballs | Inferior (depresses); medial (adducts) | Inferior rectus | Common tendinous ring (ring attaches to optic foramen) | Inferior surface of eyeball |
| Moves eyes away from nose | Eyeballs | Lateral (abducts) | Lateral rectus | Common tendinous ring (ring attaches to optic foramen) | Lateral surface of eyeball |
| Moves eyes toward nose | Eyeballs | Medial (adducts) | Medial rectus | Common tendinous ring (ring attaches to optic foramen) | Medial surface of eyeball |
| Moves eyes up and away from nose; rotates eyeball from 12 o’clock to 9 o’clock | Eyeballs | Superior (elevates); lateral (abducts) | Inferior oblique | Floor of orbit (maxilla) | Surface of eyeball between inferior 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 oblique | Sphenoid bone | Suface of eyeball between superior rectus and lateral rectus |
| Opens eyes | Upper eyelid | Superior (elevates) | Levator palpabrae superioris | Roof of orbit (sphenoid bone) | Skin of upper eyelids |
| Closes eyelids | Eyelid skin | Compression along superior–inferior axis | Orbicularis oculi | Medial bones composing the orbit | Circumference of orbit |

## 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 10.4.4 and Table 10.4.2). 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.

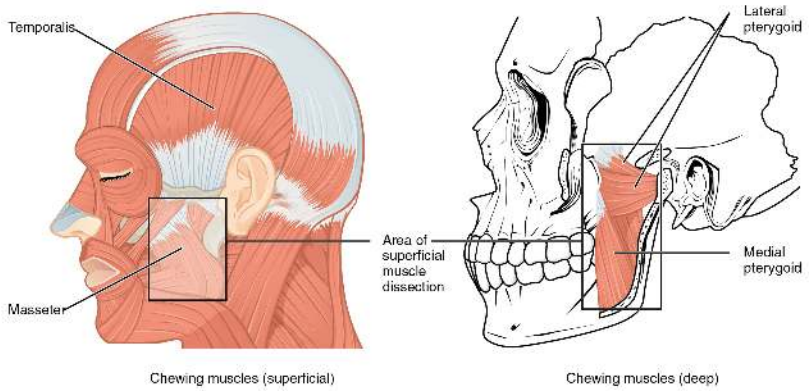



Figure 10.4.4: Muscles That Move the Lower Jaw. The muscles that move the lower jaw are typically located within the cheek and originate from processes in the skull. This provides the jaw muscles with the large amount of leverage needed for chewing.

Table 10.4.2: Muscles of the Lower Jaw

| Movement | Target | Target motion direction | Prime mover | Origin | Insertion |
|---|---|---|---|---|---|
| Closes mouth; aids chewing | Mandible | Superior (elevates) | Masseter | Maxilla arch; zygomatic arch (for masseter) | Mandible |
| Closes mouth; pulls lower jaw in under upper jaw | Mandible | Superior (elevates); posterior (retracts) | Temporalis | Temporal 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) | Lateral pterygoid | Pterygoid process of sphenoid bone | Mandible |
| Closes mouth; pushes lower jaw out under upper jaw; moves lower jaw side-to-side | Mandible | Superior (elevates); posterior (protracts); lateral (abducts); medial (adducts) | Medial pterygoid | Sphenoid bone; maxilla | Mandible; temporo-mandibular joint |

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 10.4.5 and Figure 10.4.6). Because it is so moveable, the tongue facilitates complex speech patterns and sounds.

| Movement | Target | Target motion direction | Prime mover | Origin | Insertion |
|---|---|---|---|---|---|
| **Tongue** | | | | | |
| Moves tongue down; sticks tongue out of mouth | Tongue | Inferior (depresses); anterior (protracts) | Genioglossus | Mandible | Tongue undersurface; hyoid bone |
| Moves tongue up; retracts tongue back into mouth | Tongue | Superior (elevates); posterior (retracts) | Styloglossus | Temporal bone (styloid process) | Tongue undersurface and sides |
| Flattens tongue | Tongue | Inferior (depresses) | Hyoglossus | Hyoid bone | Sides of tongue |
| Bulges tongue | Tongue | Superior (elevation) | Palatoglossus | Soft palate | Side of tongue |
| **Swallowing and speaking** | | | | | |
| Raises the 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) | Digastric | Mandible; 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) | Stylohyoid | Temporal bone (styloid process) | Hyoid bone |
| Raises hyoid bone in a way that presses tongue against the roof of the mouth, pushing food back into the pharynx during deglutition | Hyoid bone | Superior (elevates) | Mylohyoid | Mandible | Hyoid bone; median raphe |
| Raises and moves hyoid bone forward, widening pharynx during deglutition | Hyoid bone | Superior (elevates); anterior (protracts) | Geniohyoid | Mandible | Hyoid bone |
| Retracts hyoid bone and moves it down during later phases of deglutition | Hyoid bone | Inferior (depresses); posterior (retracts) | Omohyoid | Scapula | Hyoid bone |
| Depresses the hyoid bone during swallowing and speaking | Hyoid bone | Inferior (depresses) | Sternohyoid | Clavicle | Hyoid bone |
| Shrinks distance between thyroid cartilage and hyoid bone, allowing production of high-pitch vocalizations | Hyoid bone; thyroid cartilage | Hyoid bone: inferior (depresses); thyroid cartilage: superior (elevates) | Thyrohyoid | Thyroid cartilage | Hyoid bone |
| Depresses larynx, thyroid cartilage, and hyoid bone to create different vocal tones | Larynx; thyroid cartilage; hyoid bone | Inferior (depresses) | Sternothyroid | Sternum | Thyroid cartilage |
| Rotates and tilts head to he side; tilts head forward | Skull; cervical vertebrae | Individually: medial rotation; lateral flexion; bilaterally: anterior (flexes) | Sternocleid-omastoid; semispinalis capitis | Sternum; clavicle | Temporal bone (mastoid process); occipital bone |
| Rotates and tilts head to the side; tilts head backwards | Skull; cervical vertebrae | Individually: lateral rotation; lateral flexion; bilaterally: anterior (flexes) | Splenius capitis; longissimus capitis | | |

Figure **10.4.6**: Muscles for Tongue Movement, Swallowing, and Speech.

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 10.4.7). **Suprahyoid muscles** are superior to it, and the **infrahyoid muscles** are located inferiorly.

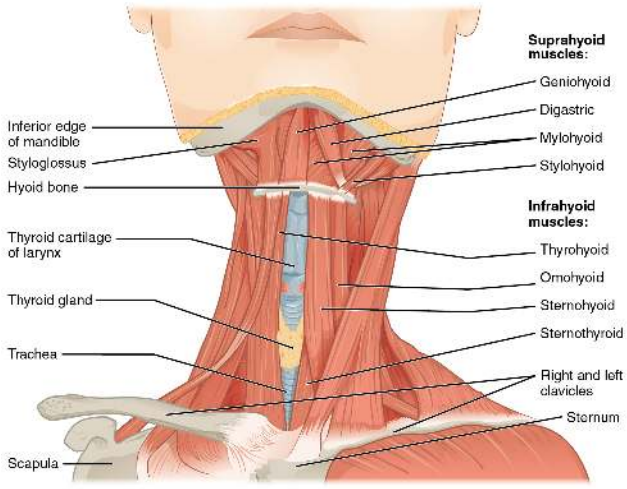



Figure 10.4.7: Muscles of the Anterior Neck. The anterior muscles of the neck facilitate swallowing and speech. The suprahyoid muscles originate from above the hyoid bone in the chin region. The infrahyoid muscles originate below the hyoid bone in the lower neck.

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 10.4.3). 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 10.4.8).

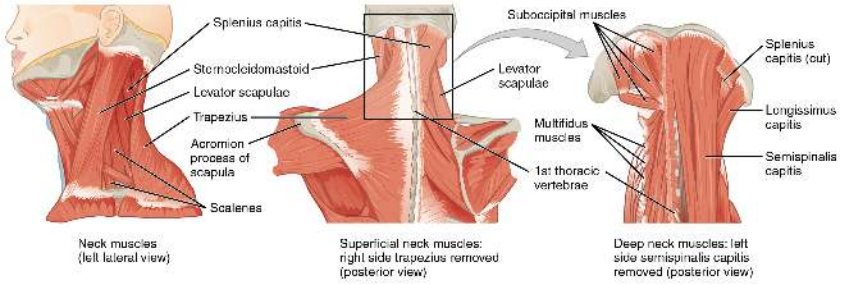



Figure **10.4.8**: Posterior and Lateral Views of the Neck. The superficial and deep muscles of the neck are responsible for moving the head, cervical vertebrae, and scapulas.

Table **10.4.3**: Muscles That Move the Head

| Movement | Target | Target motion direction | Prime mover | Origin | Insertion |
|---|---|---|---|---|---|
| Rotates and tilts head to the side; tilts head forward | Skull; vertebrae | Individually: rotates head to opposite side; bilaterally: flexion | Sternocleidomastoid | Sternum; clavicle | Temporal bone (mastoid process); occipital bone |
| Rotates and 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 vertebra | 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 | Splenius capitis | Spinous processes of cervical and thoracic vertebra | Temporal bone (mastoid process); 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 | Longissimus capitis | Transverse and articular processes of cervical and thoracic vertebra | Temporal bone (mastoid process) |

## 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 **10.4.9**).

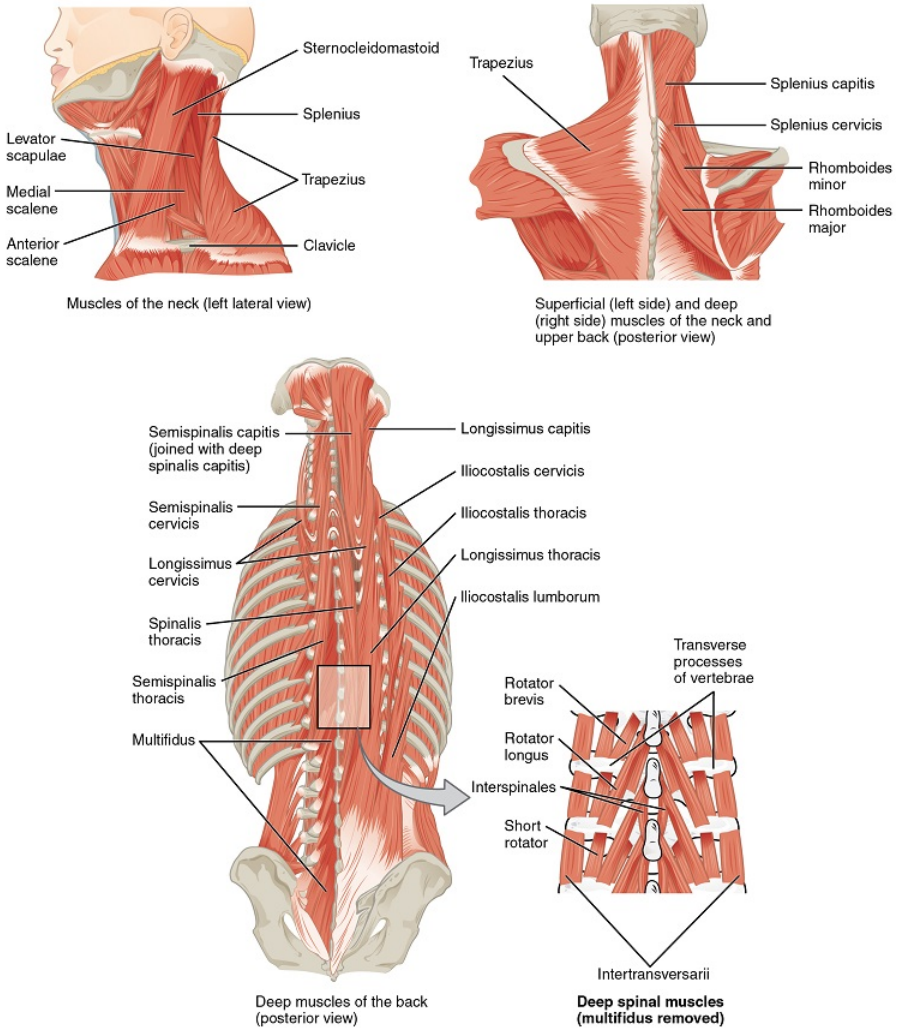



Figure **10.4.9**: Muscles of the Neck and Back. The large, complex muscles of the neck and back move the head, shoulders, and vertebral column.

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).

## Chapter 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: 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: B

Q. What is the action of the masseter?

A. swallowing

B. chewing

C. moving the lips

D. closing the eye

A. B

Q. The names of the extrinsic tongue muscles commonly end in _____.

A. -glottis

B. -glossus

C. -gluteus

D. -hyoid

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: C

## Critical Thinking Questions

Q. Explain the difference between axial and appendicular muscles.

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.

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?

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

## Contributors and Attributions

**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

**Learning Objectives**

- 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).

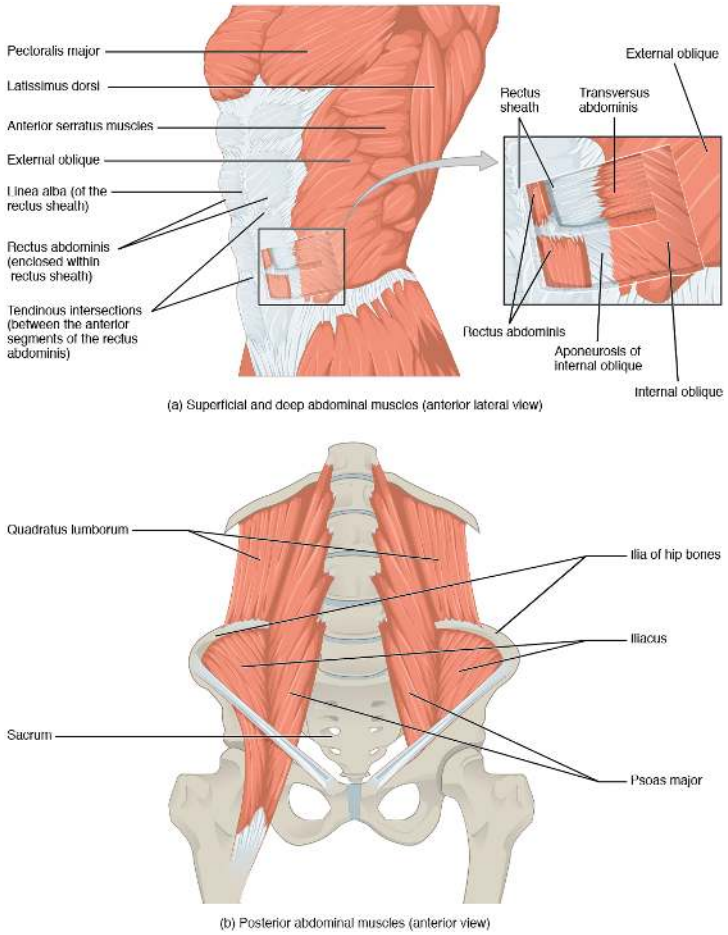



Figure 10.5.1: Muscles of the Abdomen. (a) The anterior abdominal muscles include the medially located rectus abdominis, which is covered by a sheet of connective tissue called the rectus sheath. On the flanks of the body, medial to the rectus abdominis, the abdominal wall is composed of three layers. 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.

***Table* 10.5.1**

| Muscles of the Abdomen | | | | | |
|---|---|---|---|---|---|
| Movement | Target | Target motion direction | Prime mover | Origin | Insertion |
| Twisting at waist; also bending to the side | Vertebral column | Supination; lateral flexion | External obliques; internal obliques | Ribs 5–12; ilium | Ribs 7–10; linea alba; ilium |
| Squeezing abdomen during forceful exhalations, defecation, urination, and childbirth | Abdominal cavity | Compression | Transversus abdominus | Ilium; ribs 5–10 | Sternum; linea alba; pubis |
| Sitting up | Vertebral column | Flexion | Rectus abdominis | Pubis | Sternum; ribs 5 and 7 |
| Bending to the side | Vertebral column | Lateral flexion | Quadratus lumborum | Ilium; ribs 5–10 | Rib 12; vertebrae L1–L4 |

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 Therapists**

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 | | | | | |
|---|---|---|---|---|---|
| Movement | Target | Target motion direction | Prime mover | Origin | Insertion |
| Inhalation; exhalation | Thoracic cavity | Compression; expansion | Diaphragm | Sternum; ribs 6–12; lumbar vertebrae | Central tendon |
| Inhalation;exhalation | Ribs | Elevation (expands thoracic cavity) | External intercostals | Rib superior to each intercostal muscle | Rib inferior to each intercostal muscle |
| Forced exhalation | Ribs | Movement along superior/inferior axis to bring ribs closer together | Internal intercostals | Rib inferior to each intercostal muscle | Rib superior to each intercostal muscle |

### 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.

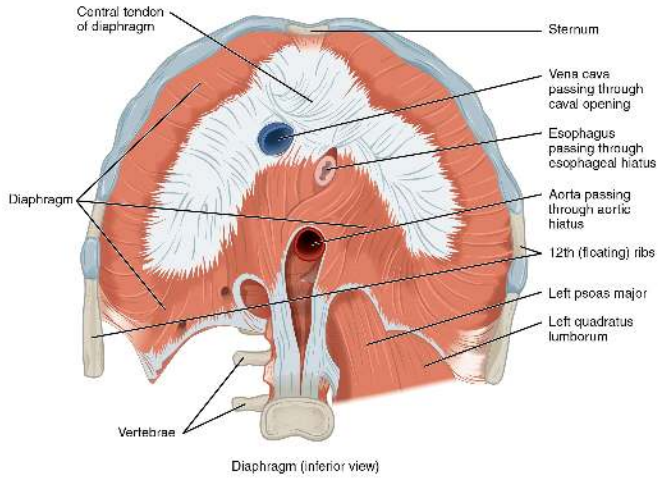



Figure 10.5.2: Muscles of the Diaphragm. The diaphragm separates the thoracic and abdominal cavities.

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**).

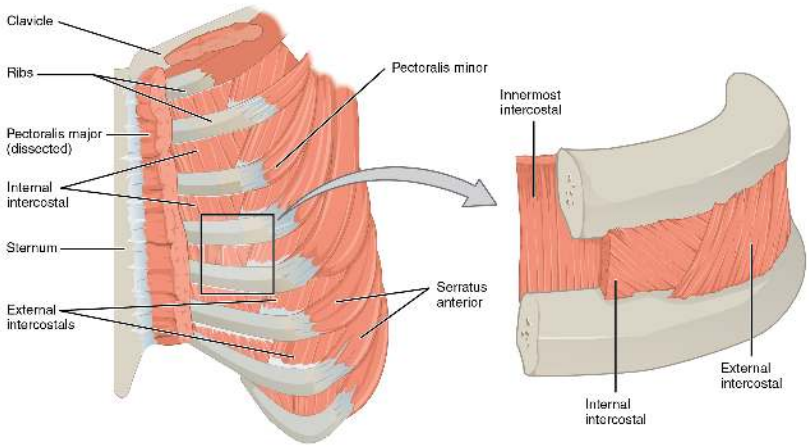



Figure **10.5.3**: Intercostal Muscles. The external intercostals are located laterally on the sides of the body. The internal intercostals are located medially near the sternum. The innermost intercostals are located deep to both the internal and external intercostals.

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 women.

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.

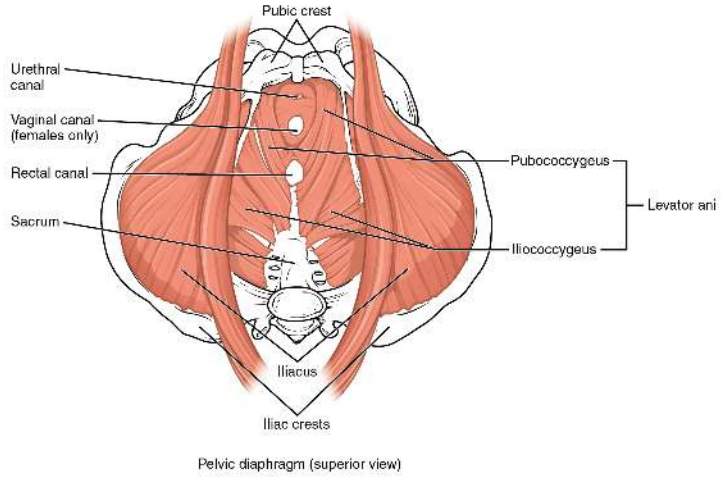



Figure **10.5.4**: Muscles of the Pelvic Floor. The pelvic floor muscles support the pelvic organs, resist intra-abdominal pressure, and work as sphincters for the urethra, rectum, and vagina.

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 men and women (Figure **10.5.6**). Women also have the **compressor urethrae** and the **sphincter urethrovaginalis**, which function to close the vagina. In men, there is the **deep transverse perineal** muscle that plays a role in ejaculation.

| Movement | Target | Target motion direction | Prime mover | Origin | Insertion |
|---|---|---|---|---|---|
| Defecation; urination; birth; coughing | Abdominal cavity | Superior (resists pressure during abdominal compression) | Levator ani pubococcygeus; levator ani iliococcygeus | Pubis; ischium | Urethra; anal canal; perineal body; coccyx |
| **Superficial muscles** | | | | | |
| None—supports perineal body maintaining anus at center of perineum | Perineal body | None | Superficial transverse perineal | Ischium | Perineal body |
| 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 | Bulbospongiosus | Perineal body | Perineal membrane; corpus spongiosum of penis; deep fascia of penis; clitoris in female |
| Compresses veins to maintain erection of penis in males; erection of clitoris in females | Veins of penis and clitoris | Compression | Ischiocavernosus | Ischium; ischial rami; pubic rami | Pubic symphysis; corpus cavernosum of penis in male; clitoris of female |
| **Deep muscles** | | | | | |
| Voluntarily compresses urethra during urination | Urethra | Compression | External urethral sphincter | Ischial rami; pubic rami | Male: median raphe; female: vaginal wall |
| Closes anus | Anus | Sphincter | External anal sphincter | Anococcygeal ligament | Perineal body |

Figure **10.5.6**: Muscles of the Perineum Common to Men and Women.

## Chapter 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: 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: 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: B

## Critical Thinking Questions

Q. Describe the fascicle arrangement in the muscles of the abdominal wall. How do they relate to each other?

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?

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

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# 10.6: Muscles of the Pectoral Girdle and Upper Limbs

**Learning Objectives**

- 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.

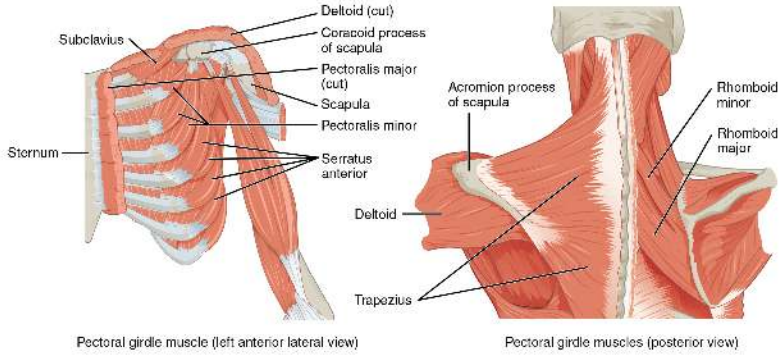



Figure **10.6.1**: Muscles That Position the Pectoral Girdle. The muscles that stabilize the pectoral girdle make it a steady base on which other muscles can move the arm. Note that the pectoralis major and deltoid, which move the humerus, are cut here to show the deeper positioning muscles.

***Table* 10.6.1**

| Muscles that Position the Pectoral Girdle | | | | | | |
|---|---|---|---|---|---|---|
| Position in the thorax | Movement | Target | Target motion direction | Prime mover | Origin | Insertion |
| Anterior thorax | Stabilizes clavicle during movement by depressing it | Clavicle | Depression | Subclavius | First rib | Inferior surface of clavicle |
| Anterior thorax | Rotates shoulder anteriorly (throwing motion); assists with inhalation | Scapula; ribs | Scapula: depresses; ribs: elevates | Pectoralis minor | Anterior surfaces of certain ribs (2–4 or 3–5) | Coracoid process of scapula |
| Anterior thorax | Moves arm from side of body to front of body; assists with inhalation | Scapula; ribs | Scapula: protracts; ribs: elevates | Serratus anterior | Muscle slips from certain ribs (1–8 or 1–9) | Anterior surface of vertebral border of scapula |
| Posterior thorax | Elevates shoulders (shrugging); pulls shoulder blades together; tilts head backwards | Scapula; cervical spine | Scapula: rotests inferiorly, retracts, elevates, and depresses; spine: extends | Trapezius | Skull; vertebral column | Acromion and spine of scapula; clavicle |
| Posterior thorax | Stabilizes scapula during pectoral girdle movement | Scapula | Retracts; rotates inferiorly | Rhomboid major | Thoracic vertebrae (T2–T5) | Medial border of scapula |
| Posterior thorax | Stabilizes scapula during pectoral girdle movement | Scapula | Retracts; rotates inferiorly | Rhomboid minor | Cervical and thoracic vertebrae (C7 and T1) | Medial border of scapula |

## 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 Figure **10.6.3**). 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.

| Movement | Target | Target motion direction | Prime mover | Origin | Insertion |
|---|---|---|---|---|---|
| **Axial muscles** | | | | | |
| Brings elbows together; moves elbow up (as during an uppercut punch) | Humerus | Flexion; adduction; medial rotation | Pectoralis major | Clavicle; sternum; cartilage of certain ribs (1–6 or 1–7); aponeurosis of external oblique muscle | Greater tubercle 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 | Latissimus dorsi | Thoracic vertebrae (T7–T12); lumbar vertebrae; lower ribs (9–12); iliac crest | Intertubercular sulcus of humerus |
| **Scapular muscles** | | | | | |
| Lifts arms at shoulder | Humerus | Abduction; flexion; extension; medial and lateral rotation | Deltoid | Trapezius; clavicle; acromion; spine of scapula | Deltoid tuberosity of humerus |
| Assists pectoralis major in bringing elbows together and stabilizes shoulder joint during movement of the pectoral girdle | Humerus | Medial rotation | Subscapularis | Subscapular fossa of scapula | Lesser tubercle of humerus |
| Rotates elbow outwards, as during a tennis swing | Humerus | Abduction | Supraspinatus | Supraspinous fossa of scapula | Greater tubercle of humerus |
| Rotates elbow outwards, as during a tennis swing | Humerus | Extension; adduction | Infraspinatus | Infraspinous fossa of scapula | Greater tubercle of humerus |
| Assists infraspinatus in rotating elbow outwards | Humerus | Extension; adduction | 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 |
| Moves elbow up and across body, as when putting hand on chest | Humerus | Flexion; adduction | Coracobra chialis | Coracoid process of scapula | Medial surface of humerus shaft |

Figure **10.6.3**: Muscles That Move the Humerus.

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 **10.6.4** and Figure **10.6.5**).

| Movement | Target | Target motion direction | Prime mover | Origin | Insertion |
|---|---|---|---|---|---|
| **Anterior muscles (flexion)** | | | | | |
| Performs a bicep curl; also allows palm of hand to point toward body while flexing | Forearm | Flexion; supination | Biceps brachii | Coracoid process; tubercle above glenoid cavity | Radial tuberosity |
| | Forearm | Flexion | Brachialis | Front of distal humerus | Coronoid process of ulna |
| Assists and stabilizes elbow during bicep-curl motion | Forearm | Flexion | Brachioradialis | Lateral supracondylar ridge at distal end of humerus | Base of styloid process of radius |
| **Posterior muscles (extension)** | | | | | |
| Extends forearm, as during a punch | Forearm | Extension | Triceps brachii | Infraglenoid tubercle of scapula; posterior shaft of humerus; posterior humeral shaft distal to radial groove | Olecranon process of ulna |
| Assists in extending forearm; also allows forearm to extend away from body | Forearm | Extension; abduction | Anconeus | Lateral epicondyle of humerus | Lateral aspect of olecranon process of ulna |
| **Anterior muscles (pronation)** | | | | | |
| Turns hand palm-down | Forearm | Pronation | Pronator teres | Medial epicondyle of humerus; coronoid process of ulna | Lateral radius |
| Assists in turning hand palm-down | Forearm | Pronation | Pronator quadratus | Distal portion of anterior ulnar shaft | Distal surface of anterior radius |
| **Posterior muscles (supination)** | | | | | |
| Turns hand palm-up | Forearm | Supination | Supinator | Lateral epicondyle of humerus; proximal ulna | Proximal end of radius |

Figure **10.6.5**: Muscles That Move the Forearm.

## 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 (see Figure **10.6.6** and Table **10.6.2**). 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** (see Figure **10.6.6**).

| Movement | Target | Target motion direction | Prime mover | Origin | Insertion |
|---|---|---|---|---|---|
| **Superficial anterior compartment of forearm** | | | | | |
| Bends wrist toward body; tilts hand to side away from body | Wrist; hand | Flexion; abduction | Flexor carpi radialis | Medial epicondyle of humerus | Base of second and third metacarpals |
| Assists in bending hand up toward shoulder | Wrist | Flexion | Palmaris longus | Medial epicondyle of humerus | Palmar aponeurosis; skin and fascia of palm |
| Assists in bending hand up toward shoulder; tilts hand to side away from body; stabilizes wrist | Wrist; hand | Flexion, abduction | Flexor carpi ulnaris | Medial epicondyle of humerus; olecranon process; posterior surface of ulna | Pisiform, hamate bones, and base of fifth metacarpal |
| Bends fingers to make a fist | Wrist; fingers 2–5 | Flexion | Flexor digitorum superficialis | Medial epicondyle of humerus; coronoid process of ulna; shaft of radius | Middle phalanges of fingers 2–5 |
| **Deep anterior compartment of forearm** | | | | | |
| Bends tip of thumb | Thumb | Flexion | Flexor pollicis longus | Anterior surface of radius; interosseous membrane | Distal phalanx of thumb |
| Bends fingers to make a fist; also bends wrist toward body | Wrist; fingers | Flexion | Flexor digitorum profundus | Coronoid process; anteromedial surface of ulna; interosseous membrane | Distal phalanges of fingers 2–5 |
| **Superficial posterior compartment of forearm** | | | | | |
| Straightens wrist away from body; tilts hand to side away from body | Wrist | Extension; abduction | Extensor radialis longus | Lateral supracondylar ridge of humerus | Base of second metacarpal |
| Assists extensor radialis longus in extending and abducting wrist; also stabilizes hand during finger flexion. | Wrist | Extension, abduction | Extensor carpi radialis brevis | Lateral epicondyle of humerus | Base of third metacarpal |
| Opens fingers and moves them sideways away from the body | Wrist; fingers | Extension; abduction | Extensor digitorum | Lateral epicondyle of humerus | Extensor expansions; distal phalanges of fingers |
| Extends little finger | Little finger | Extension | Extensor digiti minimi | Lateral epicondyle of humerus | Extensor expansion; distal phalanx of finger 5 |
| Straightens wrist away from body; tilts hand to side toward body | Wrist | Extension; adduction | Extensor carpi ulnaris | Lateral epicondyle of humerus; posterior border of ulna | Base of fifth metacarpal |
| **Deep posterior compartment of forearm** | | | | | |
| Moves thumb sideways toward body; extends thumb; moves hand sideways toward body | Wrist; thumb | Thumb: abduction, extension; wrist: abduction | Abductor pollicis longus | Posterior surface of radius and ulna; interosseous membrane | Base of first metacarpal; trapezium |
| Extends thumb | Thumb | 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 index finger; straightens wrist away from body | Wrist; index finger | Extension | Extensor indicis | Posterior surface of distal ulna; interosseous membrane | Tendon of extensor digitorum of index finger |

Figure **10.6.6**: Muscles That Move the Wrist, Hands, andForearm.

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 **10.6.7**). 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**.

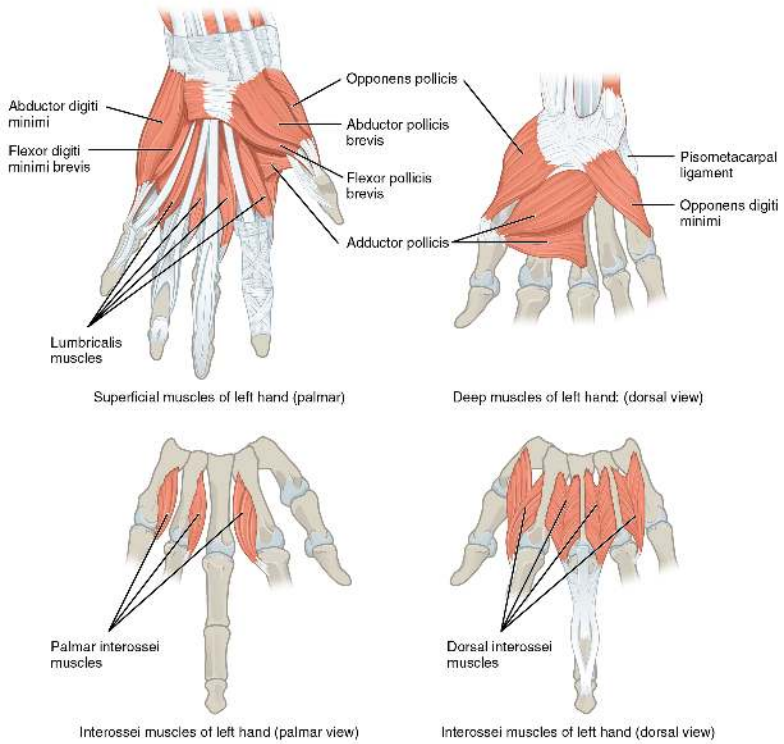



Figure **10.6.7**: Intrinsic Muscles of the Hand. The intrinsic muscles of the hand both originate and insert within the hand. These muscles provide the fine motor control of the fingers by flexing, extending, abducting, and adducting the more distal finger and thumb segments.

***Table* 10.6.2**


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| Intrinsic Muscles of the Hand | | | | | | |
|---|---|---|---|---|---|---|
| Muscle | Movement | Target | Target motion direction | Prime mover | Origin | Insertion |
| Thenar muscles | Moves thumb toward body | Thumb | Abduction | Abductor pollicis brevis | Flexor retinaculum; and nearby carpals | Lateral base of proximal phalanx of thumb |
| Thenar muscles | Moves thumb across palm to touch other fingers | Thumb | Opposition | Opponens pollicis | Flexor retinaculum; trapezium | Anterior of first metacarpal |
| Thenar muscles | Flexes thumb | Thumb | Flexion | Flexor pollicis brevis | Flexor retinaculum; trapezium | Lateral base of proximal phalanx of thumb |
| Thenar muscles | Moves thumb away from body | Thumb | Adduction | Adductor pollicis | Capitate bone; bases of metacarpals 2–4; front of metacarpal 3 | Medial base of proximal phalanx of thumb |
| Hypothenar muscles | Moves little finger toward body | Little finger | Abduction | Abductor digiti minimi | Pisiform bone | Medial side of proximal phalanx of little finger |
| Hypothenar muscles | Flexes little finger | Little finger | Flexion | Flexor digiti minimi brevis | Hamate bone; flexor retinaculum | Medial side of proximal phalanx of little finger |
| Hypothenar muscles | Moves little finger across palm to touch thumb | Little finger | Opposition | Opponens digiti minimi | Hamate bone; flexor retinaculum | Medial side of fifth metacarpal |
| Intermediate muscles | Flexes each finger at metacarpo-phalangeal joints; extends each finger at interphalangeal joints | Fingers | Flexion | Lumbricals | Palm (lateral sides of tendons in flexor digitorum profundus) | Fingers 2–5 (lateral edges of extensional expansions on first phalanges) |
| Intermediate muscles | Adducts and flexes each finger at metacarpo-phalangeal joints; extends each finger at interphalangeal joints | Fingers | Adduction; flexion; extension | 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 |
| Intermediate | Abducts and | Fingers | Abduction; | Dorsal interossei | Sides of | Both sides of |

| Intrinsic Muscles of the Hand | | | | | | |
|---|---|---|---|---|---|---|
| Muscle | Movement | Target | Target motion direction | Prime mover | Origin | Insertion |
| muscles | flexes the three middle fingers at metacarpo-phalangeal joints; extends the three middle fingers at interphalangeal joints | | flexion; extension | | metacarpals | finger 3; for each other finger, extensor expansion over first phalanx on side opposite finger 3 |

## Chapter 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: C

Q. Which muscle extends the forearm?

A. biceps brachii

B. triceps brachii

C. brachialis

D. deltoid

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: B

Q. Which muscles stabilize the pectoral girdle?

A. axial and scapular

B. axial

C. appendicular

D. axial and appendicular

Answer: A

## Critical Thinking Questions

Q. The tendons of which muscles form the rotator cuff? Why is the rotator cuff important?

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.

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

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# 10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs

**Learning Objectives**

- Identify the appendicular muscles of the pelvic girdle and lower limb
- Identify the movement and function of the pelvic girdle and lower limb

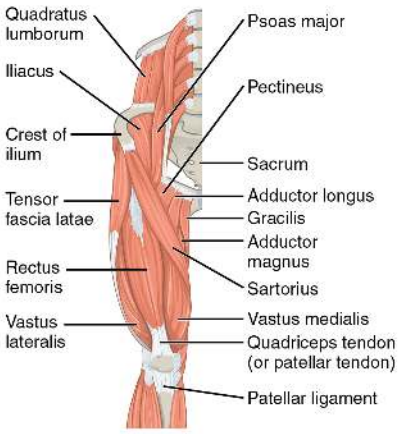
The appendicular muscles of the lower body position and stabilize the **pelvic girdle**, which serves as a foundation for the lower limbs. Comparatively, there is much more movement at the pectoral girdle than at the pelvic girdle. There is very little movement of the pelvic girdle because of its connection 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

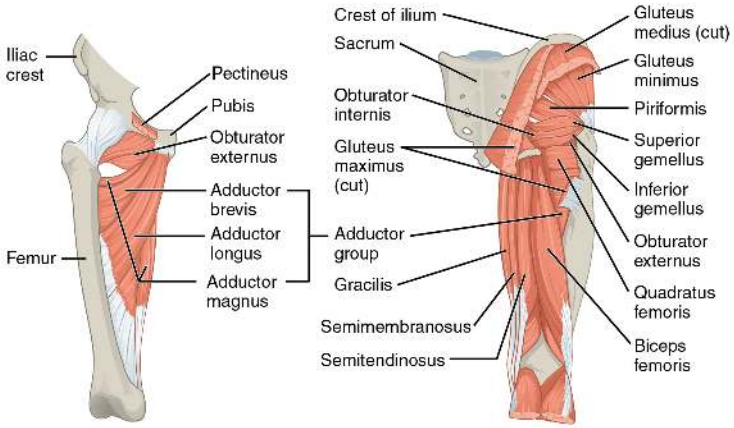
What would happen if the pelvic girdle, which attaches the lower limbs to the torso, were capable of the same range of motion as the pectoral girdle? For one thing, walking would expend more energy if the heads of the femurs were not secured in the acetabula of the pelvis. The body's center of gravity 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 Figure 10.7.2).




Superficial pelvic and thigh muscles of right leg (anterior view)




Deep pelvic and thigh muscles of right leg (anterior view)

Pelvic and thigh muscles of right leg (posterior view)

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.

| Movement | Target | Target motion direction | Prime mover | Origin | Insertion |
|---|---|---|---|---|---|
| **Iliopsoas group** | | | | | |
| Raises knee at hip, as if performing a knee attack; assists lateral rotators in twisting thigh (and lower leg) outward; assists with bending over, maintaining posture | Femur | Thigh: flexion and lateral rotation; torso: flexion | Psoas major | Lumbar vertebrae (L1–L5); thoracic vertebra (T12) | Lesser trochanter of femur |
| Raises knee at hip, as if performing a knee attack; assists lateral rotators in twisting thigh (and lower leg) outward; assists with bending over, maintaining posture | Femur | Thigh: flexion and lateral rotation; torso: flexion | Iliacus | Iliac fossa; iliac crest; lateral sacrum | Lesser trochanter of femur |
| **Gluteal group** | | | | | |
| Lowers knee and moves thigh back, as when getting ready to kick a ball | Femur | Extension | Gluteus maximus | Dorsal ilium; sacrum; coccyx | Gluteal tuberosity of femur; iliotibial tract |
| Opens thighs, as when doing a split | Femur | Abduction | Gluteus medius | Lateral surface of ilium | Greater trochanter of femur |
| Brings the thighs back together | Femur | Abduction | Gluteus minimus | External surface of ilium | Greater trochanter of femur |
| Assists with raising knee at hip and opening thighs; maintains posture by stabilizing the iliotibial track, which connects to the knee | Femur | Flexion; abduction | Tensor fascia lata | Anterior aspect of iliac crest; anterior superior iliac spine | Iliotibial tract |
| **Lateral rotators** | | | | | |
| Twists thigh (and lower leg) outward; maintains posture by stabilizing hip joint | Femur | Lateral rotation | Piriformis | Anterolateral surface of sacrum | Greater trochanter of femur |
| Twists thigh (and lower leg) outward; maintains posture by stabilizing hip joint | Femur | Lateral rotation | Obutrator 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 | Obturator externus | Outer surfaces of obturator membrane, pubic, 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 | Superior gemellus | Ischial spine | Greater trochanter of femur |
| Twists thigh (and lower leg) outward; maintains posture by stabilizing hip joint | Femur | Lateral rotation | Inferior gemellus | Ischial tuberosity | 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 |
| **Adductors** | | | | | |
| Brings the thighs back together; assists with raising the knee | Femur | Adduction; flexion | Adductor longus | Pubis near pubic symphysis | Linea aspera |
| Brings the thighs back together; assists with raising the knee | Femur | Adduction; flexion | Adductor brevis | Body of pubis; inferior ramus of pubis | Linea aspera above adductor longus |
| Brings the thighs back together; assists with raising the knee and moving the thigh back | Femur | Adduction; flexion; extension | Adductor magnus | Ischial rami; pubic rami; ischial tuberosity | Linea aspera; adductor tubercle of femur |
| Opens thighs; assists with raising the knee and turning the thigh (and lower leg) inward | Femur | Adduction; flexion; medial rotation | Pectineus | Pectineal line of pubis | Lesser trochanter to linea aspera of posterior aspect of femur |

Figure **10.7.2**: Gluteal Region Muscles That Move the Femur.

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 (see Figure **10.7.1** and Figure **10.7.3**). 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.

| Movement | Target | Target motion direction | Prime mover | Origin | Insertion |
|---|---|---|---|---|---|
| **Medial compartment of thigh** | | | | | |
| Moves back of lower legs up toward buttocks, as when kneeling; assists in opening thighs | Femur; tibia/fibula | Tibia/fibula: flexion; thigh: adduction | Gracilis | Inferior ramus; body of pubis; ischial ramus | Medial surface of tibia |
| **Anterior compartment of thigh: Quadriceps femoris group** | | | | | |
| Moves lower leg out in front of body, as when kicking; assists in raising the knee | Femur; tibia/fibula | Tibia/fibula: extension; thigh: flexion | Rectus femoris | Anterior inferior iliac spine; superior margin of acetabulum | Patella; tibial tuberosity |
| Moves lower leg out in front of body, as when kicking | Tibia/fibula | Extension | Vastus lateralis | Greater trochanter; intertrochanteric line; linea aspera | 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 | Vastus intermedius | Proximal femur shaft | Patella; tibial tuberosity |
| 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 | Tibia: flexion; thigh: flexion, abduction, lateral rotation | Sartorius | Anterior superior iliac spine | Medial aspect of proximal tibia |
| **Posterior compartment of thigh: Hamstring group** | | | | | |
| 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 | Tibia/fibula: flexion; thigh: extension, lateral rotation | Biceps femoris | Ischial tuberosity; linea aspera; distal femur | Head of fibula; lateral condyle of tibia |
| Moves back of lower legs up toward buttocks, as when kneeling; moves thigh down and back; twists the thigh (and lower leg) inward | Femur; tibia/fibula | Tibia/fibula: flexion; thigh: extension, medial rotation | 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) inward | Femur; tibia/fibula | Tibia/fibula: flexion; thigh: extension, medial rotation | Semi-membranosus | Ischial tuberosity | Medial condyle of tibia; lateral condyle of femur |

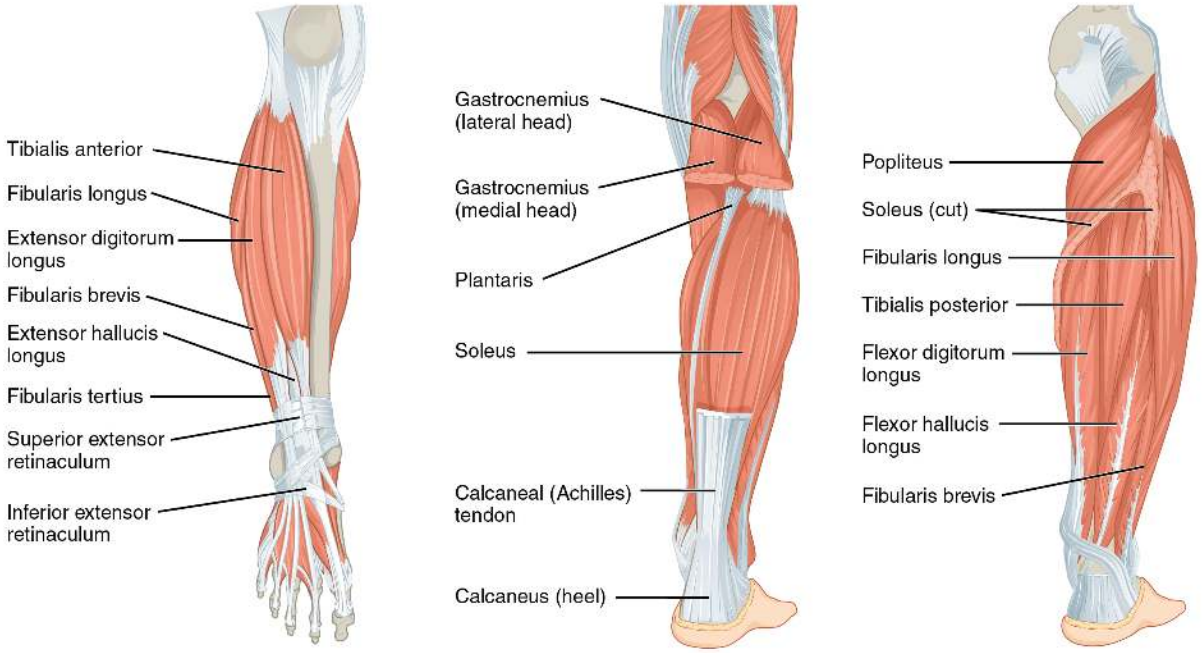
Figure **10.7.3**: Thigh Muscles That Move the Femur, Tibia, and Fibula.

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 **10.7.4** and Figure **10.7.5**).




Superficial muscles of the right lower leg (anterior view)

Superficial muscles of the right lower leg (posterior view)

Deep muscles of the right lower leg (posterior view)

Figure **10.7.4**: 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.

| Movement | Target | Target motion direction | Prime mover | Origin | Insertion |
|---|---|---|---|---|---|
| **Anterior compartment of leg** | | | | | |
| 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 | 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; extends the big toe | Foot; big toe | Foot: dorsiflexion; big toe: extension | Extensor hallucis longus | Anteromedial fibula shaft; interosseous membrane | Distal phalanx of big toe |
| 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 digitorum longus | Lateral condyle of tibia; proximal portion of fibula; interosseous membrane | Middle and distal phalanges of toes 2–5 |
| **Lateral compartment of leg** | | | | | |
| Lowers the sole of the foot to the ground, as when foot-tapping or jumping; bends the inside of the foot downwards, as when catching your balance while falling laterally toward the same side as the balancing foot | Foot | Plantar flexion and eversion | 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 and eversion | Fibularis (peroneus) brevis | Distal fibula shaft | Proximal end of fifth metatarsal |
| **Posterior compartment of leg: Superficial muscles** | | | | | |
| 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 | Gastrocnemius | Medial and lateral condyles of femur | Posterior calcaneus |
| Lowers the sole of the foot to the ground, as when foot-tapping or jumping; maintains posture while walking | Foot | Plantar flexion | Soleus | Superior tibia; fibula; interosseous membrane | 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 | Foot | Plantar flexion | Tibialis posterior | Superior tibia and fibula; interosseous membrane | Several tarsals and metatarsals 2–4 |
| **Posterior compartment of leg: Deep muscles** | | | | | |
| Moves the back of the lower legs up and back toward the 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 | Popliteus | Lateral condyle of femur; lateral meniscus | Proximal tibia |
| 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 and inversion toes: flexion | Flexor digitorum longus | Posterior tibia | Distal phalanges of toes 2–5 |
| Flexes the big toe | Big toe; foot | Big toe: flexion foot: plantar flexion | Flexor hallucis longus | Midshaft of fibula; interosseous membrane | Distal phalanx of big toe |

Figure 10.7.5: Muscles That Move the Feet and Toes.

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 10.7.6 and Figure 10.7.7). 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.

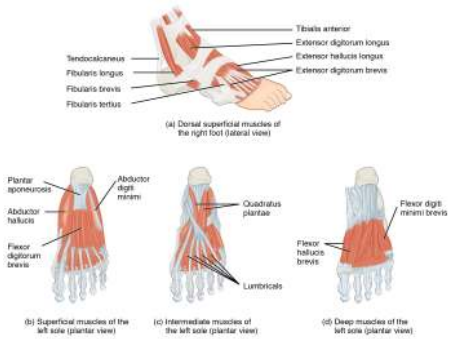



Figure 10.7.6: Intrinsic Muscles of the Foot. The muscles along the dorsal side of the foot (a) generally extend the toes while the muscles of the plantar side of the foot (b, c, d) generally flex the toes. The plantar muscles exist in three layers, providing the foot the strength to counterbalance the 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.

| Movement | Target | Target motion direction | Prime mover | Origin | Insertion |
|---|---|---|---|---|---|
| **Dorsal group** | | | | | |
| Extends toes 2–5 | Toes 2–5 | Extension | Extensor digitorum brevis | Calcaneus; extensor retinaculum | Base of proximal phalanx of big toe; extensor expansions on toes 2–5 |
| **Plantar group (layer 1)** | | | | | |
| Abducts and flexes big toe | Big toe | Adduction; flexion | Abductor hallucis | Calcaneal tuberosity; flexor retinaculum | Proximal phalanx of big toe |
| Flexes toes 2–4 | Middle toes | Flexion | Flexor digitorum brevis | Calcaneal tuberosity | Middle phalanx of toes 2–4 |
| Abducts and flexes small toe | Toe 5 | Abduction; flexion | Abductor digiti minimi | Calcaneal tuberosity | Proximal phalanx of little toe |
| **Plantar group (layer 2)** | | | | | |
| Assists in flexing toes 2–5 | Toes 2–5 | Flexion | Quadratus plantae | Medial and lateral sides of calcaneus | Tendon of flexor digitorum longus |
| Extends toes 2–5 at the interphalangeal joints; flexes the small toes at the metatarsophalangeal joints | Toes 2–5 | Extension; flexion | Lumbricals | Tendons of flexor digitorum longus | Medial side of proximal phalanx of toes 2–5 |
| **Plantar group (layer 3)** | | | | | |
| Flexes big toe | Big toe | Flexion | Flexor hallucis brevis | Lateral cuneiform; cuboid bones | Base of proximal phalanx of big toe |
| Adducts and flexes big toe | Big toe | Adduction; flexion | Adductor hallucis | Bases of metatarsals 2–4; fibularis longus tendon sheath; ligament across metatarsophalangeal joints | Base of proximal phalanx of big toe |
| Flexes small toe | Little toe | Flexion | Flexor digiti minimi brevis | Base of metatarsal 5; tendon sheath of fibularis longus | Base of proximal phalanx of little toe |
| **Plantar group (layer 4)** | | | | | |
| Abducts and flexes middle toes at metatarsophalangeal joints; extends middle toes at interphalangeal joints | Middle toes | Abduction; flexion; extension | 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 toes 3–5; flexes proximal phalanges and extends distal phalanges | Small 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 toe (except to 2) on side facing toe 2 |

Figure **10.7.7**: Intrinsic Muscles in the Foot.

## Chapter 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: 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: D

Q. What is the largest muscle in the lower leg?

A. soleus

B. gastrocnemius

C. tibialis anterior

D. tibialis posterior

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: B

## Critical Thinking Questions

Q. Which muscles form the hamstrings? How do they function together?

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?

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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# CHAPTER OVERVIEW

## 11: The Nervous System and Nervous Tissue

One easy way to begin to understand the structure of the nervous system is to start with the large divisions and work through to a more in-depth understanding. In other chapters, the finer details of the nervous system will be explained, but first looking at an overview of the system will allow you to begin to understand how its parts work together. The focus of this chapter is on nervous (neural) tissue, both its structure and its function. But before you learn about that, you will see a big picture of the system—actually, a few big pictures.


11.1: Prelude to the Nervous System

11.2: Basic Structures of the Nervous System

11.3: Nervous Tissue


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# 11.1: Prelude to the Nervous System

**Chapter Objectives**

- 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
- Name the parts of the multipolar neuron in order of polarity
- 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 the components of the membrane that establish the resting membrane potential
- Describe the changes that occur to the membrane that result in the action potential
- Explain the differences between types of graded potentials
- Categorize the major neurotransmitters by chemical type and effect

The nervous system is a very complex organ system. In Peter D. Kramer's book *Listening to Prozac*, a pharmaceutical researcher is quoted as saying, "If the human brain were simple enough for us to understand, we would be too simple to understand it" (1994). That quote is from the early 1990s; in the two decades since, progress has continued at an amazing rate within the scientific disciplines of neuroscience. It is an interesting conundrum to consider that the complexity of the nervous system may be too complex for it (that is, for us) to completely unravel. But our current level of understanding is probably nowhere close to that limit.

One easy way to begin to understand the structure of the nervous system is to start with the large divisions and work through to a more in-depth understanding. In other chapters, the finer details of the nervous system will be explained, but first looking at an overview of the system will allow you to begin to understand how its parts work together. The focus of this chapter is on nervous (neural) tissue, both its structure and its function. But before you learn about that, you will see a big picture of the system—actually, a few big pictures.



Figure **11.1.1**: Robotic Arms Playing Foosball. As the neural circuitry of the nervous system has become more fully understood and robotics more sophisticated, it is now possible to integrate technology with the body and restore abilities following traumatic events. At some point in the future, will this type of technology lead to the ability to augment our nervous systems? (credit: U.S. Army/Wikimedia Commons)

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# 11.2: Basic Structures of the Nervous System

**Learning Objectives**

- Identify the anatomical and functional divisions of the nervous system
- Relate the functional and structural differences between gray matter and white matter structures of the nervous system to the structure of neurons
- List the basic functions 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, 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 electrophysiology. 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.

## The Central and Peripheral Nervous Systems

The nervous system can be divided into two major regions: the central and peripheral nervous systems. The **central nervous system (CNS)** is the brain and spinal cord, and the **peripheral nervous system (PNS)** is everything else (Figure 11.2.1). 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.

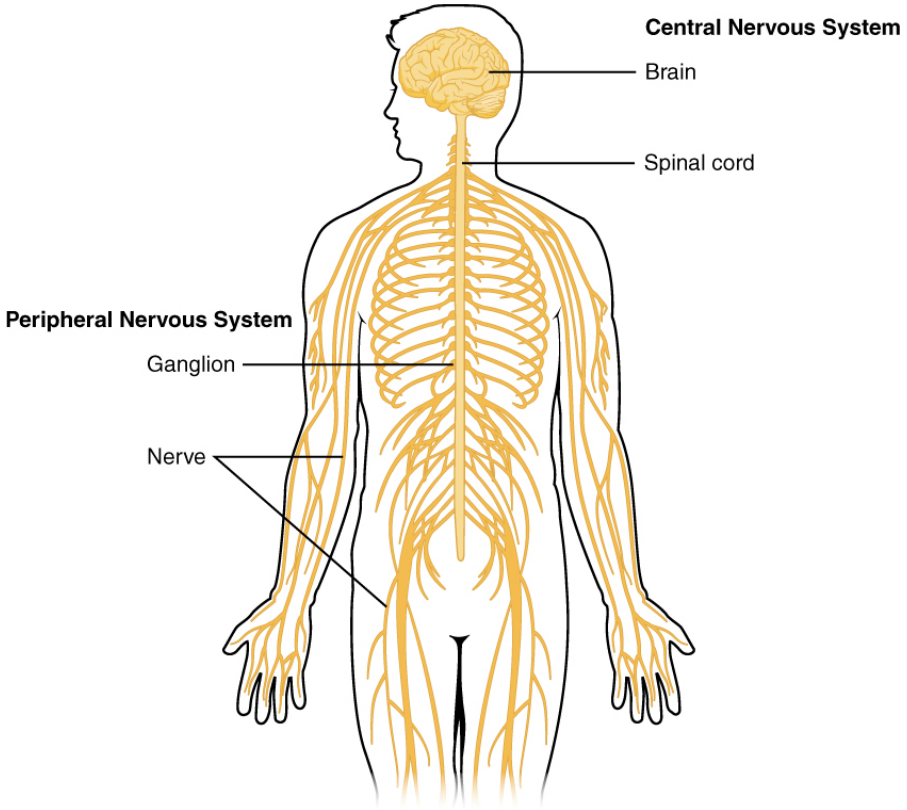



***Figure 11.2.1: Central and Peripheral Nervous System.*** *The structures of the PNS are referred to as ganglia and nerves, which can be seen as distinct structures. The equivalent structures in the CNS are not obvious from this overall perspective and are best examined in prepared tissue under the microscope.*

Nervous tissue, present in both the CNS and PNS, 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 structure of a neuron. 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. 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. 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 a lipid-rich substance called **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.

The distinction between gray matter and white matter is most often applied to central nervous tissue, which has large regions that can be seen with the unaided eye. When looking at peripheral structures, often a microscope is used and the tissue is stained with artificial colors. That is not to say that central nervous tissue cannot be stained and viewed under a microscope, but unstained tissue is most likely from the CNS—for example, a frontal section of the brain or cross section of the spinal cord.

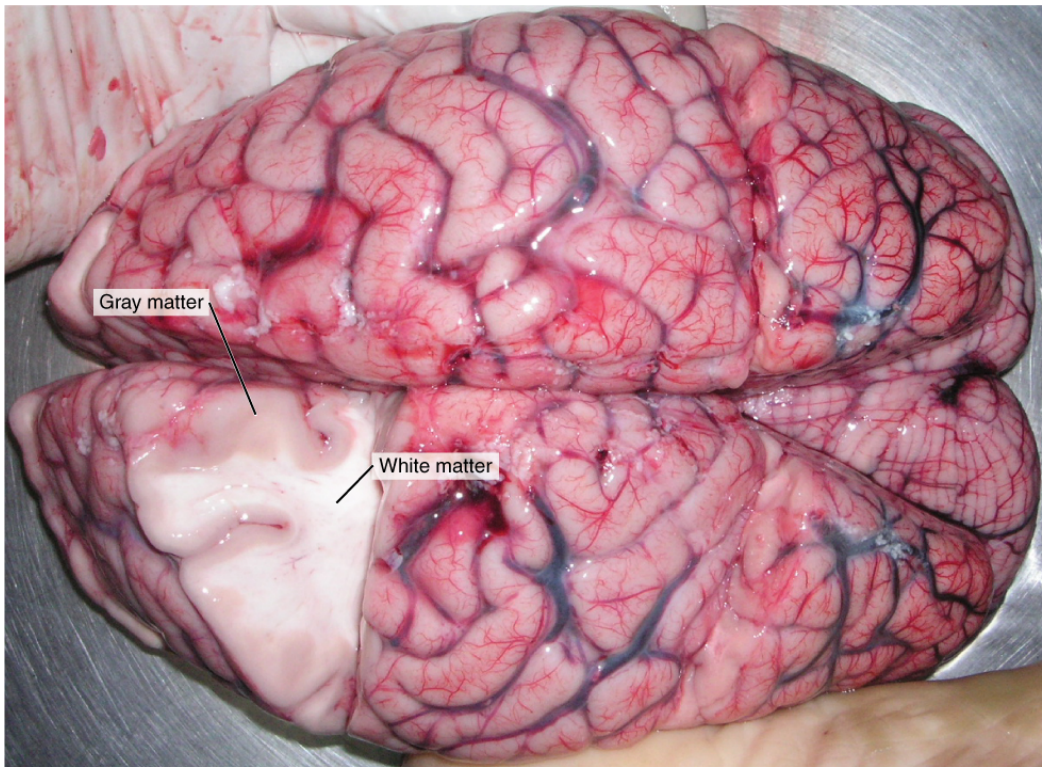



***Figure* 11.2.2*: Gray Matter and White Matter.*** *A brain removed during an autopsy, with a partial section removed, shows white matter surrounded by gray matter. Gray matter makes up the outer cortex of the brain. (credit: modification of work by "Suseno"/Wikimedia Commons)*

Regardless of the appearance of stained or unstained tissue, the cell bodies of neurons or axons can be located in discrete anatomical structures that need to be named. Those names 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**. Figure **11.2.3** indicates how the term nucleus has a few different meanings within anatomy and physiology. It is the center of an atom, where protons and neutrons are found; it is the center of a cell, where the DNA is found; and it is a center of some function in the CNS. There is also a potentially confusing use of the word ganglion (plural = ganglia) that has a historical explanation. In the central nervous system, there is a group of nuclei that are connected together and were once called the basal ganglia before "ganglion" became accepted as a description for a peripheral structure. Some sources refer to this group of nuclei as the "basal nuclei" to avoid confusion.

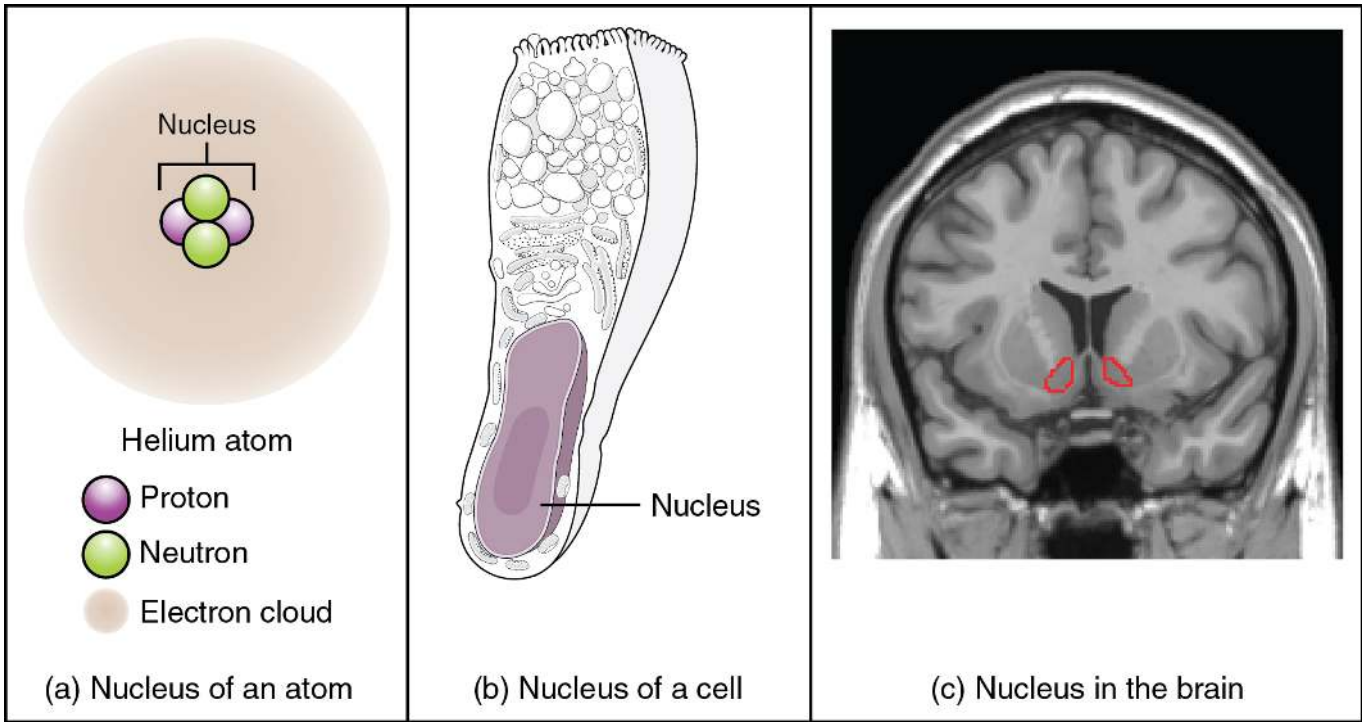



Figure **11.2.3**: What Is a Nucleus? (a) The nucleus of an atom contains its protons and neutrons. (b) The nucleus of a cell is the organelle that contains DNA. (c) A nucleus in the CNS is a localized center of function with the cell bodies of several neurons, shown here circled in red. (credit c: "Was a bee"/Wikimedia Commons)

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** whereas the same thing in the PNS would be called a **nerve**. 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. When those axons are in the PNS, the term is nerve, but if they are CNS, the term is tract. The most obvious example of this is the axons that project from the retina 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. There is a specific place where the name changes, which is the optic chiasm, but they are still the same axons (Figure **11.2.4**). A similar situation outside of science can be described for some roads. Imagine a road called "Broad Street" in a town called "Anyville." The road leaves Anyville and goes to the next town over, called "Hometown." When the road crosses the line between the two towns and is in Hometown, its name changes to "Main Street." That is the idea behind the naming of the retinal axons. In the PNS, they are called the optic nerve, and in the CNS, they are the optic tract. Table **11.2.1** helps to clarify which of these terms apply to the central or peripheral nervous systems.

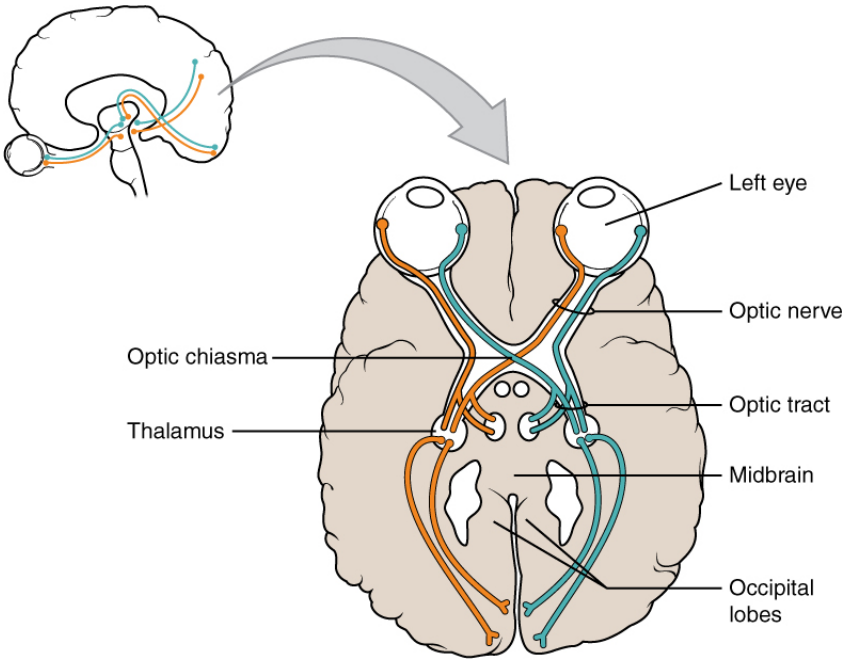



***Figure* 11.2.4*: Optic Nerve Versus Optic Tract.*** *This drawing of the connections of the eye to the brain shows the optic nerve extending from the eye to the chiasm, where the structure continues as the optic tract. The same axons extend from the eye to the brain through these two bundles of fibers, but the chiasm represents the border between peripheral and central.*

### magnetic resonance imaging

*In 2003, the Nobel Prize in Physiology or Medicine was awarded to Paul C. Lauterbur and Sir Peter Mansfield for discoveries related to magnetic resonance imaging (MRI). This is a tool to see the structures of the body (not just the nervous system) that depends on magnetic fields associated with certain atomic nuclei. The utility of this technique in the nervous system is that fat tissue and water appear as different shades between black and white. Because white matter is fatty (from myelin) and gray matter is not, they can be easily distinguished in MRI images. Visit the Nobel Prize web site to play an interactive game that demonstrates the use of this technology and compares it with other types of imaging technologies. Also, the results from an MRI session are compared with images obtained from X-ray or computed tomography. How do the imaging techniques shown in this game indicate the separation of white and gray matter compared with the freshly dissected tissue shown earlier?*

Table **11.2.1**: Structures of the CNS and PNS

| | CNS | PNS |
|---|---|---|
| Group of Neuron Cell Bodies (i.e., gray matter) | Nucleus | Ganglion |
| Bundle of Axons (i.e., white matter) | Tract | Nerve |

### 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 **11.2.6**). 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.

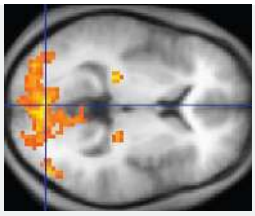


***Figure 11.2.6: fMRI.*** *This fMRI shows activation of the visual cortex in response to visual stimuli. (credit: "Superborsuk"/Wikimedia Commons)*

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.

## Chapter Review

The nervous system can be separated into divisions on the basis of anatomy and physiology. The anatomical divisions are the central and peripheral nervous systems. The CNS is the brain and spinal cord. The PNS is everything else. 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.

Considering the anatomical regions of the nervous system, there are specific names for the structures within each division. A localized collection of neuron cell bodies is referred to as a nucleus in the CNS and as a ganglion in the PNS. A bundle of axons is referred to as a tract in the CNS and as a nerve in the PNS. Whereas nuclei and ganglia are specifically in the central or peripheral divisions, axons can cross the boundary between the two. A single axon can be part of a nerve and a tract. The name for that specific structure depends on its location.

Nervous tissue can also be described as gray matter and white matter on the basis of its appearance in unstained tissue. These descriptions are more often used in the CNS. Gray matter is where nuclei are found and white matter is where tracts are found. In the PNS, ganglia are basically gray matter and nerves are white matter.

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.

## Interactive Link Questions

In 2003, the Nobel Prize in Physiology or Medicine was awarded to Paul C. Lauterbur and Sir Peter Mansfield for discoveries related to magnetic resonance imaging (MRI). This is a tool to see the structures of the body (not just the nervous system) that depends on magnetic fields associated with certain atomic nuclei. The utility of this technique in the nervous system is that fat tissue and water appear as different shades between black and white. Because white matter is fatty (from myelin) and gray matter is not, they can be easily distinguished in MRI images. Visit the Nobel Prize website to play an interactive game that demonstrates the use of this technology and compares it with other types of imaging technologies. Also, the results from an MRI session are compared with images obtained from x-ray or computed tomography. How do the imaging techniques shown in this game indicate the separation of white and gray matter compared with the freshly dissected tissue shown earlier?

THE NOBEL PRIZE

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Answer: MRI uses the relative amount of water in tissue to distinguish different areas, so gray and white matter in the nervous system can be seen clearly in these images.

Visit this site to read 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, both of which are responsible for controlling coordinated movements. To what functional division of the nervous system would these structures belong?




Answer: They are part of the somatic nervous system, which is responsible for voluntary movements such as walking or climbing the stairs.

## 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: C

Q. Which structure predominates in the white matter of the brain?

A. myelinated axons

B. neuronal cell bodies

C. ganglia of the parasympathetic nerves

D. bundles of dendrites from the enteric nervous system

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: D

Q. Which term describes a bundle of axons in the peripheral nervous system?

A. nucleus

B. ganglion

C. tract

D. nerve

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: 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.

A. Running on a treadmill involves contraction of the skeletal muscles in the legs, increase in contraction of the cardiac muscle of the heart, and the production and secretion of sweat in the skin to stay cool.

Q. When eating food, what anatomical and functional divisions of the nervous system are involved in the perceptual experience?

A. The sensation of taste associated with eating is sensed by nerves in the periphery that are involved in sensory and somatic functions.

## References

Kramer, PD. Listening to prozac. 1st ed. New York (NY): Penguin Books; 1993.

## Glossary

**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

**central nervous system (CNS)**
anatomical division of the nervous system located within the cranial and vertebral cavities, namely the brain and spinal cord

**dendrite**
one of many branchlike processes that extends from the neuron cell body and functions as a contact for incoming signals (synapses) from other neurons or sensory cells

**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

**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; the cell body, as opposed to the cell processes (axons and dendrites)

**somatic nervous system (SNS)**

functional division of the nervous system that is concerned with conscious perception, voluntary movement, and skeletal muscle reflexes

**spinal cord**

organ of the central nervous system found within the vertebral cavity and connected with the periphery through spinal nerves; mediates reflex behaviors

**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

**white matter**

regions of the nervous system containing mostly myelinated axons, making the tissue appear white because of the high lipid content of myelin

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# 11.3: Nervous Tissue

**Learning Objectives**

- Describe the basic structure of a neuron
- Identify the different types of neurons on the basis of polarity
- List the glial cells of the CNS and describe their function
- List the glial cells of the PNS and describe their function

Nervous tissue is composed of two types of cells, neurons and glial cells. 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, 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.

## Neurons

Neurons are the cells considered to be the basis of nervous tissue. 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. But 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 gives the neuron a polarity—meaning that information flows in this one direction. Figure **11.3.1** shows the relationship of these parts to one another.

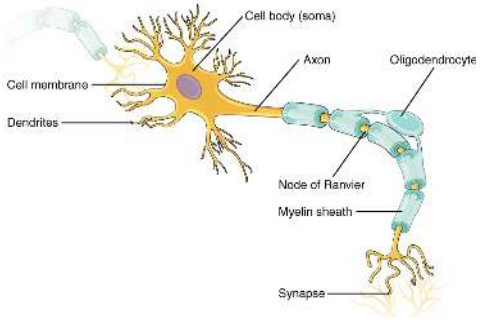



Figure **11.3.1**: Parts of a Neuron. The major parts of the neuron are labeled on a multipolar neuron from the CNS.

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**. Because the axon hillock represents the beginning of the axon, it is also referred to as the **initial segment**.

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.

QR Code representing a URL

*Visit this site to learn about how nervous tissue is composed of neurons and glial cells. Neurons are dynamic cells with the ability to make a vast number of connections, to respond incredibly quickly to stimuli, and to initiate movements on the basis of those stimuli. They are the focus of intense research because failures in physiology can lead to devastating illnesses. Why are neurons*

*only found in animals? Based on what this article says about neuron function, why wouldn't they be helpful for plants or microorganisms?*

## 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 by many different criteria. The first way to classify them is by the number of processes attached to the cell body. Using the standard model of neurons, one of these processes is the axon, and the rest are dendrites. Because information flows through the neuron from dendrites or cell bodies toward the axon, these names are based on the neuron's polarity (Figure **11.3.2**).

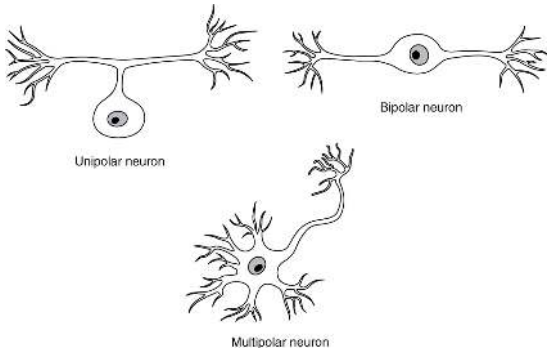



Figure **11.3.2**: Neuron Classification by Shape. Unipolar cells have one process that includes both the axon and dendrite. Bipolar cells have two processes, the axon and a dendrite. Multipolar cells have more than two processes, the axon and two or more dendrites.

**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. 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.

**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. 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 **11.3.3**). 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).

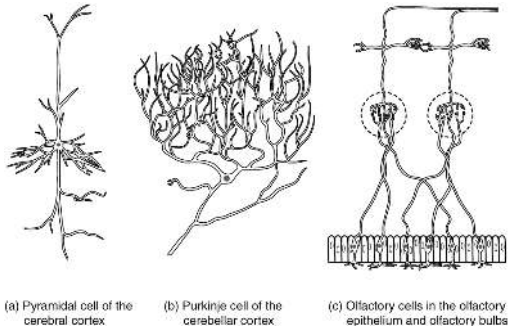



Figure **11.3.3**: Other Neuron Classifications. Three examples of neurons that are classified on the basis of other criteria. (a) The pyramidal cell is a multipolar cell with a cell body that is shaped something like a pyramid. (b) The Purkinje cell in the cerebellum was named after the scientist who originally described it. (c) Olfactory neurons are named for the functional group with which they belong.

## 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 |
| 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 **11.3.4**). 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 by maintaining the concentration of chemicals in the extracellular space, removing excess signaling molecules, reacting to tissue damage, and contributing 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.

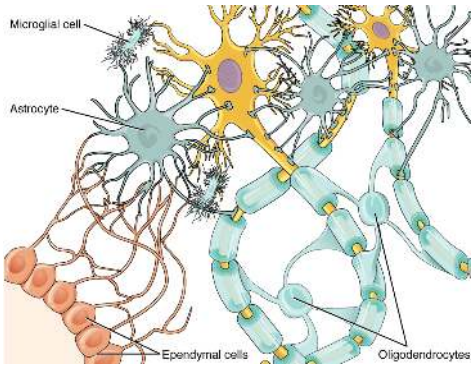



Figure **11.3.4**: Glial Cells of the CNS. The CNS has astrocytes, oligodendrocytes, microglia, and ependymal cells that support the neurons of the CNS in several ways.

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 BBB breaks down. 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 **11.3.4**.

### 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 **11.3.5**.

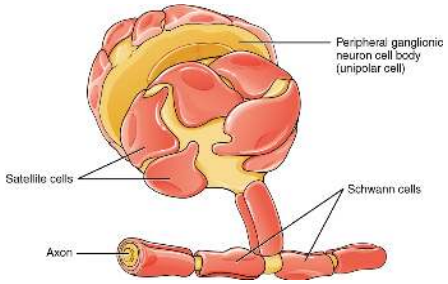



***FIgure 12.2.5: Glial Cells of the PNS.*** *The PNS has satellite cells and Schwann cells.*

## Myelin

The insulation for axons in the nervous system is provided by glial cells, oligodendrocytes in the CNS, and Schwann cells in the PNS. Whereas the manner in which either cell is associated with the axon segment, or segments, that it insulates is different, the means of myelinating an axon segment is mostly the same in the two situations. 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 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, 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, 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 **11.3.6**.a). 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.

QR Code representing a URL

*View the University of Michigan WebScope at virtualslides.med.umich.edu/H...ml?listview=1& to see an electron micrograph of a cross-section of a myelinated nerve fiber. The axon contains microtubules and neurofilaments that are bounded by a plasma membrane known as the axolemma. Outside the plasma membrane of the axon is the myelin sheath, which is composed of the tightly wrapped plasma membrane of a Schwann cell. What aspects of the cells in this image react with the stain to make them a deep, dark, black color, such as the multiple layers that are the myelin sheath?*

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 **11.3.1**, Figure **11.3.4**, and Figure **11.3.5** 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.

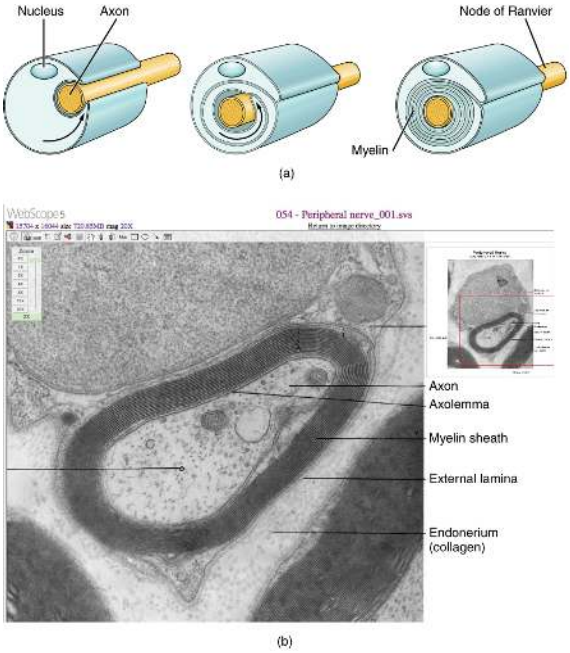



Figure **11.3.6**: The Process of Myelination. Myelinating glia wrap several layers of cell membrane around the cell membrane of an axon segment. A single Schwann cell insulates a segment of a peripheral nerve, whereas in the CNS, an oligodendrocyte may provide insulation for a few separate axon segments. EM × 1,460,000. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

DISORDERS OF THE...

**Nervous Tissue**

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.

## Chapter 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.

## Interactive Link Questions

Visit this site to learn about how nervous tissue is composed of neurons and glial cells. The neurons are dynamic cells with the ability to make a vast number of connections and to respond incredibly quickly to stimuli and to initiate movements based on those stimuli. They are the focus of intense

research as failures in physiology can lead to devastating illnesses. Why are neurons only found in animals? Based on what this article says about neuron function, why wouldn't they be helpful for plants or microorganisms?

> Answer: Neurons enable thought, perception, and movement. Plants do not move, so they do not need this type of tissue. Microorganisms are too small to have a nervous system. Many are single-celled, and therefore have organelles for perception and movement.

View the University of Michigan WebScope at virtualslides.med.umich.edu/H...ml?listview=1& to see an electron micrograph of a cross-section of a myelinated nerve fiber. The axon contains microtubules and neurofilaments, bounded by a plasma membrane known as the axolemma. Outside the plasma membrane of the axon is the myelin sheath, which is composed of the tightly wrapped plasma membrane of a Schwann cell. What aspects of the cells in this image react with the stain that makes them the deep, dark, black color, such as the multiple layers that are the myelin sheath?

> Answer: Lipid membranes, such as the cell membrane and organelle membranes.

## 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: A

Q. Which part of a neuron contains the nucleus?

A. dendrite

B. soma

C. axon

D. synaptic end bulb

> 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: 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: 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: 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?

> 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.

> 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 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 initial segment, 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

**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

**ependymal cell**
glial cell type in the CNS responsible for producing cerebrospinal fluid

**initial segment**
first part of the axon as it emerges from the axon hillock, where the electrical signals known as action potentials are generated

**microglia**
glial cell type in the CNS that serves as the resident component of the immune system

**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

**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

**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

**ventricle**
central cavity within the brain where CSF is produced and circulates

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# CHAPTER OVERVIEW

## 12: Anatomy of the Nervous Tissue

The nervous system is responsible for controlling much of the body, both through somatic (voluntary) and autonomic (involuntary) functions. The structures of the nervous system must be described in detail to understand how many of these functions are possible. There is a physiological concept known as localization of function that states that certain structures are specifically responsible for prescribed functions. It is an underlying concept in all of anatomy and physiology, but the nervous system illustrates the concept very well.


12.1: Prelude Anatomy of the Nervous Tissue

12.2: The Central Nervous System

12.3: Circulation and the Central Nervous System

12.4: The Peripheral Nervous System


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# 12.1: Prelude Anatomy of the Nervous Tissue

## Chapter Objectives

- Relate the developmental processes of the embryonic nervous system to the adult structures
- Name the major regions of the adult nervous system
- Locate regions of the cerebral cortex on the basis of anatomical landmarks common to all human brains
- Describe the regions of the spinal cord in cross-section
- 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

The nervous system is responsible for controlling much of the body, both through somatic (voluntary) and autonomic (involuntary) functions. The structures of the nervous system must be described in detail to understand how many of these functions are possible. There is a physiological concept known as localization of function that states that certain structures are specifically responsible for prescribed functions. It is an underlying concept in all of anatomy and physiology, but the nervous system illustrates the concept very well.

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 described, 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.

The place to start this study of the nervous system is the beginning of the individual human life, within the womb. The embryonic development of the nervous system allows for a simple framework on which progressively more complicated structures can be built. With this framework in place, a thorough investigation of the nervous system is possible.



***Figure 13.0.1: Human Nervous System.*** *The ability to balance like an acrobat combines functions throughout the nervous system. The central and peripheral divisions coordinate control of the body using the senses of balance, body position, and touch on the soles of the feet. (credit: Rhett Sutphin)*

## Contributors

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# 12.2: The Central Nervous System

**Learning Objectives**

- Name the major regions of the adult brain
- Describe the connections between the cerebrum and brain stem through the diencephalon, and from those regions into the spinal cord
- Recognize the complex connections within the subcortical structures of the basal nuclei
- Explain the arrangement of gray and white matter in the spinal cord

The brain and the spinal cord are the central nervous system, and they represent the main organs of the nervous system. The spinal cord is a single structure, whereas the adult brain is described in terms of four major regions: the cerebrum, the diencephalon, the brain stem, and the cerebellum. A person's conscious experiences are based on neural activity in the brain. The regulation of homeostasis is governed by a specialized region in the brain. The coordination of reflexes depends on the integration of sensory and motor pathways in the spinal cord.

## The Cerebrum

The iconic gray mantle of the human brain, which appears to make up most of the mass of the brain, is the **cerebrum** (Figure 12.2.1). The wrinkled portion is the **cerebral cortex**, and the rest of the structure is beneath that outer covering. There is a large separation between the two sides of the cerebrum called the **longitudinal fissure**. It separates the cerebrum into two distinct halves, a right and left **cerebral hemisphere**. 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.

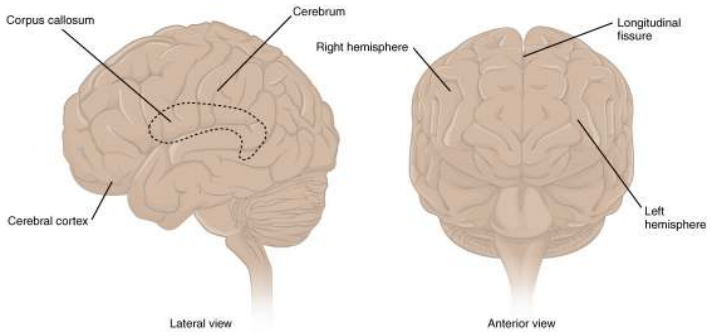



Figure 12.2.1: The Cerebrum. The cerebrum is a large component of the CNS in humans, and the most obvious aspect of it is the folded surface called the cerebral cortex.

Many of the higher neurological functions, such as memory, emotion, and consciousness, are the result of cerebral function. The complexity of the cerebrum is different across vertebrate species. The cerebrum of the most primitive vertebrates is not much more than the connection for the sense of smell. In mammals, the cerebrum comprises the outer gray matter that is the cortex (from the Latin word meaning "bark of a tree") and several deep nuclei that belong to three important functional groups. The **basal nuclei** are responsible for cognitive processing, the most important function being that associated with planning movements. The **basal forebrain** contains nuclei that are important in learning and memory. The **limbic cortex** is the region of the cerebral cortex that is part of the **limbic system**, a collection of structures involved in emotion, memory, and behavior.

### Cerebral Cortex

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. The pattern of these folds of tissue indicates specific regions of the cerebral cortex.

The head is limited by the size of the birth canal, and 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. Using these landmarks, the cortex can be separated into four major regions, or lobes (Figure 12.2.2). The **lateral sulcus** that separates the **temporal lobe** from the other regions is one such landmark. 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**. The fact that there is no obvious anatomical border between these lobes is consistent with the functions of these regions being interrelated.

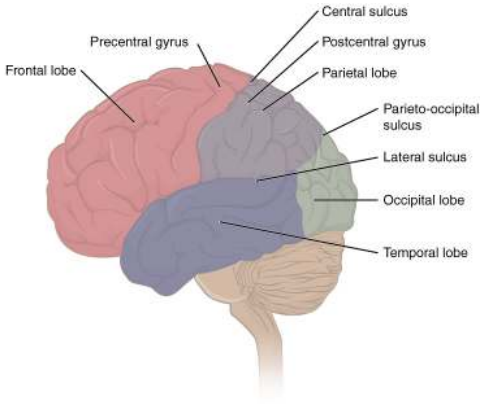



Figure 12.2.2: Lobes of the Cerebral Cortex. The cerebral cortex is divided into four lobes. Extensive folding increases the surface area available for cerebral functions.

Different regions of the cerebral cortex can be associated with particular functions, a concept known as localization of function. 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 12.2.3). The results from Brodmann's work on the anatomy align very well with the functional differences within the cortex. Areas 17 and 18 in the occipital lobe are responsible for primary visual perception. That visual information is complex, so it is processed in the temporal and parietal lobes as well.

The temporal lobe is associated with primary auditory sensation, known as Brodmann's areas 41 and 42 in the superior temporal lobe. Because regions of the temporal lobe are part of the limbic system, memory is an important function associated with that 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.

The main sensation associated with the parietal lobe is **somatosensation**, meaning the general sensations associated with the body. Posterior to the central sulcus is the **postcentral gyrus**, the primary somatosensory cortex, which is identified as Brodmann's areas 1, 2, and 3. 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.

Anterior to the central sulcus is the frontal lobe, which is primarily associated with motor functions. The **precentral gyrus** 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. Anterior to this region are a few areas that are associated with planned movements. The **premotor area** is responsible for thinking of a movement to be made. The **frontal eye fields** are important in eliciting eye movements and in attending to visual stimuli. **Broca's area** is responsible for the production of language, or controlling movements responsible for speech; in the vast majority of people, it is located only on the left side. Anterior to these regions is the **prefrontal lobe**, which serves cognitive functions that can be the basis of personality, short-term memory, and consciousness. The prefrontal lobotomy is

an outdated mode of treatment for personality disorders (psychiatric conditions) that profoundly affected the personality of the patient.

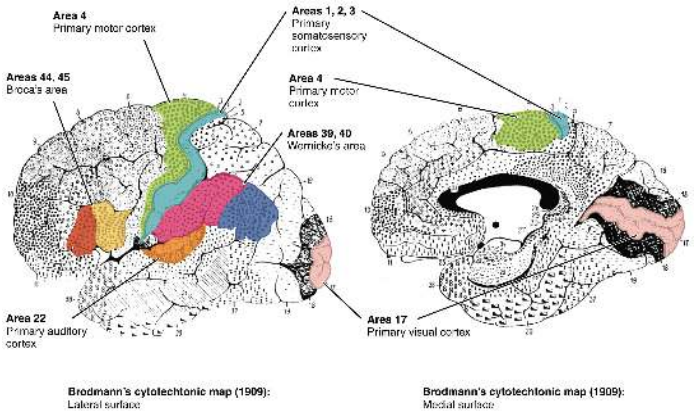



Figure **12.2.3**: Brodmann's Areas of the Cerebral Cortex. Brodmann mapping of functionally distinct regions of the cortex was based on its cytoarchitecture at a microscopic level.

## Subcortical structures

Beneath the cerebral cortex are sets of nuclei known as **subcortical nuclei** that augment cortical processes. The nuclei of the basal forebrain serve as the primary location for acetylcholine production, which modulates the overall activity of the cortex, possibly leading to greater attention to sensory stimuli. Alzheimer's disease is associated with a loss of neurons in the basal forebrain. The **hippocampus** and **amygdala** are medial-lobe structures that, along with the adjacent cortex, are involved in long-term memory formation and emotional responses. The basal nuclei are a set of nuclei in the cerebrum 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. (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 structures.)

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 **12.2.4**.

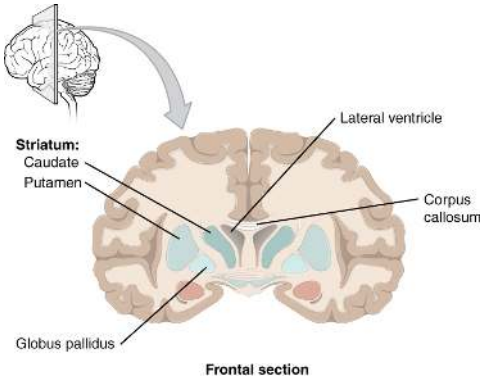



Figure **12.2.4**: Frontal Section of Cerebral Cortex and Basal Nuclei. The major components of the basal nuclei, shown in a frontal section of the brain, are the caudate (just lateral to the lateral ventricle), the putamen (inferior to the caudate and separated by the large white-matter structure called the internal capsule), and the globus pallidus (medial to the putamen).

EVERYDAY CONNECTIONS

**The Myth of Left Brain/Right Brain**

There is a persistent myth that people are “right-brained” or “left-brained,” which is an oversimplification of an important concept about the cerebral hemispheres. There is some lateralization of function, in which the left side of the brain is devoted to language function and the right side is devoted to spatial and nonverbal reasoning. Whereas these functions are predominantly associated with those sides of the brain, there is no monopoly by either side on these functions. Many pervasive functions, such as language, are distributed globally around the cerebrum.

Some of the support for this misconception has come from studies of split brains. A drastic way to deal with a rare and devastating neurological condition (intractable epilepsy) is to separate the two hemispheres of the brain. After sectioning the corpus callosum, a split-brained patient will have trouble producing verbal responses on the basis of sensory information processed on the right side of the cerebrum, leading to the idea that the left side is responsible for language function.

However, there are well-documented cases of language functions lost from damage to the right side of the brain. The deficits seen in damage to the left side of the brain are classified as aphasia, a loss of speech function; damage on the right side can affect the use of language. Right-side damage can result in a loss of ability to understand figurative aspects of speech, such as jokes, irony, or metaphors. Nonverbal aspects of speech can be affected by damage to the right side, such as facial expression or body language, and right-side damage can lead to a “flat affect” in speech, or a loss of emotional expression in speech—sounding like a robot when talking.

## The 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 two major regions of the diencephalon are the thalamus itself and the hypothalamus (Figure **12.2.6**). There are other structures, such as the **epithalamus**, which contains the pineal gland, or the **subthalamus**, which includes the subthalamic nucleus that is part of the basal nuclei.

### Thalamus

The **thalamus** is a collection of nuclei that relay information between the cerebral cortex and the periphery, spinal cord, or brain stem. 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 brain stem. The cerebrum interacts with the basal nuclei, which involves connections with the thalamus. The primary output of the basal nuclei is to the thalamus, which relays that output to the cerebral cortex. The cortex also sends information to the thalamus that will then influence the effects of the basal nuclei.

### 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.

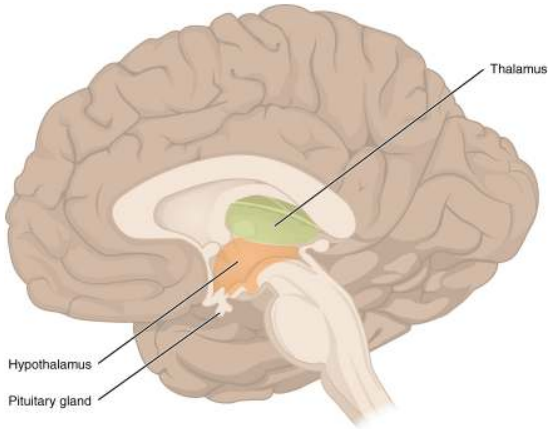



Figure 12.2.6: The Diencephalon. The diencephalon is composed primarily of the thalamus and hypothalamus, which together define the walls of the third ventricle. The thalami are two elongated, ovoid structures on either side of the midline that make contact in the middle. The hypothalamus is inferior and anterior to the thalamus, culminating in a sharp angle to which the pituitary gland is attached.

## Brain Stem

The midbrain and hindbrain (composed of the pons and the medulla) are collectively referred to as the brain stem (Figure 12.2.7). 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 brain stem, 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 and rates.

The cranial nerves connect through the brain stem 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 brain stem.

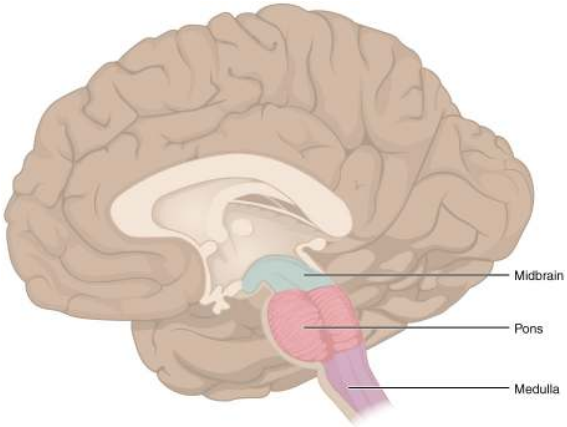



Figure 12.2.7: The Brain Stem. The brain stem comprises three regions: the midbrain, the pons, and the medulla.

### Midbrain

One of the original regions of the embryonic brain, the midbrain is a small region between the thalamus and pons. It is separated into the **tectum** and **tegmentum**, from the Latin words for roof and floor, respectively. The cerebral aqueduct passes through the center of the midbrain, such that these regions are the roof and floor of that canal.

The tectum is composed of four bumps known as the colliculi (singular = colliculus), which means “little hill” in Latin. The **inferior colliculus** is the inferior pair of these enlargements and is part of the auditory brain stem pathway. Neurons of the inferior colliculus project to the thalamus, which then sends auditory information to the cerebrum for the conscious perception of sound. The **superior colliculus** is the superior pair and combines sensory information about visual space, auditory space, and somatosensory space. Activity in the superior colliculus is related to orienting the eyes to a sound or touch stimulus. If you are walking along the sidewalk on campus and you hear chirping, the superior colliculus coordinates that information with your

awareness of the visual location of the tree right above you. That is the correlation of auditory and visual maps. If you suddenly feel something wet fall on your head, your superior colliculus integrates that with the auditory and visual maps and you know that the chirping bird just relieved itself on you. You want to look up to see the culprit, but do not.

The tegmentum is continuous with the gray matter of the rest of the brain stem. Throughout the midbrain, pons, and medulla, the tegmentum contains the nuclei that receive and send information through the cranial nerves, as well as regions that regulate important functions such as those of the cardiovascular and respiratory systems.

### Pons

The word pons comes from the Latin word for bridge. It is visible on the anterior surface of the brain stem as the thick bundle of white matter attached to the cerebellum. The pons is the main connection between the cerebellum and the brain stem. The bridge-like white matter is only the anterior surface of the pons; the gray matter beneath that is a continuation of the tegmentum from the midbrain. Gray matter in the tegmentum region of the pons contains neurons receiving descending input from the forebrain that is sent to the cerebellum.

### Medulla

The medulla 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 tegmentum of the midbrain and pons continues into the medulla because this gray matter is responsible for processing cranial nerve information. A diffuse region of gray matter throughout the brain stem, known as the **reticular formation**, is related to sleep and wakefulness, such as general brain activity and attention.

## The Cerebellum

The **cerebellum**, as the name suggests, is the “little brain.” It is covered in gyri and sulci like the cerebrum, and looks like a miniature version of that part of the brain (Figure 12.2.8). The cerebellum is largely responsible for comparing information from the cerebrum with sensory feedback from the periphery through the spinal cord. It accounts for approximately 10 percent of the mass of the brain.

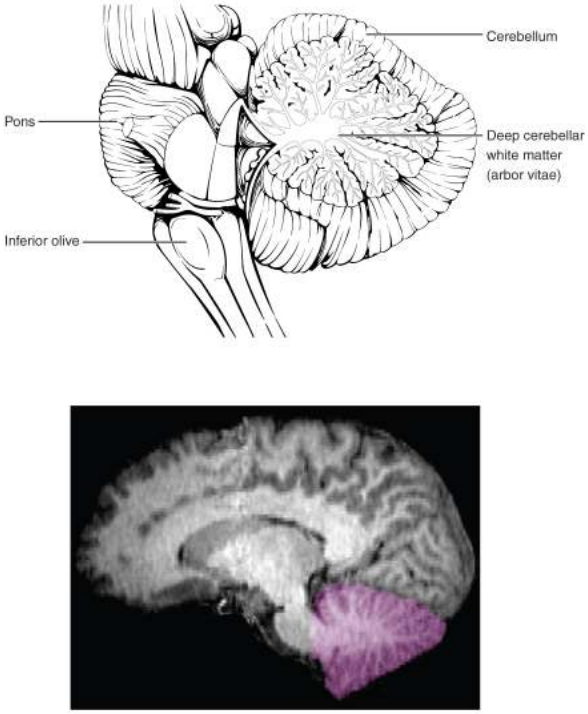



Figure 12.2.8: The Cerebellum. The cerebellum is situated on the posterior surface of the brain stem. Descending input from the cerebellum enters through the large white matter structure of the pons. Ascending input from the periphery and spinal cord enters through the fibers of the inferior olive. Output goes to the midbrain, which sends a descending signal to the spinal cord.

Descending fibers from the cerebrum have branches that connect to neurons in the pons. Those neurons project into the cerebellum, providing a copy of motor commands sent to the spinal cord. Sensory information from the periphery, which enters through spinal or cranial nerves, is copied to a nucleus in the medulla known as the **inferior olive**. Fibers from this nucleus enter the cerebellum and are compared with the descending commands from the cerebrum. 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.

## The 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. 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. The anterior midline is marked by the **anterior median fissure**, and the posterior midline is marked by the **posterior median sulcus**. Axons 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.

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.

The length of the spinal cord is divided into regions that correspond to the regions of the vertebral column. The name of a spinal cord region corresponds to the level at which spinal nerves pass through the intervertebral foramina. Immediately adjacent to the brain stem is the cervical region, followed by the thoracic, then the lumbar, and finally the sacral region. 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. The nerves that emerge from the spinal cord pass through the intervertebral formina at the respective levels. As the vertebral column grows, these nerves grow with it and result in a long bundle of nerves that resembles a horse’s tail and is named the **cauda equina**. The sacral spinal cord is at the level of the upper lumbar vertebral bones. The spinal nerves extend from their various levels to the proper level of the vertebral column.

### 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 **12.2.9**, the gray matter is subdivided into regions that are referred to as horns. The **posterior horn** is responsible for sensory processing. The **anterior horn** sends out motor signals to the skeletal muscles. The **lateral horn**, which is only found in the thoracic, upper lumbar, and sacral regions, is the central component of the sympathetic division of the autonomic nervous system.

Some of the largest neurons of the spinal cord are the multipolar motor neurons in the anterior horn. The fibers that cause contraction of skeletal muscles are the axons of these neurons. 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.

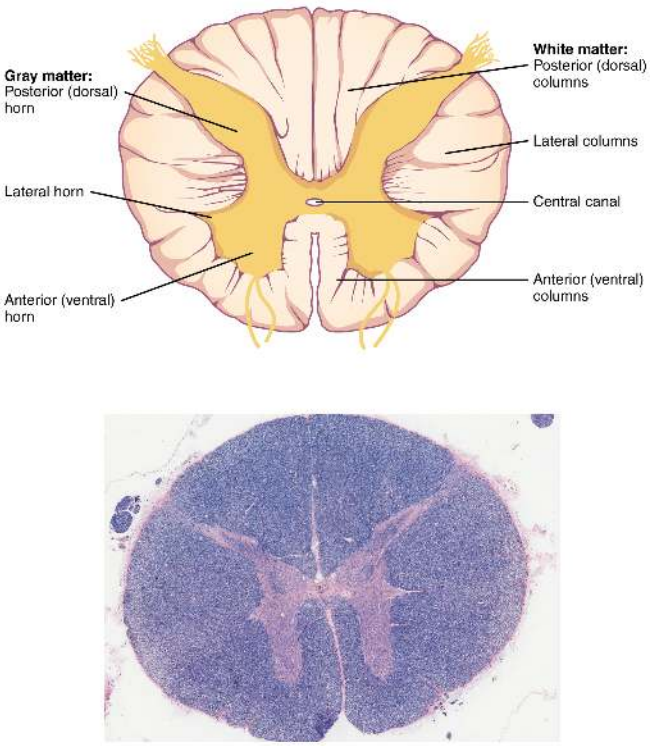



Figure **12.2.9**: Cross-section of Spinal Cord. The cross-section of a thoracic spinal cord segment shows the posterior, anterior, and lateral horns of gray matter, as well as the posterior, anterior, and lateral columns of white matter. LM × 40. (Micrograph provided by the Regents of University of 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**. 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 posterior columns are composed of axons of ascending tracts. 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.

*Watch this video to learn about the gray matter of the spinal cord that receives input from fibers of the dorsal (posterior) root and sends information out through the fibers of the ventral (anterior) root. As discussed in this video, these connections represent the interactions of the CNS with peripheral structures for both sensory and motor functions. The cervical and lumbar spinal cords have enlargements as a result of larger populations of neurons. What are these enlargements responsible for?*

DISORDERS OF THE...

**Basal Nuclei**

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.*



*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 this article 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?*

## Chapter Review

The adult brain is separated into four major regions: the cerebrum, the diencephalon, the brain stem, and the cerebellum. The cerebrum is the largest portion and contains the cerebral cortex and subcortical nuclei. It is divided into two halves by the longitudinal fissure.

The cortex 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.

Nuclei beneath the cerebral cortex, known as the subcortical nuclei, are responsible for augmenting cortical functions. The basal nuclei receive input from cortical areas and compare it with the general state of the individual through the activity of a dopamine-releasing nucleus. 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. The basal forebrain is responsible for modulating cortical activity in attention and memory. The limbic system includes deep cerebral nuclei that are responsible for emotion and memory.

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 brain stem 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 brain stem that regulate the cardiovascular and respiratory systems.

The cerebellum is connected to the brain stem, 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.

## Interactive Link Questions

Watch this video to learn about the basal nuclei (also known as the basal ganglia), which have two pathways that process information within the cerebrum. As shown in this video, the direct pathway is the shorter pathway through the system that results in increased activity in the cerebral cortex and increased motor activity. The direct pathway is described as resulting in "disinhibition" of the thalamus. What does disinhibition mean? What are the two neurons doing individually to cause this?

> Answer: Both cells are inhibitory. The first cell inhibits the second one. Therefore, the second cell can no longer inhibit its target. This is disinhibition of that target across two synapses.

Watch this video to learn about the basal nuclei (also known as the basal ganglia), which have two pathways that process information within the cerebrum. As shown in this video, the indirect pathway is the longer pathway through the system that results in decreased activity in the cerebral cortex, and therefore less motor activity. The indirect pathway has an extra couple of connections in it, including disinhibition of the subthalamic nucleus. What is the end result on the thalamus, and therefore on movement initiated by the cerebral cortex?

> Answer: By disinhibiting the subthalamic nucleus, the indirect pathway increases excitation of the globus pallidus internal segment. That, in turn, inhibits the thalamus, which is the opposite effect of the direct pathway that disinhibits the thalamus.

Watch this video to learn about the gray matter of the spinal cord that receives input from fibers of the dorsal (posterior) root and sends information out through the fibers of the ventral (anterior) root. As discussed in this video, these connections represent the interactions of the CNS with peripheral structures for both sensory and motor functions. The cervical and lumbar spinal cords have enlargements as a result of larger populations of neurons. What are these enlargements responsible for?

> Answer: There are more motor neurons in the anterior horns that are responsible for movement in the limbs. The cervical enlargement is for the arms, and the lumbar enlargement is for the legs.

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 this article 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: 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.

## Review Questions

Q. Which lobe of the cerebral cortex is responsible for generating motor commands?

A. temporal

B. parietal

C. occipital

D. frontal

Answer: D

Q. What region of the diencephalon coordinates homeostasis?

A. thalamus

B. epithalamus

C. hypothalamus

D. subthalamus

Answer: C

Q. What level of the brain stem is the major input to the cerebellum?

A. midbrain

B. pons

C. medulla

D. spinal cord

Answer: B

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

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

## Critical Thinking Questions

Q. Damage to specific regions of the cerebral cortex, such as through a stroke, can result in specific losses of function. What functions would likely be lost by a stroke in the temporal lobe?

A. The temporal lobe has sensory functions associated with hearing and vision, as well as being important for memory. A stroke in the temporal lobe can result in specific sensory deficits in these systems (known as agnosias) or losses in memory.

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

**alar plate**
developmental region of the spinal cord that gives rise to the posterior horn of the gray matter

**amygdala**
nucleus deep in the temporal lobe of the cerebrum that is related to memory and emotional behavior

**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 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

**ascending tract**
central nervous system fibers carrying sensory information from the spinal cord or periphery to the brain

**basal forebrain**
nuclei of the cerebrum related to modulation of sensory stimuli and attention through broad projections to the cerebral cortex, loss of which is related to Alzheimer's disease

**basal nuclei**
nuclei of the cerebrum (with a few components in the upper brain stem 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

**basal plate**
developmental region of the spinal cord that gives rise to the lateral and anterior horns of gray matter

**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

**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

**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

**cerebrum**

region of the adult brain that develops from the telencephalon and is responsible for higher neurological functions such as memory, emotion, and consciousness

**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 hemisphere**

one half of the bilaterally symmetrical cerebrum

**corpus callosum**

large white matter structure that connects the right and left cerebral hemispheres

**descending tract**

central nervous system fibers carrying motor commands from the brain to the spinal cord or periphery

**direct pathway**

connections within the basal nuclei from the striatum to the globus pallidus internal segment and substantia nigra pars reticulata that disinhibit the thalamus to increase cortical control of movement

**disinhibition**

disynaptic connection in which the first synapse inhibits the second cell, which then stops inhibiting the final target

**dorsal (posterior) nerve root**

axons entering the posterior horn of the spinal cord

**epithalamus**

region of the diecephalon containing the pineal gland

**frontal eye field**

region of the frontal lobe associated with motor commands to orient the eyes toward an object of visual attention

**frontal lobe**

region of the cerebral cortex directly beneath the frontal bone of the cranium

**globus pallidus**

nuclei deep in the cerebrum that are part of the basal nuclei and can be divided into the internal and external segments

**gyrus**

ridge formed by convolutions on the surface of the cerebrum or 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

**indirect pathway**
connections within the basal nuclei from the striatum through the globus pallidus external segment and subthalamic nucleus to the globus pallidus internal segment/substantia nigra pars compacta that result in inhibition of the thalamus to decrease cortical control of movement

**inferior colliculus**
half of the midbrain tectum that is part of the brain stem auditory pathway

**inferior olive**
nucleus in the medulla that is involved in processing information related to motor control

**kinesthesia**
general sensory perception of movement of the body

**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 sympathetic division of the autonomic nervous system

**lateral sulcus**
surface landmark of the cerebral cortex that marks the boundary between the temporal lobe and the frontal and parietal lobes

**limbic cortex**
collection of structures of the cerebral cortex that are involved in emotion, memory, and behavior and are part of the larger limbic system

**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

**longitudinal fissure**
large separation along the midline between the two cerebral hemispheres

**occipital lobe**
region of the cerebral cortex directly beneath the occipital bone of the cranium

**olfaction**
special sense responsible for smell, which has a unique, direct connection to the cerebrum

**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 somatosensory processing initially takes place in the cerebrum

**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 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

**precentral gyrus**
primary motor cortex located in the frontal lobe of the cerebral cortex

**prefrontal lobe**
specific region of the frontal lobe anterior to the more specific motor function areas, which can be related to the early planning of movements and intentions to the point of being personality-type functions

**premotor area**
region of the frontal lobe responsible for planning movements that will be executed through the primary motor cortex

**proprioception**
general sensory perceptions providing information about location and movement of body parts; the “sense of the self”

**putamen**
nucleus deep in the cerebrum that is part of the basal nuclei; along with the caudate, it is part of the striatum

**reticular formation**
diffuse region of gray matter throughout the brain stem that regulates sleep, wakefulness, and states of consciousness

**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

**subcortical nucleus**
all the nuclei beneath the cerebral cortex, including the basal nuclei and the basal forebrain

**substantia nigra pars compacta**
nuclei within the basal nuclei that release dopamine to modulate the function of the striatum; part of the motor pathway

**substantia nigra pars reticulata**
nuclei within the basal nuclei that serve as an output center of the nuclei; part of the motor pathway

**subthalamus**
nucleus within the basal nuclei that is part of the indirect pathway

**sulcus**
groove formed by convolutions in the surface of the cerebral cortex

**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

**temporal lobe**
region of the cerebral cortex directly beneath the temporal bone of the cranium

**thalamus**
major region of the diencephalon that is responsible for relaying information between the cerebrum and the hindbrain, spinal cord, and periphery

## Contributors and Attributions

**ventral (anterior) nerve root**
axons emerging from the anterior or lateral horns of the spinal cord

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# 12.3: Circulation and the Central Nervous System

**Learning Objectives**

- Describe the vessels that supply the CNS with blood
- 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
- Explain how a disruption in circulation would result in a stroke

The CNS is crucial to the operation of the body, and any compromise in the brain and spinal cord can lead to severe difficulties. The CNS has a privileged blood supply, as suggested by the blood-brain barrier. The function of the tissue in the CNS 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 and spinal cord. Because of this privilege, the CNS needs specialized structures for the maintenance of circulation. This begins with a unique arrangement of blood vessels carrying fresh blood into the CNS. Beyond the supply of blood, the CNS filters that blood into cerebrospinal fluid (CSF), which is then circulated through the cavities of the brain and spinal cord called ventricles.

## 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 brain to get an uninterrupted perfusion.

### Arterial Supply

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 bases of the common carotids contain stretch receptors that immediately respond to the drop in blood pressure upon standing. The **orthostatic reflex** is a reaction to this change in body position, so that blood pressure is maintained against the increasing effect of gravity (orthostatic means “standing up”). Heart rate increases—a reflex of the sympathetic division of the autonomic nervous system—and this raises blood pressure.

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. Branches off the left and right vertebral arteries merge into the **anterior spinal artery** supplying the anterior aspect of the spinal cord, found along the anterior median fissure. The two vertebral arteries then merge into the **basilar artery**, which gives rise to branches to the brain stem 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 12.3.1).

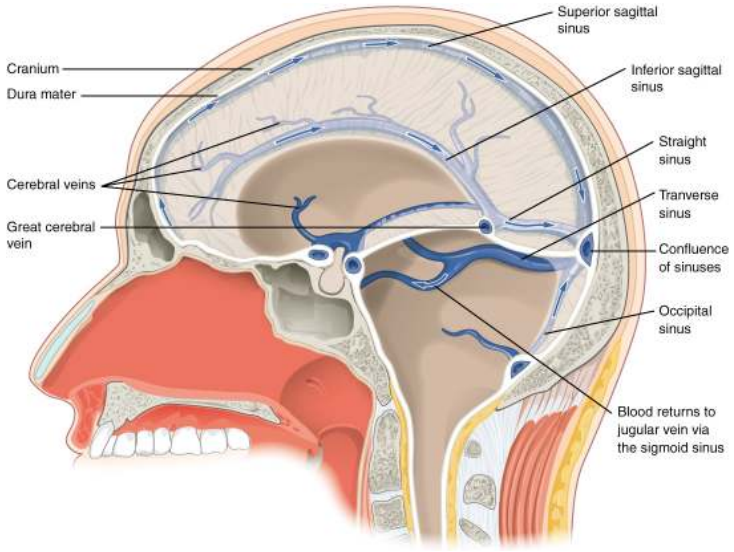



Figure **12.3.2**: Dural Sinuses and Veins. Blood drains from the brain through a series of sinuses that connect to the jugular veins.

## Protective Coverings of the Brain and Spinal Cord

The outer surface of the CNS is covered by a series of membranes composed of connective tissue called the **meninges**, which protect the brain. The **dura mater** is a thick fibrous layer and a strong protective sheath over the entire brain and spinal cord. 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 CNS. Beneath the arachnoid is a thin, filamentous mesh called the **arachnoid trabeculae**, which looks like a spider web, giving this layer its name. Directly adjacent to the surface of the CNS is the **pia mater**, a thin fibrous membrane that follows the convolutions of gyri and sulci in the cerebral cortex and fits into other grooves and indentations (Figure **12.3.3**).

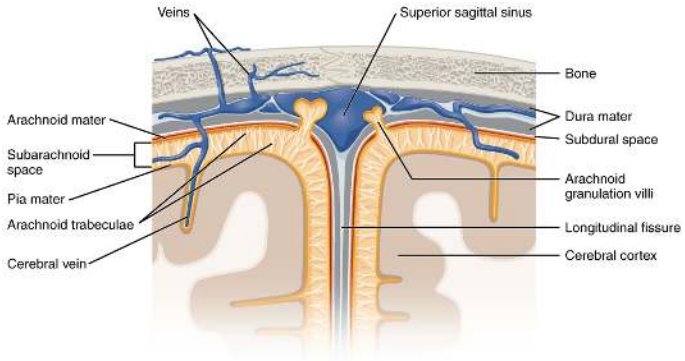



Figure **12.3.3**: Meningeal Layers of Superior Sagittal Sinus. The layers of the meninges in the longitudinal fissure of the superior sagittal sinus are shown, with the dura mater adjacent to the inner surface of the cranium, the pia mater adjacent to the surface of the brain, and the arachnoid and subarachnoid space between them. An arachnoid villus is shown emerging into the dural sinus to allow CSF to filter back into the blood for drainage.

### 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.

There are infoldings of the dura that fit into large crevasses of the brain. Two infoldings go through the midline separations of the cerebrum and cerebellum; one forms a shelf-like tent between the occipital lobes of the cerebrum and the cerebellum, and the other surrounds the pituitary gland. The dura also surrounds and supports the venous sinuses.

### Arachnoid Mater

The middle layer of the meninges is the arachnoid, named for the spider-web–like trabeculae between it 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. 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.

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.

### 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, lining the inside of the sulci in the cerebral and cerebellar cortices. At the end of the spinal cord, a thin filament extends from the inferior end of CNS at the upper lumbar region of the vertebral column to the sacral end of the vertebral column. 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 vessels that are nourishing the central nervous tissue are between the pia mater and the nervous tissue.

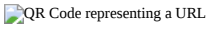
DISORDERS OF THE...

**Meninges**

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.




*Watch this video that describes the procedure known as the lumbar puncture, a medical procedure used to sample the CSF. Because of the anatomy of the CNS, it is a relative safe location to insert a needle. Why is the lumbar puncture performed in the lower lumbar area of the vertebral column?*

## The Ventricular System

Cerebrospinal fluid (CSF) circulates throughout and around the CNS. In other tissues, water and small molecules are filtered through capillaries as the major contributor to the interstitial fluid. In the brain, CSF is produced in special structures to perfuse through the nervous tissue of the CNS and is continuous with the interstitial fluid. Specifically, CSF circulates to remove metabolic wastes from the interstitial fluids of nervous tissues and return them to the blood stream. The **ventricles** are the open spaces within the brain where CSF circulates. In some of these spaces, CSF is produced by filtering of the blood that is performed by a

specialized membrane known as a choroid plexus. The CSF circulates through all of the ventricles to eventually emerge into the subarachnoid space where it will be reabsorbed into the blood.

## The 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 cerebrum. These ventricles are connected to the **third ventricle** by two openings called the **interventricular foramina**. The third ventricle is the space between the left and right sides of the diencephalon, which opens into the **cerebral aqueduct** that passes through the midbrain. The aqueduct opens into the **fourth ventricle**, which is the space between the cerebellum and the pons and upper medulla (Figure 12.3.4).

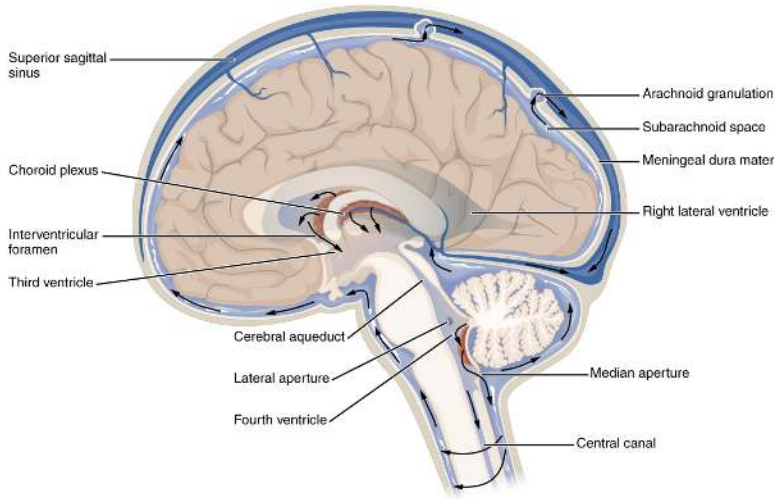



Figure 12.3.4: Cerebrospinal Fluid Circulation. The choroid plexus in the four ventricles produce CSF, which is circulated through the ventricular system and then enters the subarachnoid space through the median and lateral apertures. The CSF is then reabsorbed into the blood at the arachnoid granulations, where the arachnoid membrane emerges into the dural sinuses.

As the telencephalon enlarges and grows into the cranial cavity, it is limited by the space within the skull. The telencephalon is the most anterior region of what was the neural tube, but cannot grow past the limit of the frontal bone of the skull. Because the cerebrum fits into this space, it takes on a C-shaped formation, through the frontal, parietal, occipital, and finally temporal regions. The space within the telencephalon is stretched into this same C-shape. The two ventricles are in the left and right sides, and were at one time referred to as the first and second ventricles. The interventricular foramina connect the frontal region of the lateral ventricles with the third ventricle.

The third ventricle is the space bounded by the medial walls of the hypothalamus and thalamus. The two thalami touch in the center in most brains as the massa intermedia, which is surrounded by the third ventricle. The cerebral aqueduct opens just inferior to the epithalamus and passes through the midbrain. The tectum and tegmentum of the midbrain are the roof and floor of the cerebral aqueduct, respectively. The aqueduct opens up into the fourth ventricle. The floor of the fourth ventricle is the dorsal surface of the pons and upper medulla (that gray matter making a continuation of the tegmentum of the midbrain). The fourth ventricle then narrows into the central canal of the spinal cord.

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. Cerebrospinal fluid is produced within the ventricles by a type of specialized membrane 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. Oxygen and carbon dioxide are dissolved into the CSF, as they are in blood, and can diffuse between the fluid and the nervous tissue.

## 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. 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 (Table **12.3.1**).

QR Code representing a URL

*Watch this animation that shows the flow of CSF through the brain and spinal cord, and how it originates from the ventricles and then spreads into the space within the meninges, where the fluids then move into the venous sinuses to return to the cardiovascular circulation. What are the structures that produce CSF and where are they found? How are the structures indicated in this animation?*

***Table* 12.3.1**

Components of CSF Circulation

| | Lateral ventricles | Third ventricle | Cerebral aqueduct | Fourth ventricle | Central canal | Subarachnoid space |
|---|---|---|---|---|---|---|
| **Location in CNS** | Cerebrum | Diencephalon | Midbrain | Between pons/upper medulla and cerebellum | Spinal cord | External to entire CNS |
| **Blood vessel structure** | Choroid plexus | Choroid plexus | None | Choroid plexus | None | Arachnoid granulations |

DISORDERS OF THE...

**Central Nervous System**

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. The blockage is from 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 cortex 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. Function can return if the area is able to recover from the event.

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.

## Chapter 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 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.

## Interactive Link Questions

Watch this animation to see how blood flows to the brain and passes through the circle of Willis before being distributed through the cerebrum. The circle of Willis is a specialized arrangement of arteries that ensure constant perfusion of the cerebrum 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: 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.

Watch this video that describes the procedure known as the lumbar puncture, a medical procedure used to sample the CSF. Because of the anatomy of the CNS, it is a relative safe location to insert a needle. Why is the lumbar puncture performed in the lower lumbar area of the vertebral column?

> Answer: The spinal cord ends in the upper lumbar area of the vertebral column, so a needle inserted lower than that will not damage the nervous tissue of the CNS.

Watch this animation that shows the flow of CSF through the brain and spinal cord, and how it originates from the ventricles and then spreads into the space within the meninges, where the fluids then move into the venous sinuses to return to the cardiovascular

circulation. What are the structures that produce CSF and where are they found? How are the structures indicated in this animation?

> Answer: The choroid plexuses of the ventricles make CSF. As shown, there is a little of the blue color appearing in each ventricle that is joined by the color flowing from the other ventricles.

## 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

Q. Which portion of the ventricular system is found within the diencephalon?

A. lateral ventricles

B. third ventricle

C. cerebral aqueduct

D. fourth ventricle

> Answer: B

Q. What condition causes a stroke?

A. inflammation of meninges

B. lumbar puncture

C. infection of cerebral spinal fluid

D. disruption of blood to the brain

> Answer: D

## 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

**anterior spinal artery**
blood vessel from the merged branches of the vertebral arteries that runs along the anterior surface of the spinal cord

**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 brain stem

**carotid canal**
opening in the temporal bone through which the internal carotid artery enters the cranium

**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

**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

**foramen magnum**

large opening in the occipital bone of the skull through which the spinal cord emerges and the vertebral arteries enter the cranium

**fourth ventricle**

the portion of the ventricular system that is in the region of the brain stem 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 in the region of the cerebrum

**lumbar puncture**

procedure used to withdraw CSF from the lower lumbar region of the vertebral column that avoids the risk of damaging CNS tissue because the spinal cord ends at the upper lumbar vertebrae

**median aperture**

singular opening from the fourth ventricle into the subarachnoid space at the midline between the medulla and cerebellum

**meninges**

protective outer coverings of the CNS composed of connective tissue

**occipital sinuses**

dural sinuses along the edge of the occipital lobes of the cerebrum

**orthostatic reflex**

sympathetic function that maintains blood pressure when standing to offset the increased effect of gravity

**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

**superior sagittal sinus**

dural sinus that runs along the top of the longitudinal fissure and drains blood from the majority of the outer cerebrum

**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

## Contributors and Attributions

**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

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# 12.4: The Peripheral Nervous System

**Learning Objectives**

- 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
- Describe the sensory and motor components of spinal nerves and the plexuses that they pass through

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.

## Ganglia

A ganglion is a group of neuron cell bodies in the periphery. 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 12.4.1). The cells of the dorsal root ganglion are unipolar cells, classifying them by shape. Also, the small round nuclei of satellite cells can be seen surrounding—as if they were orbiting—the neuron cell bodies.

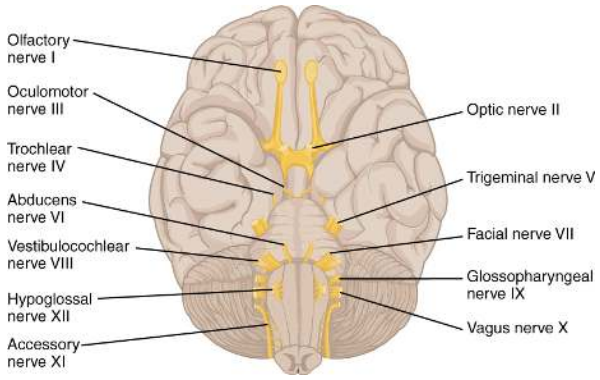



Figure 12.4.5: The Cranial Nerves. The anatomical arrangement of the roots of the cranial nerves observed from an inferior view of the brain. Three of the cranial nerves also contain autonomic fibers, and a fourth is almost purely a component of the autonomic system. The oculomotor, facial, and glossopharyngeal 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.

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Visit this site to read 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?

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 12.4.1). 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 spinal 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 **12.4.1**: Cranial Nerves


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| Mnemonic | # | Name | Function (S/M/B) | Central connection (nuclei) | Peripheral connection (ganglion or muscle) |
|---|---|---|---|---|---|
| On | I | Olfactory | Smell (S) | Olfactory bulb | Olfactory epithelium |
| Old | II | Optic | Vision (S) | Hypothalamus/thalamus/midbrain | Retina (retinal ganglion cells) |
| Olympus' | III | Oculomotor | Eye movements (M) | Oculomotor nucleus | Extraocular muscles (other 4), levator palpebrae superioris, ciliary ganglion (autonomic) |
| Towering | IV | Trochlear | Eye movements (M) | Trochlear nucleus | Superior oblique muscle |
| Tops | V | Trigeminal | Sensory/motor – face (B) | Trigeminal nuclei in the midbrain, pons, and medulla | Trigeminal |
| A | VI | Abducens | Eye movements (M) | Abducens nucleus | Lateral rectus muscle |
| Finn | VII | Facial | Motor – face, Taste (B) | Facial nucleus, solitary nucleus, superior salivatory nucleus | Facial muscles, Geniculate ganglion, Pterygopalatine ganglion (autonomic) |
| And | VIII | Auditory (Vestibulocochlear) | Hearing/balance (S) | Cochlear nucleus, Vestibular nucleus/cerebellum | Spiral ganglion (hearing), Vestibular ganglion (balance) |
| German | IX | Glossopharyngeal | Motor – throat Taste (B) | Solitary nucleus, inferior salivatory nucleus, nucleus ambiguus | Pharyngeal muscles, Geniculate ganglion, Otic ganglion (autonomic) |
| Viewed | X | Vagus | Motor/sensory – viscera (autonomic) (B) | Medulla | Terminal ganglia serving thoracic and upper abdominal organs (heart and small intestines) |
| Some | XI | Spinal Accessory | Motor – head and neck (M) | Spinal accessory nucleus | Neck muscles |
| Hops | XII | Hypoglossal | Motor – lower throat (M) | Hypoglossal nucleus | Muscles of the larynx and lower pharynx |

## 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. The dorsal root ganglion for each nerve is an enlargement of the spinal nerve.

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 enervate 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.

Of the four nerve plexuses, two are found at the cervical level, one at the lumbar level, and one at the sacral level (Figure **12.4.6**). 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 C4 through T1 reorganize through this plexus to give rise to the nerves of the arms, as the name brachial suggests. A large nerve from this plexus is the **radial nerve** from which the **axillary nerve** branches to go to the armpit region. The radial nerve continues through the arm and is paralleled by the **ulnar nerve** and the **median nerve**. The **lumbar plexus** arises from all the lumbar spinal nerves and gives rise to nerves enervating 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 **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 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.

These plexuses are described as arising from spinal nerves and giving rise to certain systemic nerves, but they contain fibers that serve sensory functions or fibers that serve motor functions. This means that some fibers extend from cutaneous or other peripheral sensory surfaces and send action potentials into the CNS. Those are axons of sensory neurons in the dorsal root ganglia that enter the spinal cord through the dorsal nerve root. Other fibers are the axons of motor neurons of the anterior horn of the spinal cord, which emerge in the ventral nerve root and send action potentials to cause skeletal muscles to contract in their target regions. For example, the radial nerve contains fibers of cutaneous sensation in the arm, as well as motor fibers that move muscles in the arm.

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.

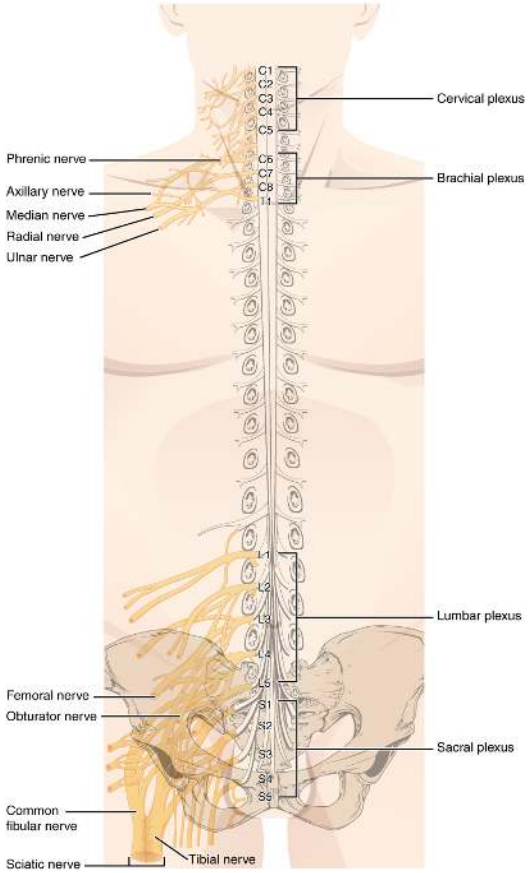



Figure **12.4.6**: Nerve Plexuses of the Body. There are four main nerve plexuses in the human body. The cervical plexus supplies nerves to the posterior head and neck, as well as to the diaphragm. The brachial plexus supplies nerves to the arm. The lumbar plexus supplies nerves to the anterior leg. The sacral plexus supplies nerves to the posterior leg.

AGING AND THE...

**Nervous System**

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.

## Chapter 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. Ganglia are of two types, sensory or autonomic. Sensory ganglia contain unipolar sensory neurons and are found on the

dorsal root of all spinal nerves as well as associated with many of the cranial nerves. Autonomic ganglia are in the sympathetic chain, the associated paravertebral or prevertebral ganglia, or in terminal ganglia near or within the organs controlled by the autonomic nervous system.

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. Sensory fibers are axons of sensory ganglia that carry sensory information into the brain and target sensory nuclei. Motor fibers are axons of motor neurons in motor nuclei of the brain stem and target skeletal muscles of the head and neck. 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.

## Interactive Link Questions

Figure If you zoom in on the DRG, you can see smaller satellite glial cells surrounding the large cell bodies of the sensory neurons. From what structure do satellite cells derive during embryologic development?

Answer: Figure They derive from the neural crest.

Figure To what structures in a skeletal muscle are the endoneurium, perineurium, and epineurium comparable?

Answer: Figure 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.

Visit this site to read 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: 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.

## 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. cranial nerve 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 functions in the head and neck?

A. olfactory

B. trochlear

C. glossopharyngeal

D. vagus

Answer: D

Q. Which of these structures is not under direct control of the peripheral nervous system?

A. trigeminal ganglion

B. gastric plexus

C. sympathetic chain ganglia

D. cervical plexus

Answer: B

## 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

**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

**cervical plexus**
nerve plexus associated with the upper cervical spinal nerves

**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

**dorsal (posterior) root ganglion**
sensory ganglion attached to the posterior nerve root of a spinal nerve

**endoneurium**
innermost layer of connective tissue that surrounds individual axons within a nerve

**enteric nervous system**
peripheral structures, namely ganglia and nerves, that are incorporated into the digestive system organs

**enteric plexus**
neuronal plexus in the wall of the intestines, which is part of the enteric nervous system

**epineurium**
outermost layer of connective tissue that surrounds an entire nerve

**esophageal plexus**
neuronal plexus in the wall of the esophagus that is part of the enteric nervous system

**extraocular muscles**
six skeletal muscles that control eye movement within the orbit

**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

**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

**gastric plexuses**
neuronal networks in the wall of the stomach that are part of the enteric nervous system

**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

**intercostal nerve**

systemic nerve in the thoracic cavity that is found between two ribs

**lumbar plexus**

nerve plexus associated with the lumbar spinal nerves

**median nerve**

systemic nerve of the arm, located between the ulnar and radial nerves

**nerve plexus**

network of nerves without neuronal cell bodies included

**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

**paravertebral ganglia**

autonomic ganglia superior to the sympathetic chain ganglia

**perineurium**

layer of connective tissue surrounding fascicles within a nerve

**phrenic nerve**

systemic nerve from the cervical plexus that enervates the diaphragm

**plexus**

network of nerves or nervous tissue

**prevertebral ganglia**

autonomic ganglia that are anterior to the vertebral column and functionally related to the sympathetic chain ganglia

**radial nerve**

systemic nerve of the arm, the distal component of which is located near the radial bone

**sacral plexus**

nerve plexus associated with the lower lumbar and sacral spinal nerves

**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 accessory nerve**
eleventh cranial nerve; responsible for contraction of neck muscles

**spinal nerve**
one of 31 nerves connected to the spinal cord

**sympathetic chain ganglia**
autonomic ganglia in a chain along the anterolateral aspect of the vertebral column that are responsible for contributing to homeostatic mechanisms of the autonomic nervous system

**systemic nerve**
nerve in the periphery distal to a nerve plexus or spinal nerve

**terminal ganglion**
autonomic ganglia that are near or within the walls of organs that are responsible for contributing to homeostatic mechanisms of the autonomic nervous system

**tibial nerve**
systemic nerve of the posterior leg that begins as part of the sciatic 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

**ulnar nerve**
systemic nerve of the arm located close to the ulna, a bone of the forearm

**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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# CHAPTER OVERVIEW

## 13: The Somatic Nervous System

The somatic nervous system is the part of the peripheral nervous system and is associated with skeletal muscle voluntary control of body movements. The somatic nervous system is traditionally considered a division within the peripheral nervous system. However, this misses an important point: somatic refers to a functional division, whereas peripheral refers to an anatomic division. The somatic nervous system is responsible for our conscious perception of the environment and for our voluntary responses to that perception by means of skeletal muscles. Peripheral sensory neurons receive input from environmental stimuli, but the neurons that produce motor responses originate in the central nervous system.

13.1: Prelude to The Somatic Nervous System
13.2: Sensory Perception

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# 13.1: Prelude to The Somatic Nervous System

When high temperature is sensed in the skin, a reflexive 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.

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# 13.2: Sensory Perception

**Learning Objectives**

- Describe different types of sensory receptors
- Describe the structures responsible for the special senses of taste, smell, hearing, balance, and vision
- Distinguish how different tastes are transduced
- Describe the means of mechanoreception for hearing and balance
- List the supporting structures around the eye and describe the structure of the eyeball
- Describe the processes of phototransduction

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 potential 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. A transmembrane protein receptor is a protein in the cell membrane that mediates a physiological change in a neuron, most often through the opening of ion channels or changes in the cell signaling processes. Transmembrane receptors are activated by chemicals called ligands. For example, a molecule in food can serve as a ligand for taste receptors. Other transmembrane proteins, which are not accurately called receptors, are sensitive to mechanical or thermal changes. Physical changes in these proteins increase ion flow across the membrane, and can generate an action potential or a graded potential in the sensory neurons.

## 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 potential.

### Structural Receptor Types

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 encapsulated 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**.

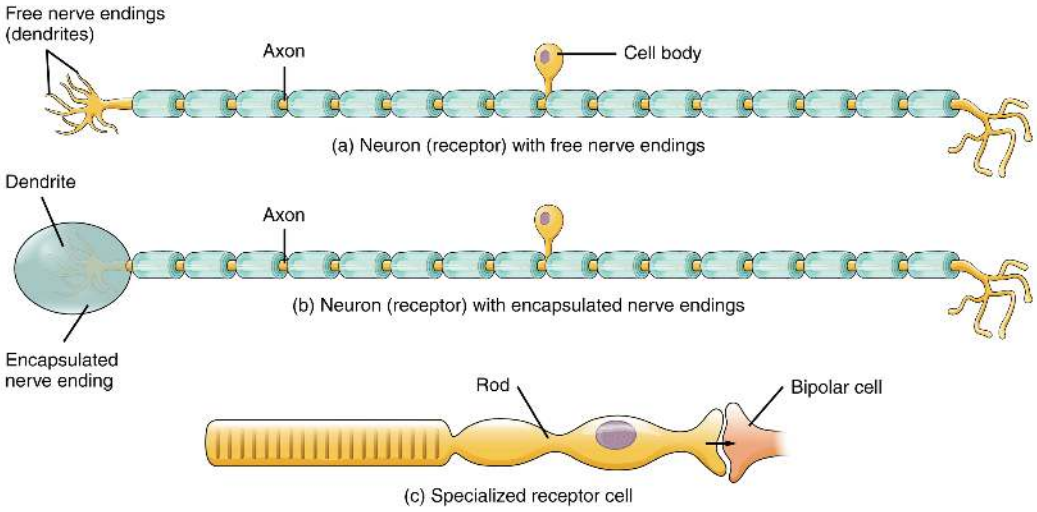


***Figure 13.2.1: Receptor Classification by Cell Type.*** *Receptor cell types can be classified on the basis of their structure. Sensory neurons can have either (a) free nerve endings or (b) encapsulated endings. Photoreceptors in the eyes, such as rod cells, are examples of (c) specialized receptor cells. These cells release neurotransmitters onto a bipolar cell, which then synapses with the optic nerve neurons.*

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 membrane potential 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. Some stimuli are physical variations in the environment that affect receptor cell membrane potentials. 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.

Within the realm of physiology, senses can be classified as either general or specific. 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** (body movement) and **kinesthesia** (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.

### 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. Within the structure of the papillae are **taste buds** that contain specialized **gustatory receptor cells** for the transduction of taste stimuli. These receptor cells are sensitive to the chemicals contained within foods that are ingested, and they release neurotransmitters based on the amount of the chemical in the food. Neurotransmitters from the gustatory cells can activate sensory neurons in the facial, glossopharyngeal, and vagus cranial nerves.

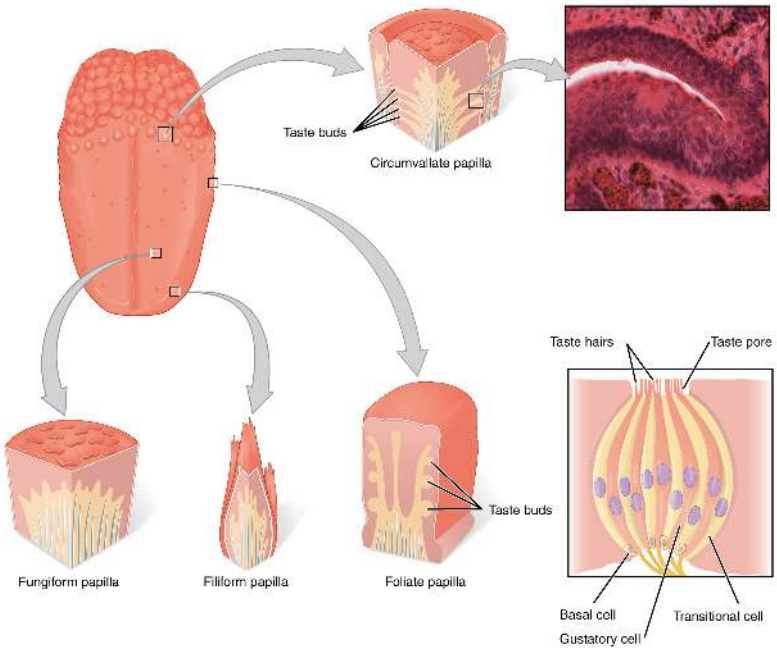



Figure **13.2.2**: The Tongue. The tongue is covered with small bumps, called papillae, which contain taste buds that are sensitive to chemicals in ingested food or drink. Different types of papillae are found in different regions of the tongue. The taste buds contain specialized gustatory receptor cells that respond to chemical stimuli dissolved in the saliva. These receptor cells activate sensory neurons that are part of the facial and glossopharyngeal nerves. LM × 1600. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Salty taste is simply the perception of sodium ions ($Na^+$) in the saliva. When you eat something salty, the salt crystals dissociate into the component ions $Na^+$ and $Cl^–$, which dissolve into the saliva in your mouth. The $Na^+$ concentration becomes high outside the gustatory cells, creating a strong concentration gradient that drives the diffusion of the ion into the cells. The entry of $Na^+$ into these cells results in the depolarization of the cell membrane and the generation of a receptor potential.

Sour taste is the perception of $H^+$ concentration. Just as with sodium ions in salty flavors, these hydrogen ions enter the cell and trigger depolarization. Sour flavors are, essentially, the perception of acids in our food. Increasing hydrogen ion concentrations in the saliva (lowering saliva pH) triggers progressively stronger graded potentials in the gustatory cells. For example, orange juice—which contains citric acid—will taste sour because it has a pH value of approximately 3. Of course, it is often sweetened so that the sour taste is masked.

The first two tastes (salty and sour) are triggered by the cations $Na^+$ and $H^+$. The other tastes result from food molecules binding to a G protein–coupled receptor. A G protein signal transduction system ultimately leads to depolarization of the gustatory cell. The sweet taste is the sensitivity of gustatory cells to the presence of glucose dissolved in the saliva. Other monosaccharides such as fructose, or artificial sweeteners such as aspartame (NutraSweet™), saccharine, or sucralose (Splenda™) also activate the sweet receptors. The affinity for each of these molecules varies, and some will taste sweeter than glucose because they bind to the G protein–coupled receptor differently.

Bitter taste is similar to sweet in that food molecules bind to G protein–coupled receptors. However, there are a number of different ways in which this can happen because there are a large diversity of bitter-tasting molecules. Some bitter molecules depolarize gustatory cells, whereas others hyperpolarize gustatory cells. Likewise, some bitter molecules increase G protein activation within the gustatory cells, whereas other bitter molecules decrease G protein activation. The specific response depends on which molecule is binding to the receptor.

One major group of bitter-tasting molecules are alkaloids. **Alkaloids** are nitrogen-containing molecules that often have a basic pH. Alkaloids are commonly found in bitter-tasting plant products, such as coffee, hops (in beer), tannins (in wine), tea, and aspirin. By containing toxic alkaloids, the plant is less susceptible to microbe infection and less attractive to herbivores.

Therefore, the function of bitter taste may primarily be related to stimulating the gag reflex to avoid ingesting poisons. Because of this, many bitter foods that are normally ingested are often combined with a sweet component to make them more palatable (cream and sugar in coffee, for example). The highest concentration of bitter receptors appear to be in the posterior tongue, where a gag reflex could still spit out poisonous food.

The taste known as umami is often referred to as the savory taste. Like sweet and bitter, it is based on the activation of G protein–coupled receptors by a specific molecule. The molecule that activates this receptor is the amino acid L-glutamate. Therefore, the umami flavor is often perceived while eating protein-rich foods. Not surprisingly, dishes that contain meat are often described as savory.

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 and glossopharyngeal cranial nerves, as well as a component within the vagus nerve 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.

*Watch this video to learn about Dr. Danielle Reed of the Monell Chemical Senses Center in Philadelphia, Pennsylvania, who became interested in science at an early age because of her sensory experiences. She recognized that her sense of taste was unique compared with other people she knew. Now, she studies the genetic differences between people and their sensitivities to taste stimuli. In the video, there is a brief image of a person sticking out their tongue, which has been covered with a colored dye. This is how Dr. Reed is able to visualize and count papillae on the surface of the tongue. People fall into two groups known as "tasters" and "non-tasters" based on the density of papillae on their tongue, which also indicates the number of taste buds. Non-tasters can taste food, but they are not as sensitive to certain tastes, such as bitterness. Dr. Reed discovered that she is a non-taster, which explains why she perceived bitterness differently than other people she knew. Are you very sensitive to tastes? Can you see any similarities among the members of your family?*



## Olfaction (Smell)

Like taste, the sense of smell, or **olfaction**, is also responsive to chemical stimuli. The olfactory receptor neurons 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 contains bipolar sensory neurons. Each **olfactory sensory neuron** has dendrites that extend from the apical surface of the epithelium into the mucus lining the cavity. 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. These receptors are G protein–coupled, and will produce a graded membrane potential in the olfactory neurons.

The axon of an olfactory neuron extends from the basal surface of the epithelium, through an olfactory foramen in the cribriform plate of the ethmoid bone, and into the brain. The group of axons called the olfactory tract connect to the **olfactory bulb** on the ventral surface of the frontal lobe. 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 nasal epithelium, including the olfactory cells, can be harmed by airborne toxic chemicals. Therefore, the 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.

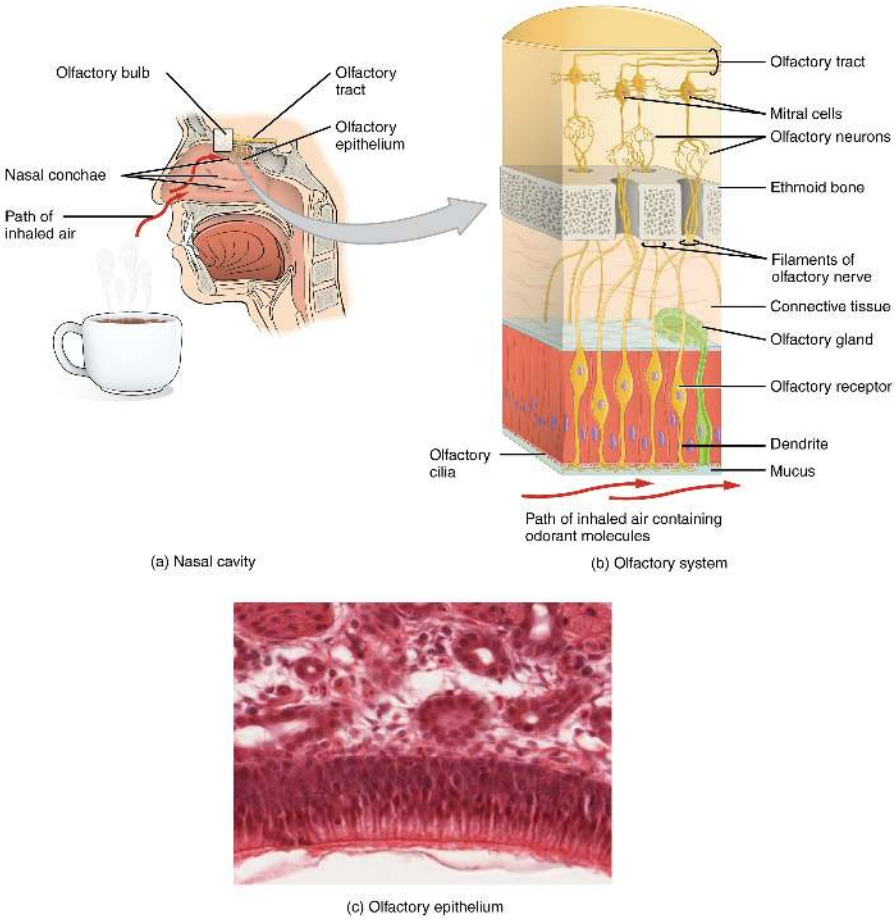



***Figure 13.2.3: The Olfactory System.*** *(a) The olfactory system begins in the peripheral structures of the nasal cavity. (b) The olfactory receptor neurons are within the olfactory epithelium. (c) Axons of the olfactory receptor neurons project through the cribriform plate of the ethmoid bone and synapse with the neurons of the olfactory bulb (tissue source: simian). LM × 812. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)*

### 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.

## 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 13.2.4). 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. 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 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.

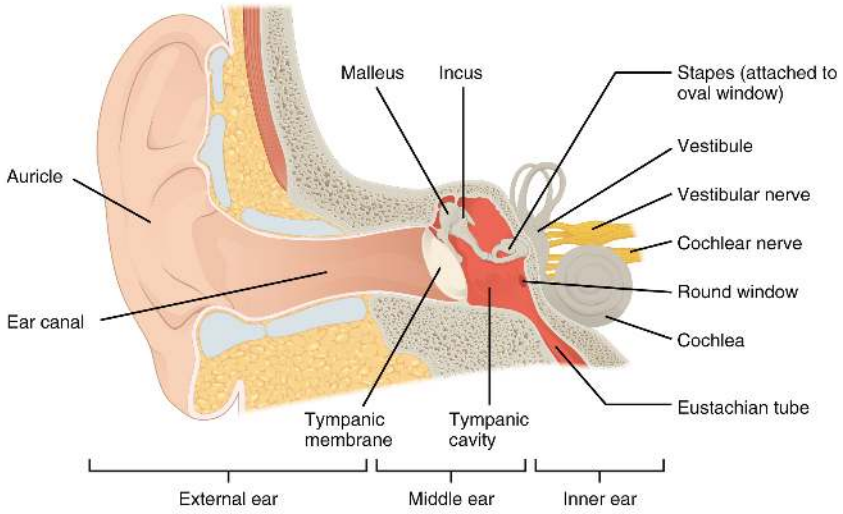



***Figure* 13.2.4*: Structures of the Ear.*** *The external ear contains the auricle, ear canal, and tympanic membrane. The middle ear contains the ossicles and is connected to the pharynx by the Eustachian tube. The inner ear contains the cochlea and vestibule, which are responsible for audition and equilibrium, respectively.*

The inner ear is often described as a bony labyrinth, as it is composed of a series of canals embedded within the temporal bone. It has two separate regions, the **cochlea** and the **vestibule**, which are responsible for hearing and balance, respectively. The neural signals from these two regions are relayed to the brain stem through separate fiber bundles. However, these two distinct bundles travel together from the inner ear to the brain stem as the vestibulocochlear nerve. 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. 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 (Figure **13.2.5**). The membrane covering the round window will bulge out or pucker in with the movement of the fluid within the scala tympani.

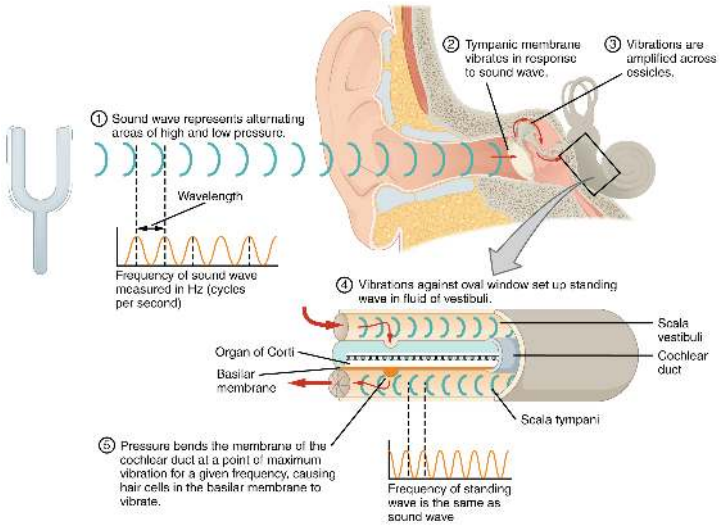



Figure **13.2.5**: Transmission of Sound Waves to Cochlea. A sound wave causes the tympanic membrane to vibrate. This vibration is amplified as it moves across the malleus, incus, and stapes. The amplified vibration is picked up by the oval window causing pressure waves in the fluid of the scala vestibuli and scala tympani. The complexity of the pressure waves is determined by the changes in amplitude and frequency of the sound waves entering the ear.

A cross-sectional view of the cochlea shows that the scala vestibuli and scala tympani run along both sides of the cochlear duct (Figure **13.2.6**). 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. As the fluid waves move through the scala vestibuli and scala tympani, the basilar membrane moves at a specific spot, 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.

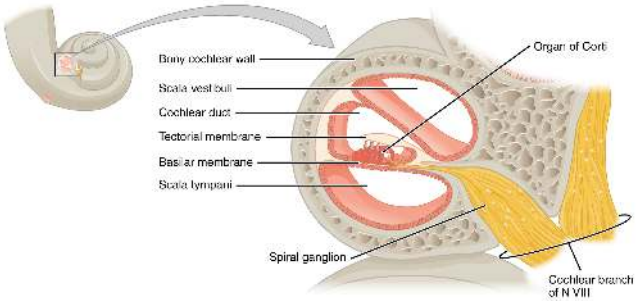



Figure **13.2.6**: Cross Section of the Cochlea. The three major spaces within the cochlea are highlighted. The scala tympani and scala vestibuli lie on either side of the cochlear duct. The organ of Corti, containing the mechanoreceptor hair cells, is adjacent to the scala tympani, where it sits atop the basilar membrane.

The organs of Corti contain **hair cells**, which are named for the hair-like **stereocilia** extending from the cell's apical surfaces (Figure **13.2.7**). 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. 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. 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 depolarize 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. When no sound is present, and the stereocilia are standing straight, a small amount of tension still exists on the tethers, keeping the membrane potential of the hair cell slightly depolarized.

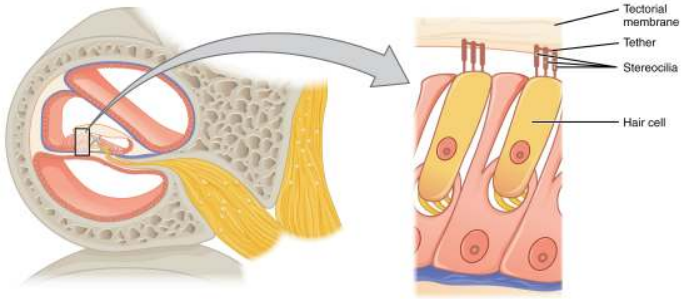



Figure 13.2.7: Hair Cell. The hair cell is a mechanoreceptor with an array of stereocilia emerging from its apical surface. The stereocilia are tethered together by proteins that open ion channels when the array is bent toward the tallest member of their array, and closed when the array is bent toward the shortest member of their array.

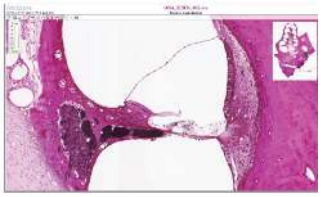


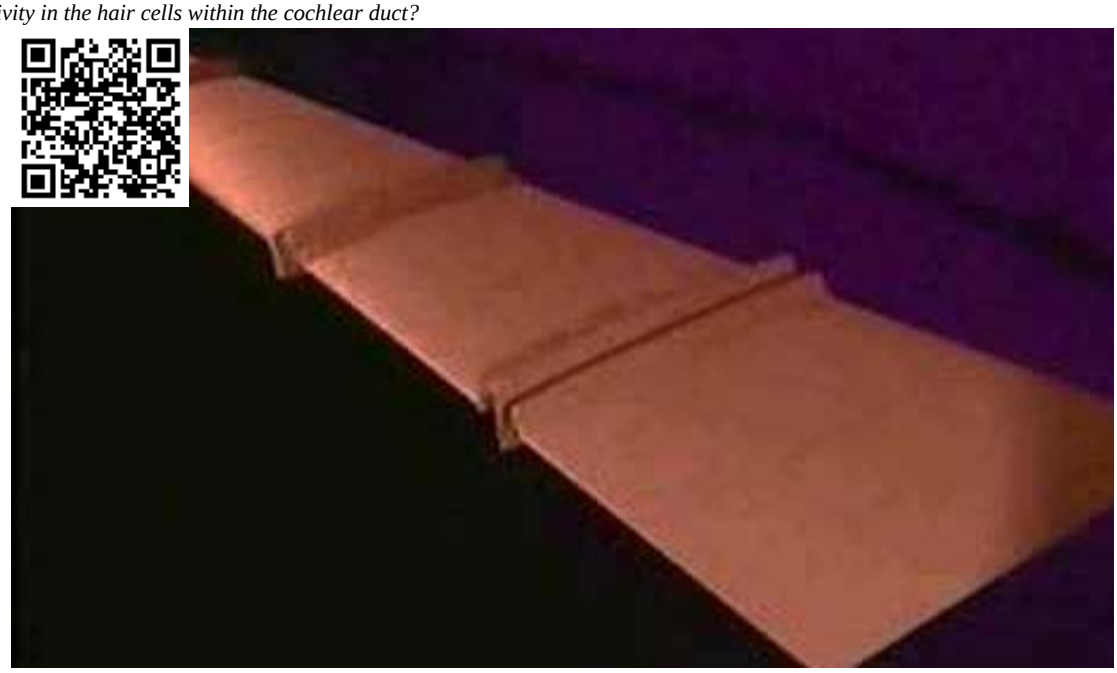
Figure 13.2.8: Cochlea and Organ of Corti. LM × 412. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

*View the University of Michigan WebScope at virtualslides.med.umich.edu/H....svs/view.apml 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?*

*Watch this video to learn more about how the structures of the ear convert sound waves into a neural signal by moving the "hairs," or stereocilia, of the cochlear duct. Specific locations along the length of the duct encode specific frequencies, or pitches. The brain interprets the meaning of the sounds we hear as music, speech, noise, etc. Which ear structures are responsible for the amplification and transfer of sound from the external ear to the inner ear?*



*Watch this animation to learn more about the inner ear and to see the cochlea unroll, with the base at the back of the image and the apex at the front. Specific wavelengths of sound cause specific regions of the basilar membrane to vibrate, much like the keys of a piano produce sound at different frequencies. Based on the animation, where do frequencies—from high to low pitches—cause activity in the hair cells within the cochlear duct?*



## 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 within the vestibule of the inner ear. Head position is sensed by the **utricle** and **saccule**, whereas head movement is sensed by the **semicircular canals**. The neural signals generated in the **vestibular ganglion** are transmitted through the vestibulocochlear nerve to the brain stem and cerebellum.

The utricle and saccule are both largely composed of **macula** tissue (plural = maculae). The macula is composed of hair cells surrounded by support cells. The stereocilia of the hair cells extend into a viscous gel called the **otolithic membrane** (Figure 13.2.10). 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 some hair cells to depolarize as others hyperpolarize. The exact position of the head is interpreted by the brain based on the pattern of hair-cell depolarization.

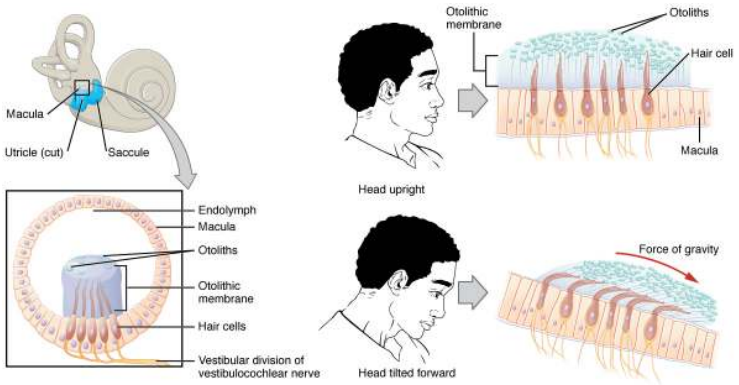



Figure 13.2.10: Linear Acceleration Coding by Maculae. The maculae are specialized for sensing linear acceleration, such as when gravity acts on the tilting head, or if the head starts moving in a straight line. The difference in inertia between the hair cell stereocilia and the otolithic membrane in which they are embedded leads to a shearing force that causes the stereocilia to bend in the direction of that linear acceleration.

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 13.2.11). 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 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.

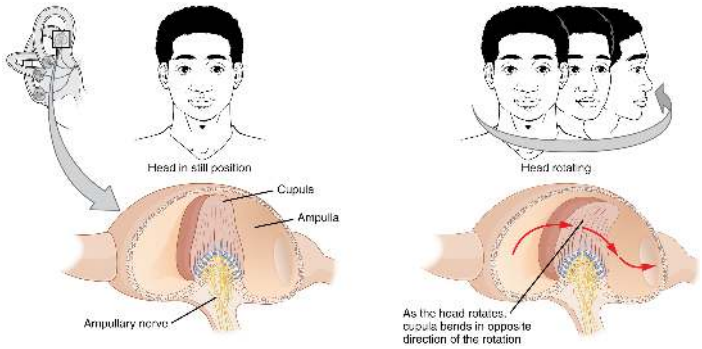



Figure 13.2.11: Rotational Coding by Semicircular Canals. Rotational movement of the head is encoded by the hair cells in the base of the semicircular canals. As one of the canals moves in an arc with the head, the internal fluid moves in the opposite direction, causing the cupula and stereocilia to 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.

## 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. The bony orbits surround the eyeballs, protecting them and anchoring the soft tissues of the eye (Figure 13.2.12). 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. The inner surface of each lid is a thin membrane known as the **palpebral conjunctiva**. The conjunctiva extends over the white areas of the eye (the sclera), connecting the eyelids to the eyeball. Tears are produced by the **lacrimal gland**, located beneath the lateral edges of the nose. Tears produced by this gland flow through the **lacrimal duct** to the medial corner of the eye, where the tears flow over the conjunctiva, washing away foreign particles.

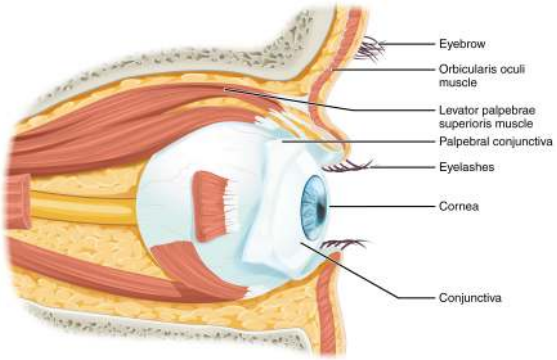



Figure 13.2.12: The Eye in the Orbit. The eye is located within the orbit and surrounded by soft tissues that protect and support its function. The orbit is surrounded by cranial bones of the skull.

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 13.2.13). Four of the muscles are arranged at the cardinal points around the eye and are named for those locations. They are the **superior rectus**, **medial rectus**, **inferior rectus**, and **lateral rectus**. 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 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 rotates the eye medially. The **inferior oblique** muscle originates from the floor of the orbit and inserts into the inferolateral surface of the eye. When it contracts, it laterally rotates the eye, in opposition to the superior oblique. 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 **13.2.12**).

The extraocular muscles are innervated by three cranial nerves. The lateral rectus, which causes abduction of the eye, is innervated by the abducens nerve. The superior oblique is innervated by the trochlear nerve. All of the other muscles are innervated by the oculomotor nerve, as is the levator palpebrae superioris. The motor nuclei of these cranial nerves connect to the brain stem, which coordinates eye movements.

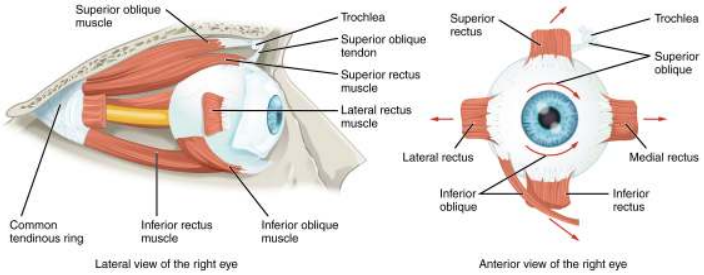



Figure **13.2.13**: Extraocular Muscles. The extraocular muscles move the eye within the orbit.

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** and clear **cornea**. 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 **13.2.14**). 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 **zonule fibers**. These two structures bend 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 iris is a smooth muscle that opens or closes the **pupil**, which is the hole at the center of the eye that allows light to enter. The iris constricts the pupil in response to bright light and dilates the pupil in response to dim light. The innermost layer of the eye is the **neural tunic**, or **retina**, which contains the nervous tissue responsible for photoreception.

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 is 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**.

The retina is composed of several layers and contains specialized cells for the initial processing of visual stimuli. The photoreceptors (rods and cones) change their membrane potential when stimulated by light energy. The change in membrane potential alters the amount of neurotransmitter that the photoreceptor cells release onto **bipolar cells** in the **outer synaptic layer**. It is the bipolar cell in the retina that connects a photoreceptor to a **retinal ganglion cell (RGC)** in the **inner synaptic layer**. There, **amacrine 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** (see Figure **13.2.14**). 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.

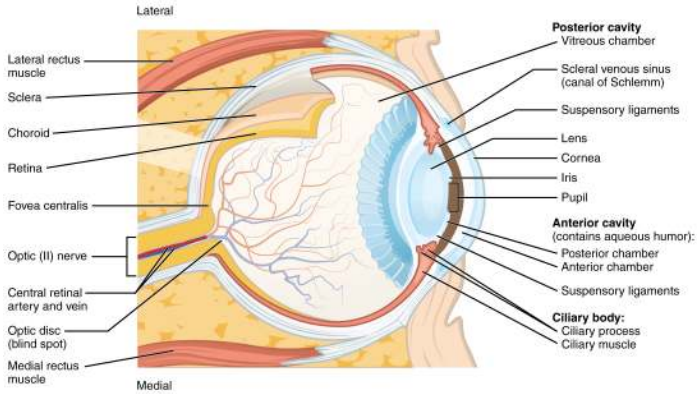



Figure **13.2.14**: Structure of the Eye. The sphere of the eye can be divided into anterior and posterior chambers. The wall of the eye is composed of three layers: the fibrous tunic, vascular tunic, and neural tunic. Within the neural tunic is the retina, with three layers of cells and two synaptic layers in between. The center of the retina has a small indentation known as the fovea.

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

area known as the **fovea**. At the fovea, the retina lacks the supporting cells and blood vessels, and only contains photoreceptors. Therefore, **visual acuity**, or the sharpness of vision, is greatest at the fovea. This is because the fovea is where the least amount of incoming light is absorbed by other retinal structures (see Figure **13.2.14**). 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.

Light falling on the retina causes chemical changes to pigment molecules in the photoreceptors, ultimately leading to a change in the activity of the RGCs. Photoreceptor cells have two parts, the **inner segment** and the **outer segment** (Figure **13.2.15**). The inner segment contains the nucleus and other common organelles of a cell, whereas the outer segment is a specialized region in which photoreception takes place. There are two types of photoreceptors—rods and cones—which differ in the shape of their outer segment. The rod-shaped outer segments of the **rod photoreceptor** contain a stack of membrane-bound discs that contain the photosensitive pigment **rhodopsin**. The cone-shaped outer segments of the **cone photoreceptor** contain their photosensitive pigments in infoldings of the cell membrane. There are three cone photopigments, called **opsins**, which are each sensitive to a particular wavelength of light. The wavelength of visible light determines its color. The pigments in human eyes are specialized in perceiving three different primary colors: red, green, and blue.

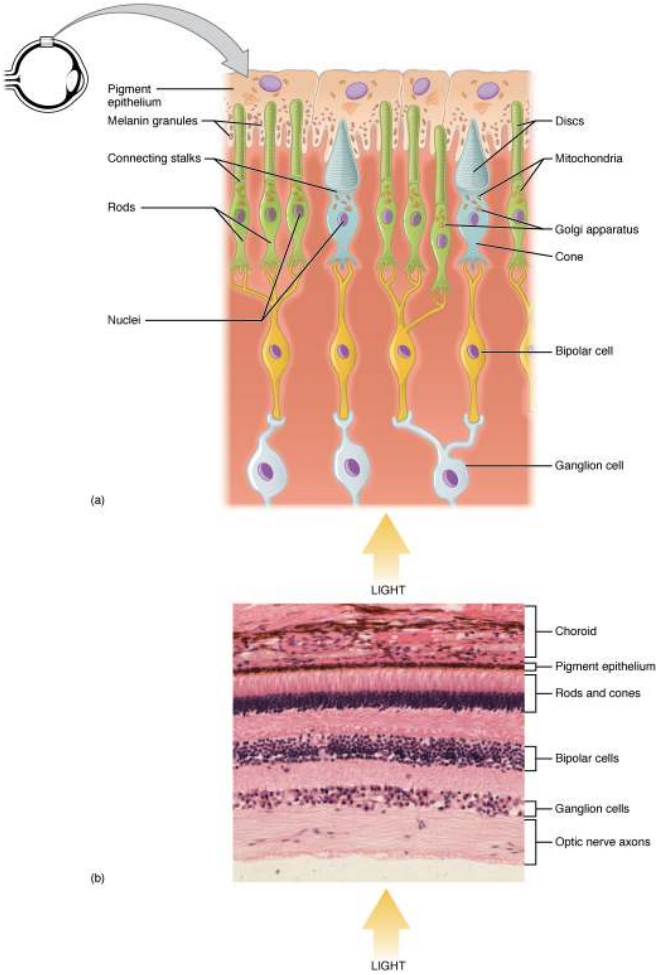
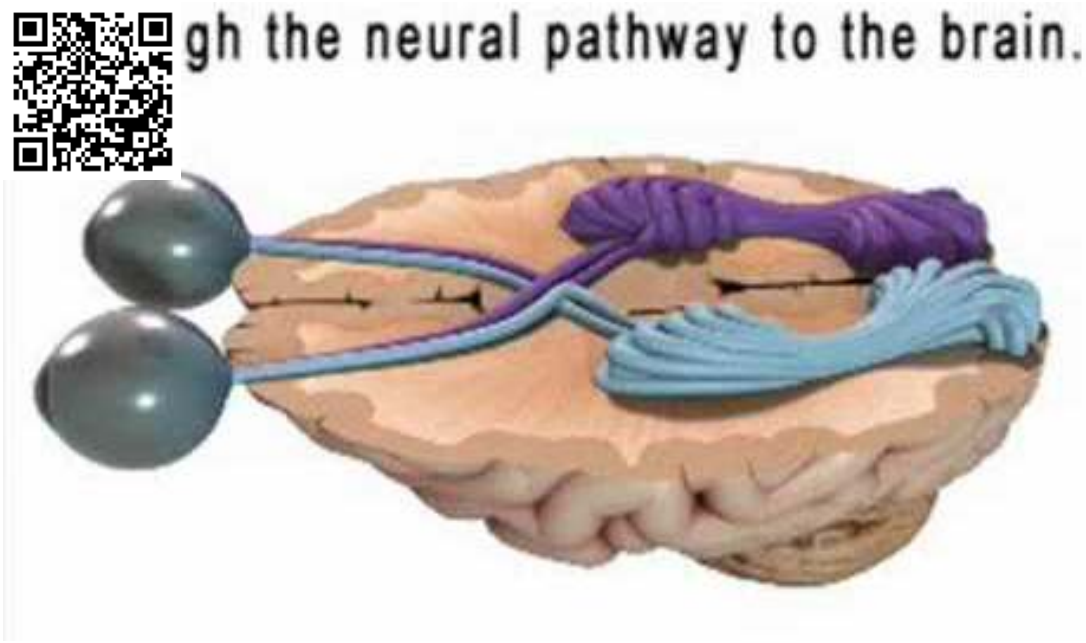



Figure **13.2.15**: Photoreceptor. (a) All photoreceptors have inner segments containing the nucleus and other important organelles and outer segments with membrane arrays containing the photosensitive opsin molecules. Rod outer segments are long columnar shapes with stacks of membrane-bound discs that contain the rhodopsin pigment. Cone outer segments are short, tapered shapes with folds of membrane in place of the discs in the rods. (b) Tissue of the retina shows a dense layer of nuclei of the rods and cones. LM × 800. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

*Watch this video to learn more about a transverse section through the brain that depicts the visual pathway from the eye to the occipital cortex. The first half of the pathway is the projection from the RGCs through the optic nerve to the lateral geniculate nucleus in the thalamus on either side. This first fiber in the pathway synapses on a thalamic cell that then projects to the visual cortex in the occipital lobe where "seeing," or visual perception, takes place. This video gives an abbreviated overview of the visual system by concentrating on the pathway from the eyes to the occipital lobe. The video makes the statement (at 0:45) that "specialized cells in the retina called ganglion cells convert the light rays into electrical signals." What aspect of retinal processing is simplified by that statement? Explain your answer.*




## Chapter Review

The senses are olfaction (smell), gustation (taste), somatosensation (sensations associated with the skin and body), 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. Somatosensation belongs to the general senses, which are those sensory structures that are distributed throughout the body and in the walls of various organs. 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. 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 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 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.

## Interactive Link Questions

Watch this video to learn about Dr. Danielle Reed of the Monell Chemical Senses Center in Philadelphia, PA, who became interested in science at an early age because of her sensory experiences. She recognized that her sense of taste was unique compared with other people she knew. Now, she studies the genetic differences between people and their sensitivities to taste stimuli. In the video, there is a brief image of a person sticking out their tongue, which has been covered with a colored dye. This is how Dr. Reed is able to visualize and count papillae on the surface of the tongue. People fall into two large groups known as “tasters” and “non-tasters” on the basis of the density of papillae on their tongue, which also indicates the number of taste buds. Non-tasters can taste food, but they are not as sensitive to certain tastes, such as bitterness. Dr. Reed discovered that she is a non-taster, which explains why she perceived bitterness differently than other people she knew. Are you very sensitive to tastes? Can you see any similarities among the members of your family?



Answer: Answers will vary, but a typical answer might be: I can eat most anything (except mushrooms!), so I don’t think that I’m that sensitive to tastes. My whole family likes eating a variety of foods, so it seems that we all have the same level of sensitivity.

Figure **13.2.8** 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?

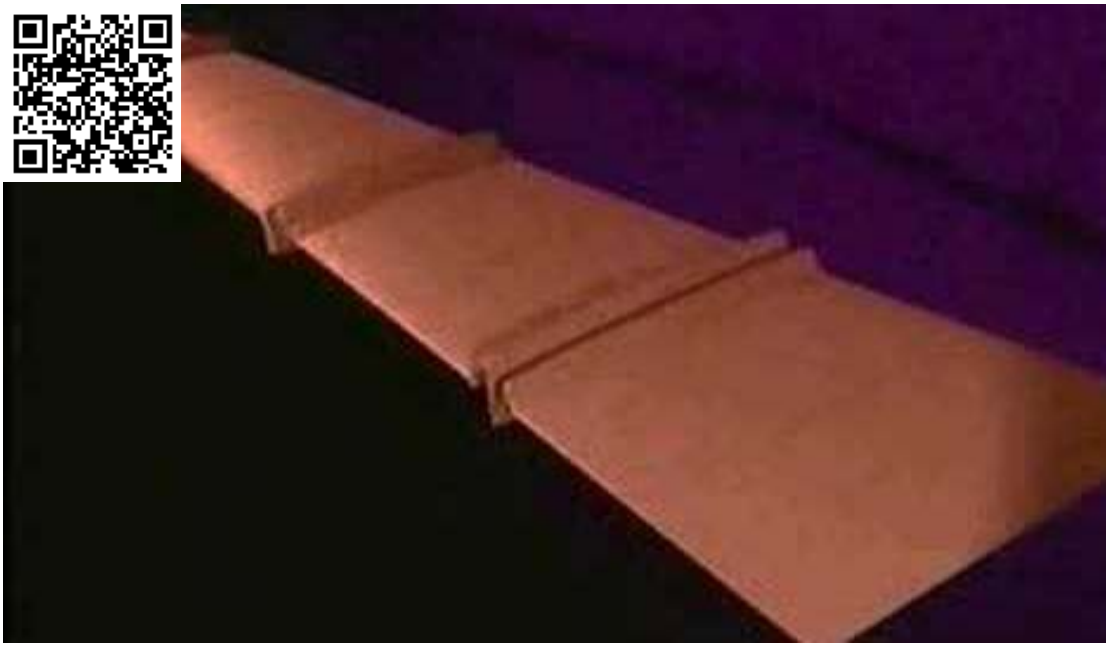
Answer: Figure **13.2.8** The hair cells are located in the organ of Corti, which is located on the basilar membrane. The stereocilia of those cells would normally be attached to the tectorial membrane (though they are detached in the micrograph because of processing of the tissue).

Watch this video to learn more about how the structures of the ear convert sound waves into a neural signal by moving the “hairs,” or stereocilia, of the cochlear duct. Specific locations along the length of the duct encode specific frequencies, or pitches. The brain interprets the meaning of the sounds we hear as music, speech, noise, etc. Which ear structures are responsible for the amplification and transfer of sound from the external ear to the inner ear?



Answer: The small bones in the middle ear, the ossicles, amplify and transfer sound between the tympanic membrane of the external ear and the oval window of the inner ear.

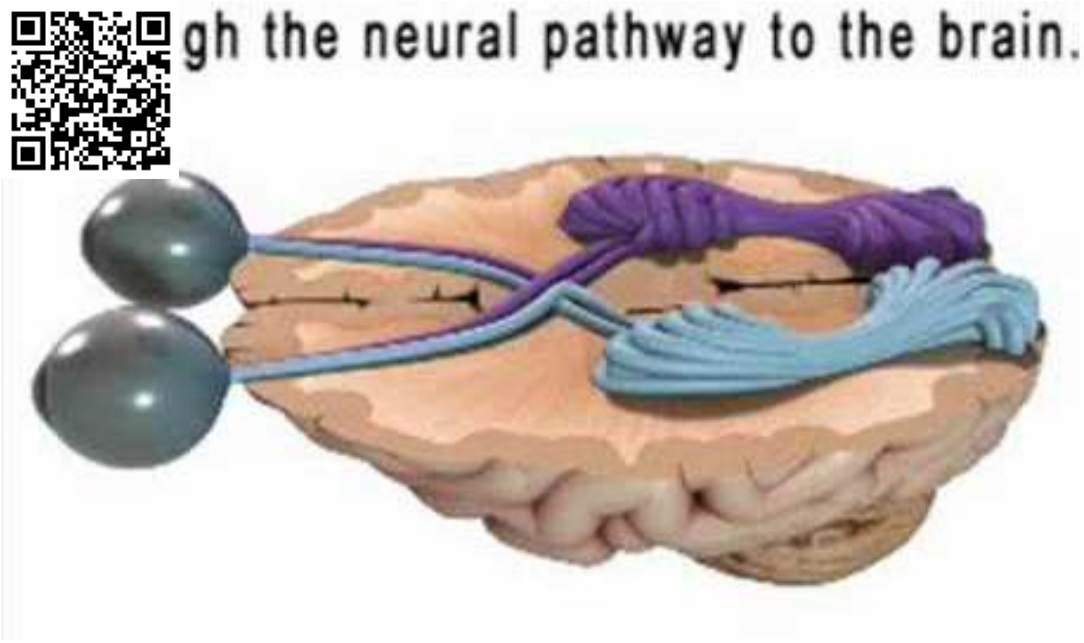
Watch this animation to learn more about the inner ear and to see the cochlea unroll, with the base at the back of the image and the apex at the front. Specific wavelengths of sound cause specific regions of the basilar membrane to vibrate, much like the keys of a piano produce sound at different frequencies. Based on the animation, where do frequencies—from high to low pitches—cause activity in the hair cells within the cochlear duct?



Answer: High frequencies activate hair cells toward the base of the cochlea, and low frequencies activate hair cells toward the apex of the cochlea.

Watch this video to learn more about a transverse section through the brain that depicts the visual pathway from the eye to the occipital cortex. The first half of the pathway is the projection from the RGCs through the optic nerve to the lateral geniculate nucleus in the thalamus on either side. This first fiber in the pathway synapses on a thalamic cell that then projects to the visual cortex in the occipital lobe where “seeing,” or visual perception, takes place. This video gives an abbreviated overview of the visual system by concentrating on the pathway from the eyes to the occipital lobe. The

video makes the statement (at 0:45) that “specialized cells in the retina called ganglion cells convert the light rays into electrical signals.” What aspect of retinal processing is simplified by that statement? Explain your answer.




Answer: Photoreceptors convert light energy, or photons, into an electrochemical signal. The retina contains bipolar cells and the RGCs that finally convert it into action potentials that are sent from the retina to the CNS. It is important to recognize when popular media and online sources oversimplify complex physiological processes so that misunderstandings are not generated. This video was created by a medical device manufacturer who might be trying to highlight other aspects of the visual system than retinal processing. The statement they make is not incorrect, it just bundles together several steps, which makes it sound like RGCs are the transducers, rather than photoreceptors.

## 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

Q. Which submodality of taste is sensitive to the pH of saliva?

A. umami

B. sour

C. bitter

D. sweet

Answer: B

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

## Critical Thinking Questions

Q. The sweetener known as stevia can replace glucose in food. What does the molecular similarity of stevia to glucose mean for the gustatory sense?

A. The stevia molecule is similar to glucose such that it will bind to the glucose receptor in sweet-sensitive taste buds. However, it is not a substrate for the ATP-generating metabolism within cells.

Q. Why does the blind spot from the optic disc in either eye not result in a blind spot in the visual field?

A. The visual field for each eye is projected onto the retina as light is focused by the lens. The visual information from the right visual field falls on the left side of the retina and vice versa. The optic disc in the right eye is on the medial side of the fovea, which would be the left side of the retina. However, the optic disc in the left eye would be on the right side of that fovea, so the right visual field falls on the side of the retina in the left field where there is no blind spot.

## Glossary

**alkaloid**
substance, usually from a plant source, that is chemically basic with respect to pH and will stimulate bitter receptors

**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

**anosmia**
loss of the sense of smell; usually the result of physical disruption of the first cranial nerve

**aqueous humor**
watery fluid that fills the anterior chamber containing the cornea, iris, ciliary body, and lens of the eye

**audition**
sense of hearing

**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

**capsaicin**
molecule that activates nociceptors by interacting with a temperature-sensitive ion channel and is the basis for “hot” sensations in spicy food

**chemoreceptor**
sensory receptor cell that is sensitive to chemical stimuli, such as in taste, smell, or pain

**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

**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

**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

**contralateral**
word meaning “on the opposite side,” as in axons that cross the midline in a fiber tract

**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

**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

**equilibrium**
sense of balance that includes sensations of position and movement of the head

**external ear**
structures on the lateral surface of the head, including the auricle and the ear canal back to the tympanic membrane

**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

**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

**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

**gustation**
sense of taste

**gustatory receptor cells**
sensory cells in the taste bud that transduce the chemical stimuli of gustation

**hair cells**
mechanoreceptor cells found in the inner ear that transduce stimuli for the senses of hearing and balance

**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

**inner segment**
in the eye, the section of a photoreceptor that contains the nucleus and other major organelles for normal cellular functions

**inner synaptic layer**
layer in the retina where bipolar cells connect to RGCs

**interoceptor**
sensory receptor that is positioned to interpret stimuli from internal organs, such as stretch receptors in the wall of blood vessels

**ipsilateral**
word meaning on the same side, as in axons that do not cross the midline in a fiber tract

**iris**
colored portion of the anterior eye that surrounds the pupil

**kinesthesia**
sense of body movement based on sensations in skeletal muscles, tendons, joints, and the skin

**lacrimal duct**
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

**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

**malleus**
(also, hammer) ossicle that is directly attached to the tympanic membrane

**mechanoreceptor**
receptor cell that transduces mechanical stimuli into an electrochemical signal

**medial rectus**
extraocular muscle responsible for adduction of the eye

**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

**neural tunic**
layer of the eye that contains nervous tissue, namely the retina

**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 epithelium**
region of the nasal epithelium where olfactory neurons are located

**olfactory sensory neuron**
receptor cell of the olfactory system, sensitive to the chemical stimuli of smell, the axons of which compose the first cranial nerve

**opsin**
protein that contains the photosensitive cofactor retinal for phototransduction

**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

**osmoreceptor**
receptor cell that senses differences in the concentrations of bodily fluids on the basis of osmotic pressure

**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

**outer segment**
in the eye, the section of a photoreceptor that contains opsin molecules that transduce light stimuli

**outer synaptic layer**
layer in the retina at which photoreceptors connect to bipolar cells

**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

**papilla**
for gustation, a bump-like projection on the surface of the tongue that contains taste buds

**photoisomerization**
chemical change in the retinal molecule that alters the bonding so that it switches from the 11-*cis*-retinal isomer to the all-*trans*-retinal isomer

**photon**
individual “packet” of light

**photoreceptor**
receptor cell specialized to respond to light stimuli

**proprioception**
sense of position and movement of the body

**proprioceptor**
receptor cell that senses changes in the position and kinesthetic aspects of the body

**pupil**
open hole at the center of the iris that light passes through into the eye

**receptor cell**
cell that transduces environmental stimuli into neural signals

**retina**
nervous tissue of the eye at which phototransduction takes place

**retinal**
cofactor in an opsin molecule that undergoes a biochemical change when struck by a photon (pronounced with a stress on the last syllable)

**retinal ganglion cell (RGC)**
neuron of the retina that projects along the second cranial nerve

**rhodopsin**
photopigment molecule found in the rod photoreceptors

**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

**semicircular canals**
structures within the inner ear responsible for transducing rotational movement information

**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

**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

**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

**superior oblique**
extraocular muscle responsible for medial rotation of the eye

**superior rectus**
extraocular muscle responsible for looking up

**taste buds**
structures within a papilla on the tongue that contain gustatory receptor cells

**tectorial membrane**
component of the organ of Corti that lays over the hair cells, into which the stereocilia are embedded

**thermoreceptor**
sensory receptor specialized for temperature stimuli

**topographical**
relating to positional information

**transduction**
process of changing an environmental stimulus into the electrochemical signals of the nervous system

**trochlea**
cartilaginous structure that acts like a pulley for the superior oblique muscle

**tympanic membrane**
ear drum

**umami**
taste submodality for sensitivity to the concentration of amino acids; also called the savory sense

**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 ganglion**
location of neuronal cell bodies that transmit equilibrium information along the eighth cranial nerve

**vestibule**
in the ear, the portion of the inner ear responsible for the sense of equilibrium

**visceral sense**
sense associated with the internal organs

**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

**zonule fibers**
fibrous connections between the ciliary body and the lens

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# CHAPTER OVERVIEW

## 14: The Autonomic Nervous System

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 spread of humans around the world to the present state of the modern age occurred much more quickly than any species would adapt to environmental pressures such as predators. However, 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.


14.1: Prelude to The Autonomic Nervous System

14.2: Divisions of the Autonomic Nervous System

14.3: Autonomic Reflexes and Homeostasis



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# 14.1: Prelude to The Autonomic Nervous System

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. (credit: Vernon Swanepoel)

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# 14.2: Divisions of the Autonomic Nervous System

**Learning Objectives**

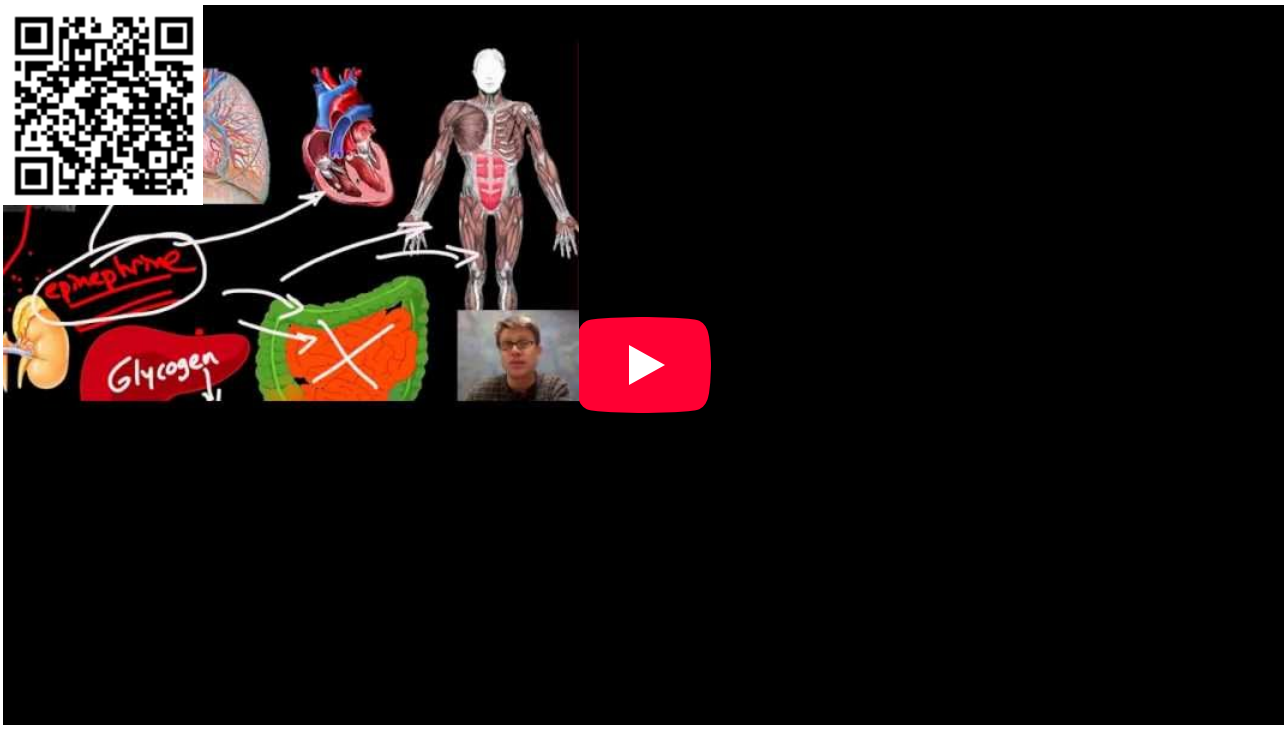
- Name the components that generate the sympathetic and parasympathetic responses of the autonomic nervous system
- Explain the differences in output connections within the two divisions of the autonomic nervous system
- Describe the signaling molecules and receptor proteins involved in communication within the two divisions of the autonomic nervous system

The nervous system can be divided into two functional parts: the somatic nervous system and the autonomic nervous system. The major differences between the two systems are evident in the responses that each produces. The somatic nervous system causes contraction of skeletal muscles. The autonomic nervous system controls cardiac and smooth muscle, as well as glandular tissue. The somatic nervous system is associated with voluntary responses (though many can happen without conscious awareness, like breathing), and the autonomic nervous system is associated with involuntary responses, such as those related to homeostasis.

The autonomic nervous system regulates many of the internal organs through a balance of two aspects, or divisions. In addition to the endocrine system, the autonomic nervous system is instrumental in homeostatic mechanisms in the body. The two divisions of the autonomic nervous system are the **sympathetic division** and the **parasympathetic division**. The sympathetic system is associated with the **fight-or-flight response**, and parasympathetic activity is referred to by the epithet of **rest and digest**. Homeostasis is the balance between the two systems. At each target effector, dual innervation determines 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.

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*Watch this video to learn more about adrenaline and the fight-or-flight response. When someone is said to have a rush of adrenaline, the image of bungee jumpers or skydivers usually comes to mind. But adrenaline, also known as epinephrine, is an important chemical in coordinating the body's fight-or-flight response. In this video, you look inside the physiology of the fight-or-flight response, as envisioned for a firefighter. His body's reaction is the result of the sympathetic division of the autonomic nervous system causing system-wide changes as it prepares for extreme responses. What two changes does adrenaline bring about to help the skeletal muscle response?*




## Sympathetic Division of the Autonomic Nervous System

To respond to a threat—to fight or to run away—the sympathetic system causes divergent 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 the various organ systems of the body through connections emerging from the thoracic and upper lumbar spinal cord. It is referred to as the **thoracolumbar system** to reflect this anatomical basis. A **central neuron** in the lateral horn of any of these spinal regions projects to ganglia adjacent to the vertebral column through the ventral spinal roots. The majority of ganglia of the sympathetic system belong to a network of **sympathetic chain ganglia** that runs alongside the vertebral column. The ganglia appear as a series of clusters of neurons linked by axonal bridges. There are typically 23 ganglia in the 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 cervical and sacral levels are not connected to the spinal cord directly through the spinal roots, but through ascending or descending connections through the bridges within the chain.

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.

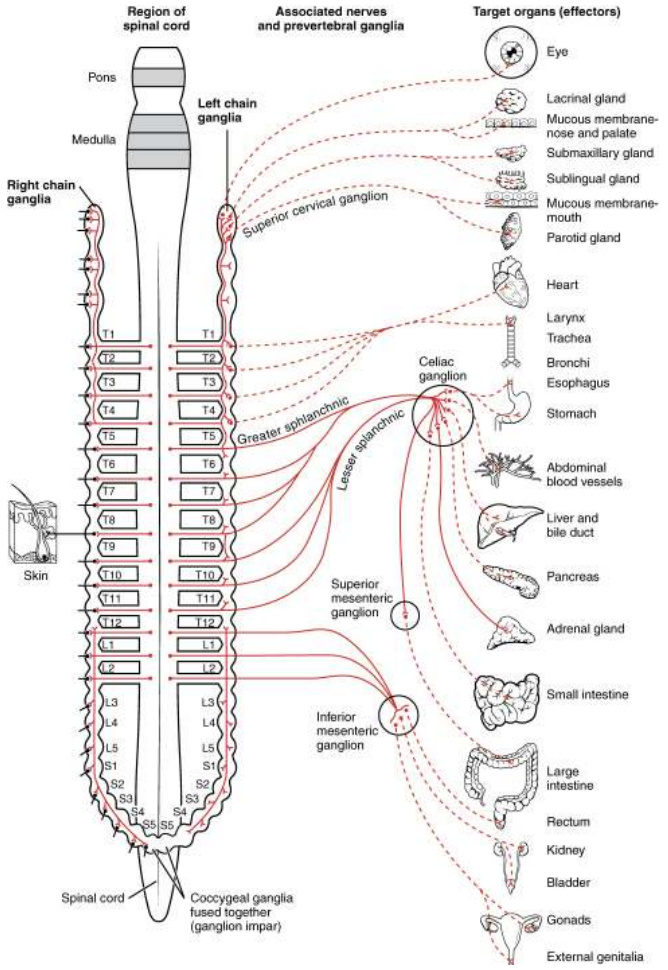



Figure **14.2.1**: Connections of Sympathetic Division of the Autonomic Nervous System. Neurons from the lateral horn of the spinal cord (preganglionic nerve fibers - solid lines)) project to the chain ganglia on either side of the vertebral column or to collateral (prevertebral) ganglia that are anterior to the vertebral column in the abdominal cavity. Axons from these ganglionic neurons (postganglionic nerve fibers - dotted lines) then project to target effectors throughout the body.

To continue with the analogy of the circuit diagram, there are three different types of “junctions” that operate within the sympathetic system (Figure **14.2.1**). The first type is most direct: the sympathetic nerve projects to the chain ganglion at the same level as the **target effector** (the organ, tissue, or gland to be innervated). An example of this type is spinal nerve T1 that synapses with the T1 chain ganglion to innervate the trachea. The fibers of this branch are called **white rami communicantes** (singular = ramus communicans); they are myelinated and therefore referred to as white (see Figure15.1.2.a). The axon from the central neuron (the preganglionic fiber shown as a solid line) synapses with the **ganglionic neuron** (with the postganglionic fiber shown as a dashed line). This neuron then projects to a target effector—in this case, the trachea—via **gray rami communicantes**, which are unmyelinated axons.

In some cases, the target effectors are located superior or inferior to the spinal segment at which the preganglionic fiber emerges. With respect to the “wiring” involved, the synapse with the ganglionic neuron occurs at chain ganglia superior or inferior to the location of the central neuron. An example of this is spinal nerve T1 that innervates the eye. The spinal nerve tracks up through the chain until it reaches the **superior cervical ganglion**, where it synapses with the postganglionic neuron (see Figure **14.2.2**.b). The cervical ganglia are referred to as **paravertebral ganglia**, given their location adjacent to prevertebral ganglia in the sympathetic chain.

Not all axons from the central neurons terminate in the chain ganglia. Additional branches from the ventral nerve root continue through the chain and on to one of the 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 collateral ganglion outside the chain before making the connection to the postganglionic nerves that innervate the stomach (see Figure **14.2.2**.c).

**Collateral ganglia**, also called **prevertebral ganglia**, are situated anterior to the vertebral column and receive inputs from splanchnic nerves as well as central sympathetic neurons. They are associated with controlling organs in the abdominal cavity, and are also considered part of the enteric nervous system. The three collateral ganglia are the **celiac ganglion**, the **superior mesenteric ganglion**, and the **inferior mesenteric ganglion** (see Figure 14.2.1). The word celiac is derived from the Latin word "coelom," which refers to a body cavity (in this case, the abdominal cavity), and the word mesenteric refers to the digestive system.

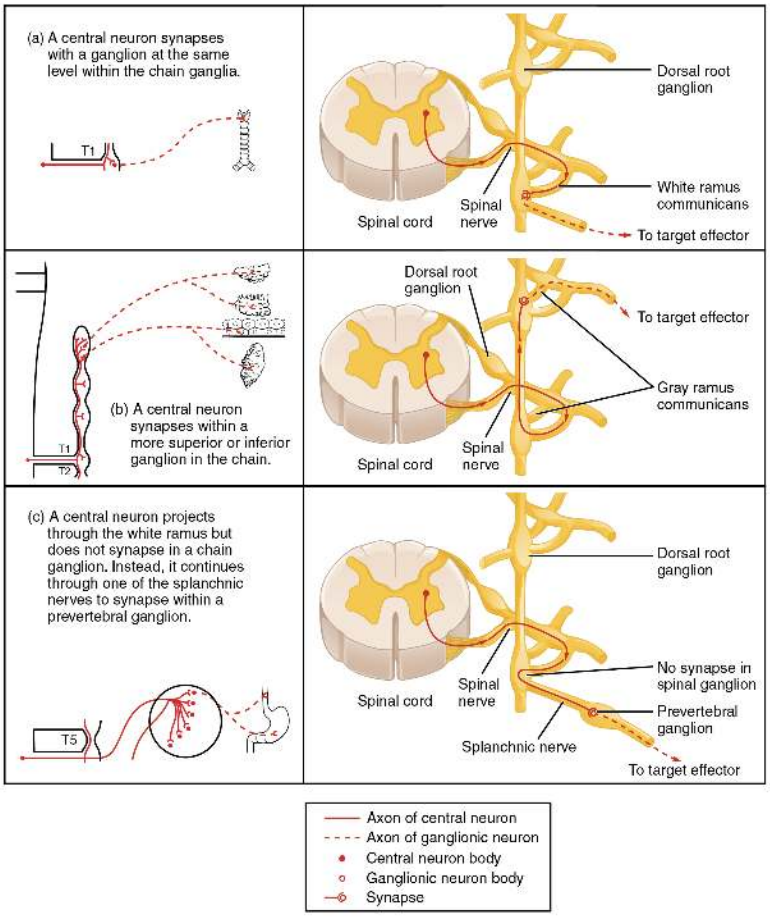



Figure 14.2.2: Sympathetic Connections and Chain Ganglia. The axon from a central sympathetic neuron in the spinal cord can project to the periphery in a number of different ways. (a) The fiber can project out to the ganglion at the same level and synapse on a ganglionic neuron. (b) A branch can project to more superior or inferior ganglion in the chain. (c) A branch can project through the white ramus communicans, but not terminate on a ganglionic neuron in the chain. Instead, it projects through one of the splanchnic nerves to a collateral ganglion or the adrenal medulla (not pictured).

An axon from the central neuron that projects to a sympathetic ganglion is referred to as a **preganglionic fiber** or neuron, and represents the output from the CNS to the ganglion. Because the sympathetic ganglia are adjacent to the vertebral column, preganglionic sympathetic fibers are relatively short, and they are myelinated. A **postganglionic fiber**—the axon from a ganglionic neuron that projects to the target effector—represents the output of a ganglion that directly influences the organ. Compared with the preganglionic fibers, postganglionic sympathetic fibers are long because of the relatively greater distance from the ganglion to the target effector. These fibers are unmyelinated. (Note that the term "postganglionic neuron" may be used to describe the projection from a ganglion to the target. The problem with that usage is that the cell body is in the ganglion, and only the fiber is postganglionic. Typically, the term neuron applies to the entire cell.)

One type of preganglionic sympathetic fiber does not terminate in a ganglion. These are the axons from central sympathetic neurons that project to the **adrenal medulla**, the interior portion of the adrenal gland. These axons are still referred to as preganglionic fibers, but the target is not a ganglion. The adrenal medulla releases signaling molecules into the bloodstream, rather than using axons to communicate with target structures. 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 ganglia, reinforcing the idea that the gland is, functionally, a sympathetic ganglion.

The projections of the sympathetic division of the autonomic nervous system diverge widely, resulting in a broad influence of the system throughout the body. As a response to a threat, the sympathetic system would increase heart rate and breathing rate and cause blood flow to the skeletal muscle to increase and blood flow to the digestive system to decrease. Sweat gland secretion should also increase as part of an integrated response. All of those physiological changes are going to be required to occur together to run away from the hunting lioness, or the modern equivalent. This divergence is seen in the branching patterns of preganglionic sympathetic neurons—a single preganglionic sympathetic neuron may have 10–20 targets. An axon that leaves a central neuron of the lateral horn in the thoracolumbar spinal cord will pass through the white ramus communicans and enter the sympathetic chain, where it will branch toward a variety of targets. At the level of the spinal cord at which the preganglionic sympathetic fiber exits the spinal cord, a branch will synapse on a neuron in the adjacent chain ganglion. Some branches will extend up or down to a different level of the chain ganglia. Other branches will pass through the chain ganglia and project through one of the splanchnic nerves to a collateral ganglion. Finally, some branches may project through the splanchnic nerves to the adrenal medulla. 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.

## Parasympathetic Division of the Autonomic Nervous System

The parasympathetic division of the autonomic nervous system is named because its central neurons are located on either side of the thoracolumbar region of the spinal cord (para- = “beside” or “near”). The parasympathetic system can also be referred to as the **craniosacral system** (or outflow) because the preganglionic neurons are located in nuclei of the brain stem and the lateral horn of the sacral spinal cord.

The connections, or “circuits,” of the parasympathetic division are similar to the general layout of the sympathetic division with a few specific differences (Figure **14.2.3**). The preganglionic fibers from the cranial region travel in cranial nerves, whereas preganglionic fibers from the sacral region travel in spinal nerves. The targets of these fibers are **terminal ganglia**, which are located near—or even within—the target effector. These ganglia are often referred to as **intramural ganglia** when they are found within the walls of the target organ. The postganglionic fiber projects from the terminal ganglia a short distance to the target effector, or to the specific target tissue within the organ. 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.

The cranial component of the parasympathetic system is based in particular nuclei of the brain stem. In the midbrain, the **Edinger–Westphal nucleus** is part of the oculomotor complex, and axons from those neurons travel with the fibers in the oculomotor nerve (cranial nerve III) that innervate the extraocular muscles. The preganglionic parasympathetic fibers within cranial nerve III terminate in the **ciliary ganglion**, which is located in the posterior orbit. The postganglionic parasympathetic fibers then project to the smooth muscle of the iris to control pupillary size. In the upper medulla, the salivatory nuclei contain neurons with axons that project through the facial and glossopharyngeal nerves to ganglia that control salivary glands. Tear production is influenced by parasympathetic fibers in the facial nerve, which activate a ganglion, and ultimately the lacrimal (tear) gland. 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. Parasympathetic preganglionic fibers primarily influence the heart, bronchi, and esophagus in the thoracic cavity and the stomach, liver, pancreas, gall bladder, and small intestine of the abdominal cavity. The postganglionic fibers from the ganglia activated by the vagus nerve are often incorporated into the structure of the organ, such as the **mesenteric plexus** of the digestive tract organs and the intramural ganglia.

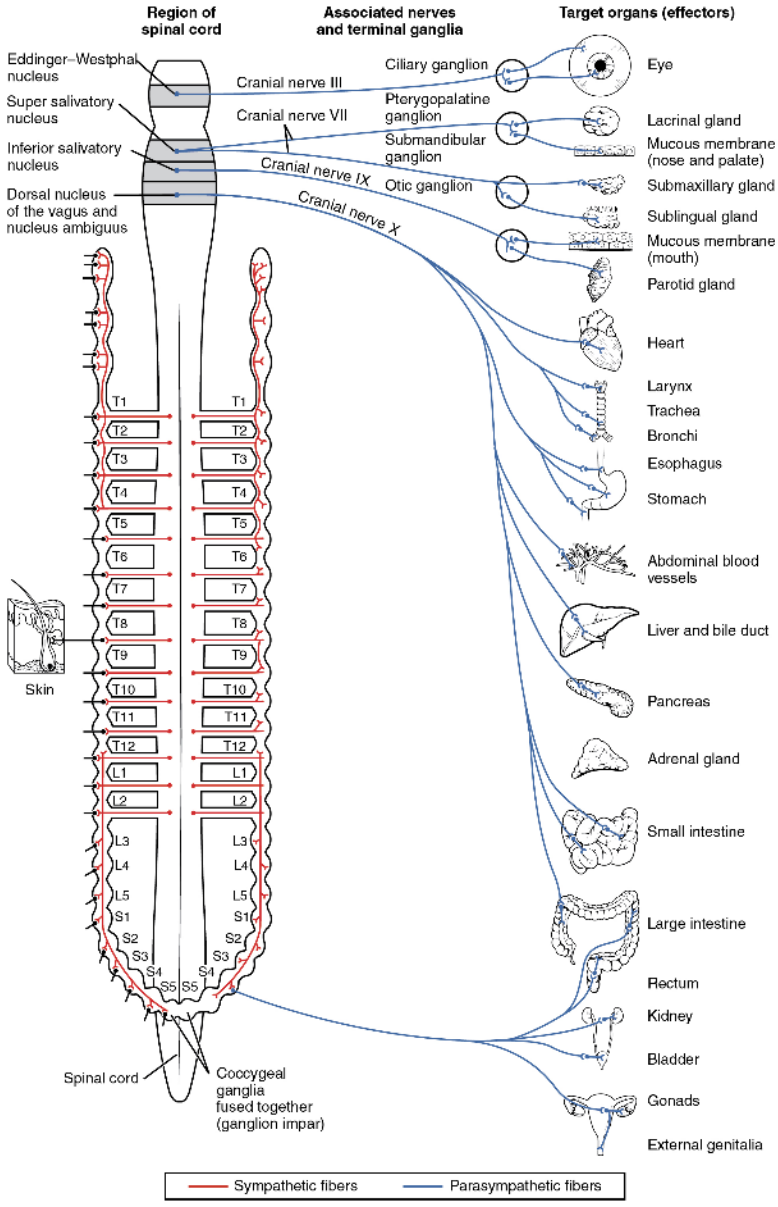



Figure **14.2.3**: Connections of Parasympathetic Division of the Autonomic Nervous System. Neurons from brain-stem nuclei, or from the lateral horn of the sacral spinal cord, project to terminal ganglia near or within the various organs of the body. Axons from these ganglionic neurons then project the short distance to those target effectors.

## Chemical Signaling in the Autonomic Nervous System

Where an autonomic neuron connects with a target, there is a synapse. The electrical signal of the action potential causes the release of a signaling molecule, which will bind to receptor proteins on the target cell. Synapses of the autonomic system are classified as either **cholinergic**, meaning that **acetylcholine (ACh)** is released, or **adrenergic**, meaning that **norepinephrine** is released. The terms cholinergic and adrenergic refer not only to the signaling molecule that is released but also to the class of receptors that each binds.

The cholinergic system includes two classes of receptor: the **nicotinic receptor** and the **muscarinic receptor**. Both receptor types bind to ACh and cause changes in the target cell. The nicotinic receptor is a **ligand-gated cation channel** and the muscarinic receptor is a **G protein–coupled receptor**. The receptors are named for, and differentiated by, other molecules that bind to them. Whereas nicotine will bind to the nicotinic receptor, and muscarine will bind to the muscarinic receptor, there is no cross-reactivity between the receptors. The situation is similar to locks and keys. Imagine two locks—one for a classroom and the other for an office—that are opened by two separate keys. The classroom key will not open the office door and the office key will not open the

classroom door. This is similar to the specificity of nicotine and muscarine for their receptors. However, a master key can open multiple locks, such as a master key for the Biology Department that opens both the classroom and the office doors. This is similar to ACh that binds to both types of receptors. The molecules that define these receptors are not crucial—they are simply tools for researchers to use in the laboratory. These molecules are **exogenous**, meaning that they are made outside of the human body, so a researcher can use them without any confounding **endogenous** results (results caused by the molecules produced in the body).

The adrenergic system also has two types of receptors, named the **alpha (α)-adrenergic receptor** and **beta (β)-adrenergic receptor**. Unlike cholinergic receptors, these receptor types are not classified by which drugs can bind to them. All of them are G protein–coupled receptors. There are three types of α-adrenergic receptors, termed $\alpha_1$, $\alpha_2$, and $\alpha_3$, and there are two types of β-adrenergic receptors, termed $\beta_1$ and $\beta_2$. An additional aspect of the adrenergic system is that there is a second signaling molecule called **epinephrine**. The chemical difference between norepinephrine and epinephrine is the addition of a methyl group ($CH_3$) in epinephrine. The prefix "nor-" actually refers to this chemical difference, in which a methyl group is missing.

The term adrenergic should remind you of the word adrenaline, which is associated with the fight-or-flight response described at the beginning of the chapter. Adrenaline and epinephrine are two names for the same molecule. The adrenal gland (in Latin, ad- = "on top of"; renal = "kidney") secretes adrenaline. The ending "-ine" refers to the chemical being derived, or extracted, from the adrenal gland. A similar construction from Greek instead of Latin results in the word epinephrine (epi- = "above"; nephr- = "kidney"). In scientific usage, epinephrine is preferred in the United States, whereas adrenaline is preferred in Great Britain, because "adrenalin" was once a registered, proprietary drug name in the United States. Though the drug is no longer sold, the convention of referring to this molecule by the two different names persists. Similarly, norepinephrine and noradrenaline are two names for the same molecule.

Having understood the cholinergic and adrenergic systems, their role in the autonomic system is relatively simple to understand. All preganglionic fibers, both sympathetic and parasympathetic, release ACh. All ganglionic neurons—the targets of these preganglionic fibers—have nicotinic receptors in their cell membranes. The nicotinic receptor is a ligand-gated cation channel that results in depolarization of the postsynaptic membrane. The postganglionic parasympathetic fibers also release ACh, but the receptors on their targets are muscarinic receptors, which are G protein–coupled receptors and do not exclusively cause depolarization of the postsynaptic membrane. Postganglionic sympathetic fibers release norepinephrine, except for fibers that project to sweat glands and to blood vessels associated with skeletal muscles, which release ACh (Table).

Autonomic System Signaling Molecules

| | Sympathetic | Parasympathetic |
|---|---|---|
| **Preganglionic** | Acetylcholine → nicotinic receptor | Acetylcholine → nicotinic receptor |
| **Postganglionic** | Norepinephrine → α- or β-adrenergic receptors<br>Acetylcholine → muscarinic receptor (associated with sweat glands and the blood vessels associated with skeletal muscles only | Acetylcholine → muscarinic receptor |

Signaling molecules can belong to two broad groups. Neurotransmitters are released at synapses, whereas hormones are released into the bloodstream. These are simplistic definitions, but they can help to clarify this point. Acetylcholine can be considered a neurotransmitter because it is released by axons at synapses. The adrenergic system, however, presents a challenge. Postganglionic sympathetic fibers release norepinephrine, which can be considered a neurotransmitter. But the adrenal medulla releases epinephrine and norepinephrine into circulation, so they should be considered hormones.

What are referred to here as synapses may not fit the strictest definition of synapse. Some sources will refer to the connection between a postganglionic fiber and a target effector as neuroeffector junctions; neurotransmitters, as defined above, would be called neuromodulators. 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 called a **varicosity** (Figure 14.2.4).

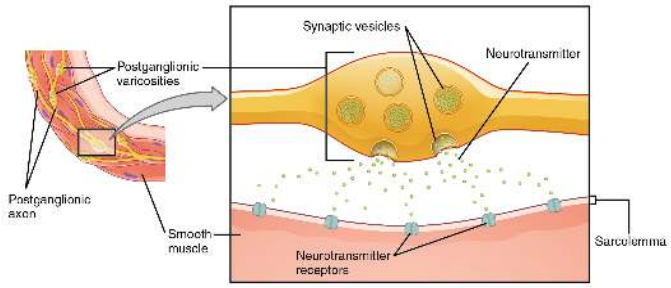



Figure **14.2.4**: Autonomic Varicosities. The connection between autonomic fibers and target effectors is not the same as the typical synapse, such as the neuromuscular junction. Instead of a synaptic end bulb, a neurotransmitter is released from swellings along the length of a fiber that makes an extended network of connections in the target effector.

EVERYDAY CONNECTIONS

**Fight or Flight? What About Fright and Freeze?**

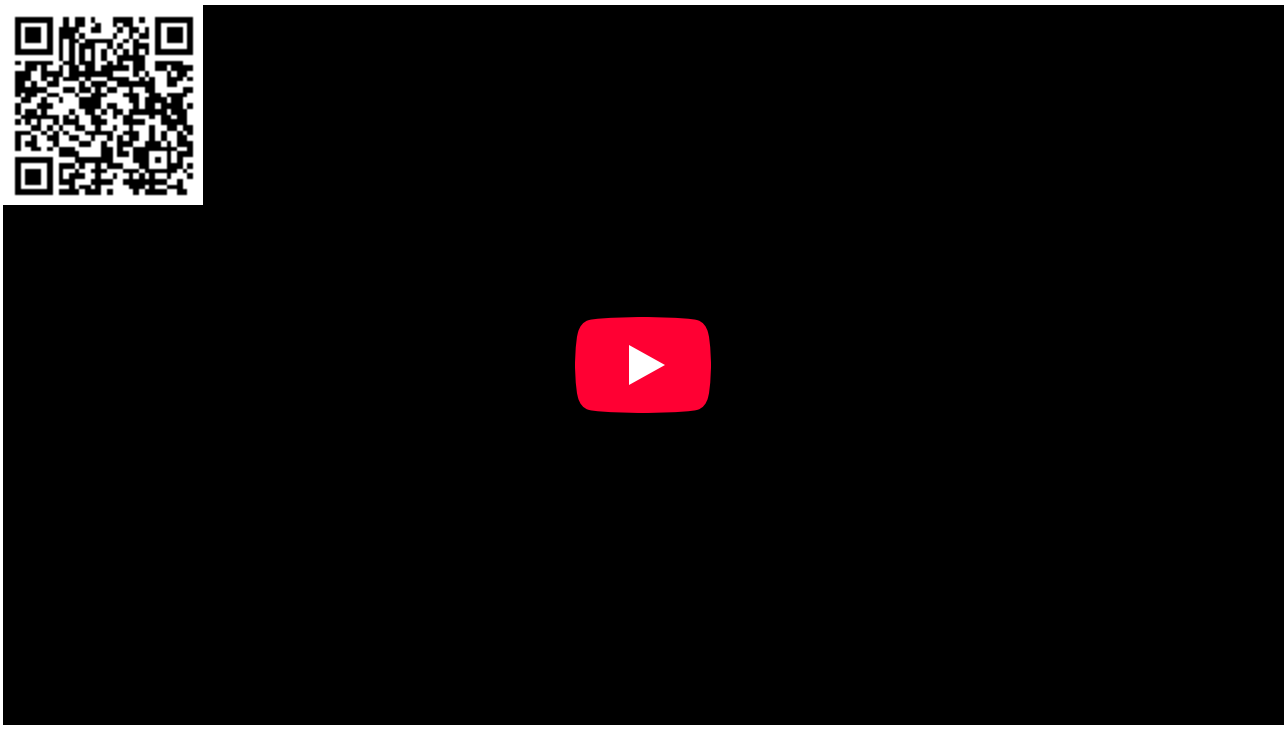
The original usage of the epithet “fight or flight” comes from a scientist named Walter Cannon who worked at Harvard in 1915. The concept of homeostasis and the functioning of the sympathetic system had been introduced in France in the previous century. Cannon expanded the idea, and introduced the idea 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”).

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*Watch this video to learn more about the nervous system. As described in this video, the nervous system has a way to deal with threats and stress that is separate from the conscious control of the somatic nervous system. The system comes from a time when threats were about survival, but in the modern age, these responses become part of stress and anxiety. This video describes how the autonomic system is only part of the response to threats, or stressors. What other organ system gets involved, and what part of the brain coordinates the two systems for the entire response, including epinephrine (adrenaline) and cortisol?*



## Chapter Review

The primary responsibilities of the autonomic nervous system are to regulate homeostatic mechanisms in the body, which is also part of what the endocrine system does. The key to understanding the autonomic system is to explore the response pathways—the output of the nervous system. 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 and spinal nerve to a sympathetic ganglion, either in the sympathetic chain ganglia or one of the collateral locations, where it synapses on a ganglionic neuron. These preganglionic fibers release ACh, which excites the ganglionic neuron through the nicotinic receptor. The axon from the ganglionic neuron—the postganglionic fiber—then projects to a target effector where it will release norepinephrine to bind to an adrenergic receptor, causing a change in the physiology of that organ in keeping with the broad, divergent sympathetic response. The postganglionic connections to sweat glands in the skin and blood vessels supplying skeletal muscle are, however, exceptions; those fibers release ACh onto muscarinic receptors. The sympathetic system 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. This hormonal component means that the sympathetic chemical signal can spread throughout the body very quickly and affect many organ systems at once.

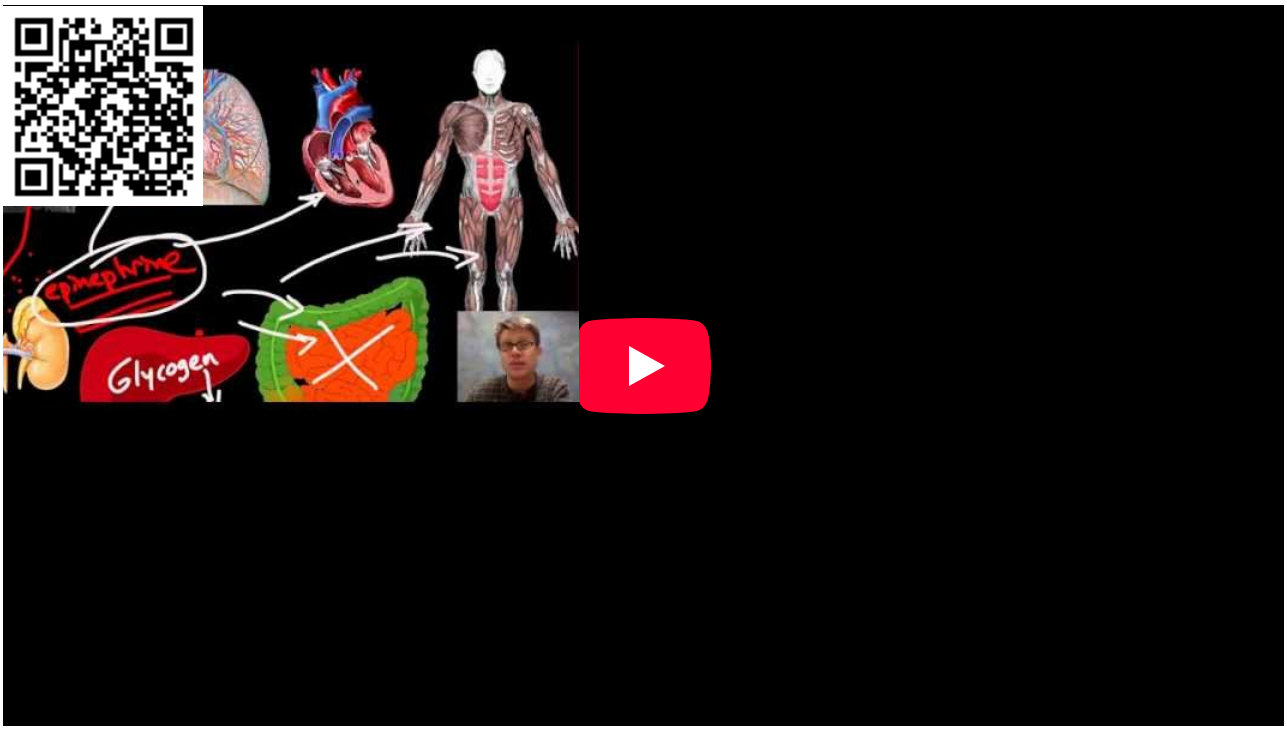
The parasympathetic output is based in the brain stem and sacral spinal cord. Neurons from particular nuclei in the brain stem or from the lateral horn of the sacral spinal cord (preganglionic neurons) project to terminal (intramural) ganglia located close to or within the wall of target effectors. These preganglionic fibers also release ACh onto nicotinic receptors to excite the ganglionic neurons. The postganglionic fibers then contact the target tissues within the organ to release ACh, which binds to muscarinic receptors to induce rest-and-digest responses.

Signaling molecules utilized by the autonomic nervous system are released from axons and can be considered as either neurotransmitters (when they directly interact with the effector) or as hormones (when they are released into the bloodstream). The same molecule, such as norepinephrine, could be considered either a neurotransmitter or a hormone on the basis of whether it is

released from a postganglionic sympathetic axon or from the adrenal gland. 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.

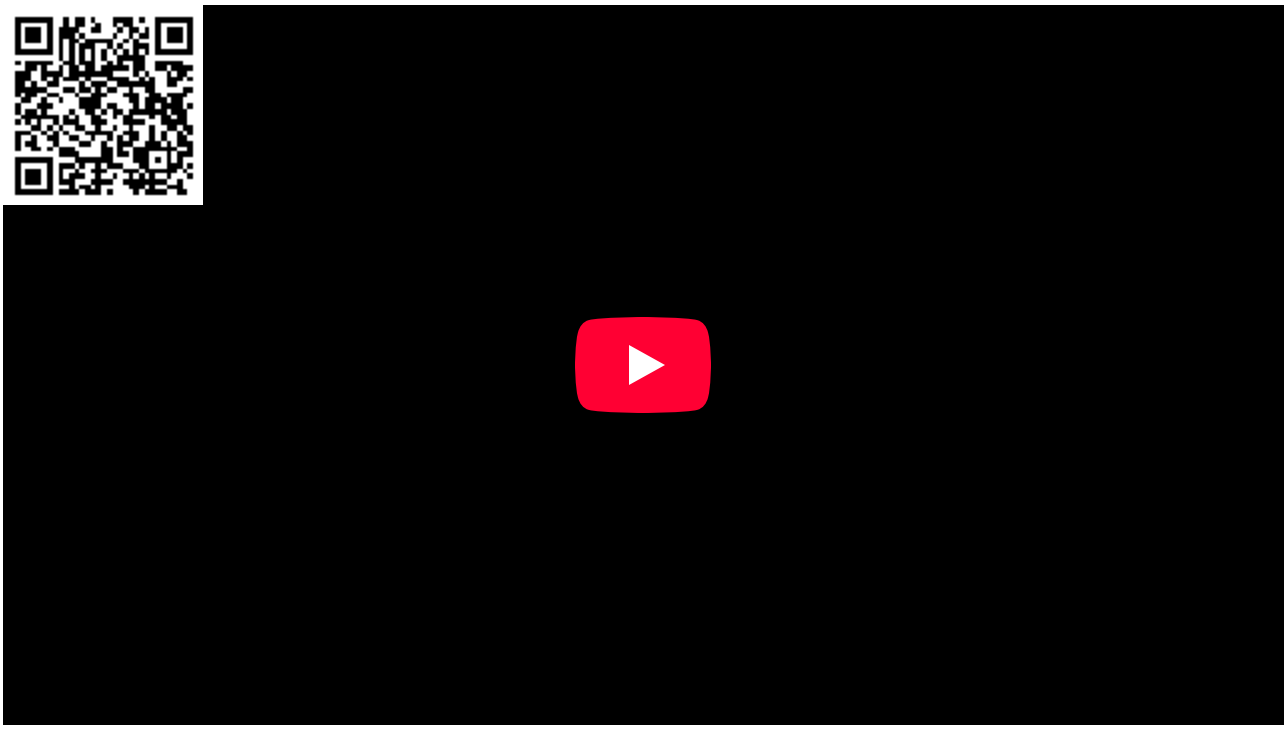
## Interactive Link Questions

Watch this video to learn more about adrenaline and the fight-or-flight response. When someone is said to have a rush of adrenaline, the image of bungee jumpers or skydivers usually comes to mind. But adrenaline, also known as epinephrine, is an important chemical in coordinating the body's fight-or-flight response. In this video, you look inside the physiology of the fight-or-flight response, as envisioned for a firefighter. His body's reaction is the result of the sympathetic division of the autonomic nervous system causing system-wide changes as it prepares for extreme responses. What two changes does adrenaline bring about to help the skeletal muscle response?




Answer: The heart rate increases to send more blood to the muscles, and the liver releases stored glucose to fuel the muscles.

Watch this video to learn more about the nervous system. As described in this video, the nervous system has a way to deal with threats and stress that is separate from the conscious control of the somatic nervous system. The system comes from a time when threats were about survival, but in the modern age, these responses become part of stress and anxiety. This video describes how the autonomic system is only part of the response to threats, or stressors. What other organ system gets involved, and what part of the brain coordinates the two systems for the entire response, including epinephrine (adrenaline) and cortisol?



Answer: The endocrine system is also responsible for responses to stress in our lives. The hypothalamus coordinates the autonomic response through projections into the spinal cord and through influence over the pituitary gland, the effective center of the endocrine system.

## 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 signaling molecule is *most likely* responsible for an increase in digestive activity?

A. epinephrine

B. norepinephrine

C. acetylcholine

D. adrenaline

Answer: C

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. 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.

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.

## Glossary

**alpha (α)-adrenergic receptor**
one of the receptors to which epinephrine and norepinephrine bind, which comes in three subtypes: $\alpha_1$, $\alpha_2$, and $\alpha_3$

**acetylcholine (ACh)**
neurotransmitter that binds at a motor end-plate to trigger depolarization

**adrenal medulla**
interior portion of the adrenal (or suprarenal) gland that releases epinephrine and norepinephrine into the bloodstream as hormones

**adrenergic**
synapse where norepinephrine is released, which binds to α- or β-adrenergic receptors

**beta (β)-adrenergic receptor**

one of the receptors to which epinephrine and norepinephrine bind, which comes in two subtypes: $\beta_1$ and $\beta_2$

**celiac ganglion**
one of the collateral ganglia of the sympathetic system that projects to the digestive system

**central neuron**
specifically referring to the cell body of a neuron in the autonomic system that is located in the central nervous system, specifically the lateral horn of the spinal cord or a brain stem nucleus

**cholinergic**
synapse at which acetylcholine is released and binds to the nicotinic or muscarinic receptor

**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

**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

**dorsal nucleus of the vagus nerve**
location of parasympathetic neurons that project through the vagus nerve to terminal ganglia in the thoracic and abdominal cavities

**Eddinger–Westphal nucleus**
location of parasympathetic neurons that project to the ciliary ganglion

**endogenous**
describes substance made in the human body

**epinephrine**
signaling molecule released from the adrenal medulla into the bloodstream as part of the sympathetic response

**exogenous**
describes substance made outside of the human body

**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

**G protein–coupled receptor**
membrane protein complex that consists of a receptor protein that binds to a signaling molecule—a G protein—that is activated by that binding and in turn activates an effector protein (enzyme) that creates a second-messenger molecule in the cytoplasm of the target cell

**ganglionic neuron**

specifically refers to the cell body of a neuron in the autonomic system that is located in a ganglion

**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 of the central sympathetic neurons that do not synapse in the chain ganglia but project onto the celiac ganglion

**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

**lesser splanchnic nerve**
nerve that contains fibers of the central sympathetic neurons that do not synapse in the chain ganglia but project onto the inferior mesenteric ganglion

**ligand-gated cation channel**
ion channel, such as the nicotinic receptor, that is specific to positively charged ions and opens when a molecule such as a neurotransmitter binds to it

**mesenteric plexus**
nervous tissue within the wall of the digestive tract that contains neurons that are the targets of autonomic preganglionic fibers and that project to the smooth muscle and glandular tissues in the digestive organ

**muscarinic receptor**
type of acetylcholine receptor protein that is characterized by also binding to muscarine and is a metabotropic receptor

**nicotinic receptor**
type of acetylcholine receptor protein that is characterized by also binding to nicotine and is an ionotropic receptor

**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

**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

**parasympathetic division**
division of the autonomic nervous system responsible for restful and digestive functions

**paravertebral ganglia**
autonomic ganglia superior to the sympathetic chain ganglia

**postganglionic fiber**
axon from a ganglionic neuron in the autonomic nervous system that projects to and synapses with the target effector; sometimes referred to as a postganglionic neuron

**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

**prevertebral ganglia**
autonomic ganglia that are anterior to the vertebral column and functionally related to the sympathetic chain ganglia

**rest and digest**
set of functions associated with the parasympathetic system that lead to restful actions and digestion

**superior cervical ganglion**
one of the paravertebral ganglia of the sympathetic system that projects to the head

**superior mesenteric ganglion**
one of the collateral ganglia of the sympathetic system that projects to the digestive system

**sympathetic chain 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

**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

**varicosity**
structure of some autonomic connections that is not a typical synaptic end bulb, but a string of swellings along the length of a fiber that makes a network of connections with the target effector

**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

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# 14.3: Autonomic Reflexes and Homeostasis

**Learning Objectives**

- Compare the structure of somatic and autonomic reflex arcs
- Explain the differences in sympathetic and parasympathetic reflexes
- Differentiate between short and long reflexes
- Determine the effect of the autonomic nervous system on the regulation of the various organ systems on the basis of the signaling molecules involved
- Describe the effects of drugs that affect autonomic function

The autonomic nervous system regulates organ systems through circuits that resemble the reflexes described in the somatic nervous system. The main difference between the somatic and autonomic systems is in what target tissues are effectors. Somatic responses are solely based on skeletal muscle contraction. The autonomic system, however, targets cardiac and smooth muscle, as well as glandular tissue. Whereas the basic circuit is a **reflex arc**, there are differences in the structure of those reflexes for the somatic and autonomic systems.

## The Structure of Reflexes

One difference between a **somatic reflex**, such as the withdrawal reflex, and a **visceral reflex**, which is an autonomic 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 brain stem, to a ganglion—followed by the postganglionic fiber projecting to a target effector. The other part of a reflex, the **afferent branch**, is often the same between the two systems. 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 (Figure **14.3.1**). The Latin root "effere" means "to carry." Adding the prefix "ef-" suggests the meaning "to carry away," whereas adding the prefix "af-" suggests "to carry toward or inward."

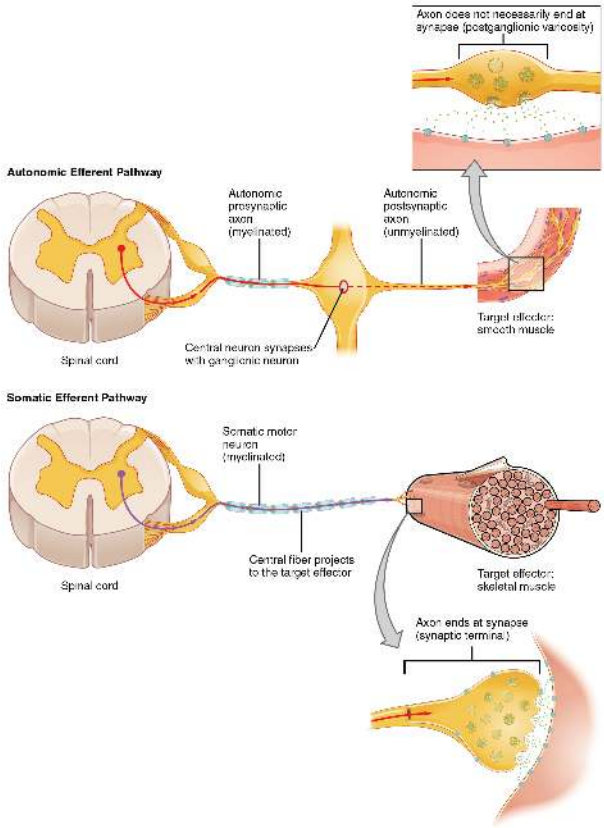



Figure **14.3.1**: Comparison of Somatic and Visceral Reflexes. The afferent inputs to somatic and visceral reflexes are essentially the same, whereas the efferent branches are different. Somatic reflexes, for instance, involve a direct connection from the ventral horn of the spinal cord to the skeletal muscle. Visceral reflexes involve a projection from the central neuron to a ganglion, followed by a second projection from the ganglion to the target effector.

## Afferent Branch

The afferent branch of a reflex arc does differ between somatic and visceral reflexes in some instances. 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. The baroreceptor apparatus is part of the ending of 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. Projections from the medial and inferior divisions of the cervical ganglia do enter the spinal cord at the middle to lower cervical levels, which is where the somatosensory fibers enter.

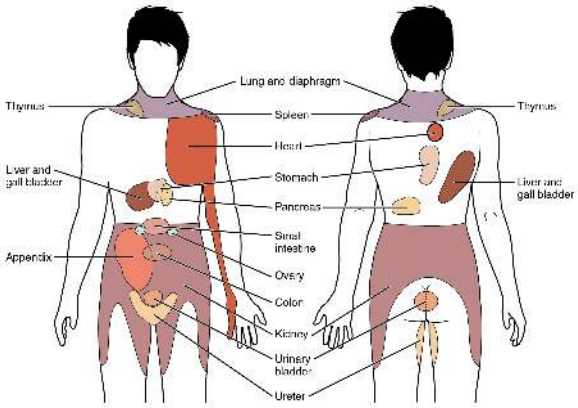



Figure **14.3.2**: Referred Pain Chart. Conscious perception of visceral sensations map to specific regions of the body, as shown in this chart. Some sensations are felt locally, whereas others are perceived as affecting areas that are quite distant from the involved organ.

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 brain stem. 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.

### Efferent Branch

The efferent branch of the visceral reflex arc begins with the projection from the central neuron along the preganglionic fiber. This fiber then makes a synapse on the ganglionic neuron that projects to the target effector.

The effector organs that are the targets of the autonomic system range from the iris and ciliary body of the eye to the urinary bladder and reproductive organs. The thoracolumbar output, through the various sympathetic ganglia, reaches all of these organs. The cranial component of the parasympathetic system projects from the eye to part of the intestines. The sacral component picks up with the majority of the large intestine and the pelvic organs of the urinary and reproductive systems.

## Chapter Review

Autonomic nervous system function is based on the visceral reflex. This reflex is similar to the somatic reflex, but the efferent branch is composed of two neurons. The central neuron projects from the spinal cord or brain stem 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.

The role of visceral reflexes is to maintain a balance of function in the organ systems of the body. The two divisions of the autonomic system each play a role in effecting change, usually in competing directions. 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.

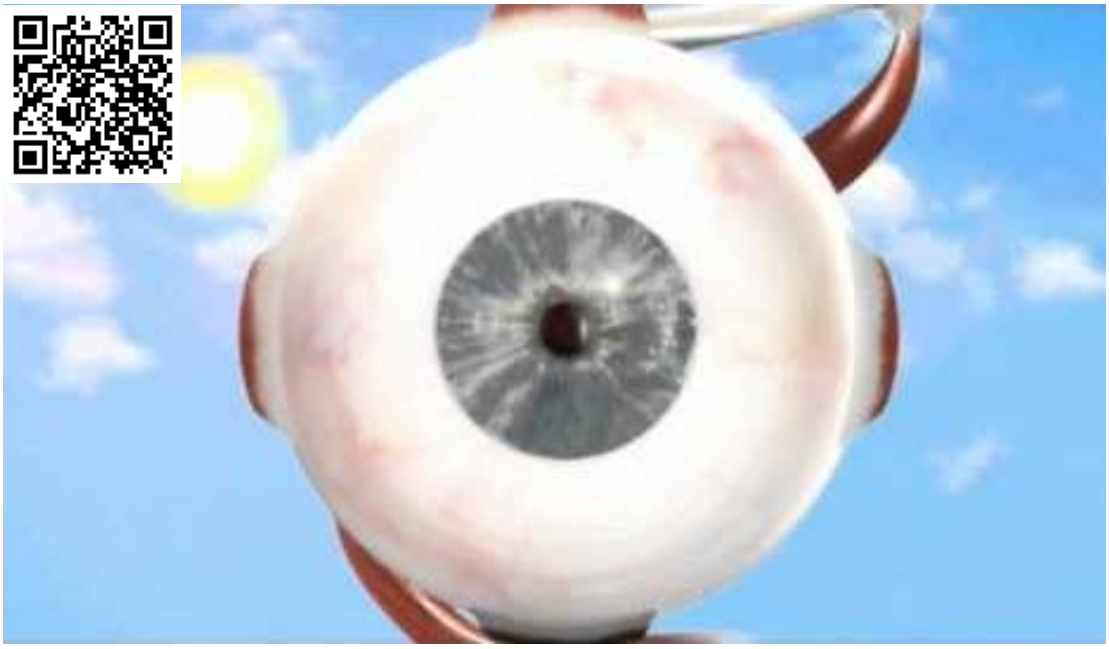
In a few systems of the body, the competing input from the two divisions is not the norm. The sympathetic tone of blood vessels is caused by the lack of parasympathetic input to the systemic circulatory system. Only certain regions receive parasympathetic input that relaxes the smooth muscle wall of the blood vessels. Sweat glands are another example, which only receive input from the sympathetic system.

## Interactive Link Questions

Read this article to learn about a teenager who experiences a series of spells that suggest a stroke. He undergoes endless tests and seeks input from multiple doctors. In the end, one expert, one question, and a simple blood pressure cuff answers the question. Why would the heart have to beat faster when the teenager changes his body position from lying down to sitting, and then to standing?

> Answer: The effect of gravity on circulation means that it is harder to get blood up from the legs as the body takes on a vertical orientation.

Watch this video to learn about the pupillary reflexes. The pupillary light reflex involves sensory input through the optic nerve and motor response through the oculomotor nerve to the ciliary ganglion, which projects to the circular fibers of the iris. As shown in this short animation, pupils will constrict to limit the amount of light falling on the retina under bright lighting conditions. What constitutes the afferent and efferent branches of the competing reflex (dilation)?



Answer: The optic nerve still carries the afferent input, but the output is from the thoracic spinal cord, through the superior cervical ganglion, to the radial fibers of the iris.

## 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

Q. What neurotransmitter will result in constriction of the pupil?

A. norepinephrine

B. acetylcholine

C. epinephrine

D. serotonin

Answer: B

Q. What gland produces a secretion that causes fight-or-flight responses in effectors?

A. adrenal medulla

B. salivatory gland

C. reproductive gland

D. thymus

> Answer: A

Q. Which of the following is an incorrect pairing?

A. norepinephrine dilates the pupil

B. epinephrine increases blood pressure

C. acetylcholine decreases digestion

D. norepinephrine increases heart rate

> Answer: C

## Critical Thinking Questions

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.

Q. Medical practice is paying more attention to the autonomic system in considering disease states. Why would autonomic tone be important in considering cardiovascular disease?

> A. Within the cardiovascular system, different aspects demonstrate variation in autonomic tone. Heart rate is under parasympathetic tone, and blood pressure is under sympathetic tone. Pharmaceuticals that treat cardiovascular disorders may be more effective if they work with the normal state of the autonomic system. Alternatively, some disorders may be exacerbated by autonomic deficits and common therapies might not be as effective.

## Glossary

**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

**afferent branch**
component of a reflex arc that represents the input from a sensory neuron, for either a special or general sense

**baroreceptor**
mechanoreceptor that senses the stretch of blood vessels to indicate changes in blood pressure

**efferent branch**
component of a reflex arc that represents the output, with the target being an effector, such as muscle or glandular tissue

**long reflex**
reflex arc that includes the central nervous system

**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

**visceral reflex**

reflex involving an internal organ as the effector, under the control of the autonomic nervous system

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# CHAPTER OVERVIEW

## 15: The Endocrine System

In order to survive, animals must constantly adapt to changes in the environment. The nervous and endocrine systems both work together to bring about this adaptation. In general the nervous system responds rapidly to short-term changes by sending electrical impulses along nerves and the endocrine system brings about longer-term adaptations by sending out chemical messengers called hormones into the blood stream.


15.1: Prelude to the Endocrine System
15.2: An Overview of the Endocrine System
15.3: The Pituitary Gland and Hypothalamus
15.4: The Thyroid Gland
15.5: The Parathyroid Glands
15.6: The Adrenal Glands
15.7: The Pineal Gland
15.8: The Endocrine Pancreas
15.9: Organs with Secondary Endocrine Functions


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# 15.1: Prelude to the Endocrine System

**Chapter Objectives:**

- 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. (credit: "seenthroughmylense"/flickr.com)

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# 15.2: An Overview of the Endocrine System

**Learning Objectives**

- Distinguish the types of intercellular communication, their importance, mechanisms, and effects
- Identify the major organs and tissues of the endocrine system and their location in the body

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. Neurotransmitters act locally and rapidly. When an electrical signal in the form of an action potential arrives at the synaptic terminal, they diffuse across the synaptic cleft (the gap between a sending neuron and a receiving neuron or muscle 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 in 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**: 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 |
| Environment targeted | Internal | Internal and external |

## 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 (Figure **15.2.1**). Some of these 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.

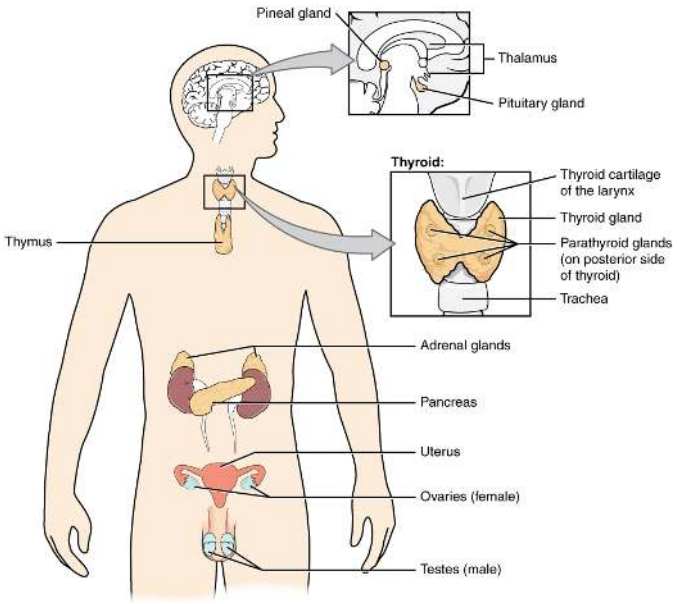



Figure 15.2.1: Endocrine System. Endocrine glands and cells are located throughout the body and play an important role in homeostasis.

The 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 of the small intestine.

## Other Types of Chemical Signaling

In endocrine signaling, hormones secreted into the extracellular fluid diffuse into the blood or lymph, 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 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 the province of the **paracrine**, also called a paracrine factor, which is a chemical that induces a response in neighboring cells. Although paracrines may enter the bloodstream, their concentration is generally too low to elicit a response from distant tissues. A familiar example to those with asthma is histamine, a paracrine that is released by immune cells in the bronchial tree. Histamine causes the smooth muscle cells of the bronchi to constrict, narrowing the airways. Another example is the neurotransmitters of the nervous system, which act only locally within the synaptic cleft.

### 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.

## Chapter 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.

## Interactive Link Questions

Visit this link to watch an animation of the events that occur when a hormone binds to a cell membrane receptor. What is the secondary messenger made by adenylyl cyclase during the activation of liver cells by epinephrine?

Answer: cAMP

## 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: C

Q. Chemical signaling that affects neighboring cells is called _____.

A. autocrine

B. paracrine

C. endocrine

D. neuron

Answer: B

## Critical Thinking Questions

Q. Describe several main differences in the communication methods used by the endocrine system and the nervous system.

> 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.

> 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.

> 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

**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

**paracrine**
chemical signal that elicits a response in neighboring cells; also called paracrine factor

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# 15.3: The Pituitary Gland and Hypothalamus

**Learning Objectives**

- 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 sellaturcica 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.

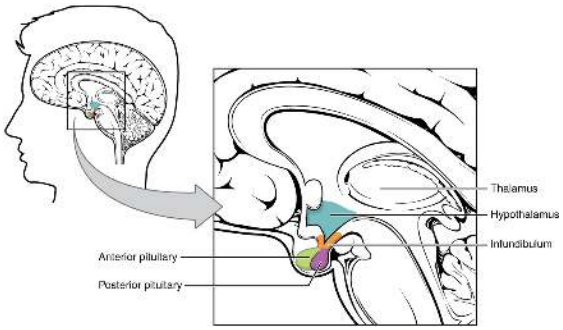



Figure 15.3.1: Hypothalamus–Pituitary Complex. The hypothalamus region lies inferior and anterior to the thalamus. It connects to the pituitary gland by the stalk-like infundibulum. The pituitary gland consists of an anterior and posterior lobe, with each lobe secreting different hormones in response to signals from the hypothalamus.

Table 15.3.1: Pituitary Hormones

| Pituitary lobe | Associated hormones | Chemical class | Effect |
|---|---|---|---|
| Anterior | Growth hormone (GH) | Protein | Promotes growth of body tissues |
| Anterior | Prolactin (PRL) | Peptide | Promotes milk production from mammary glands |
| Anterior | Thyroid-stimulating hormone (TSH) | Glycoprotein | Stimulates thyroid hormone release from thyroid |
| Anterior | Adrenocorticotropic hormone (ACTH) | Peptide | Stimulates hormone release by adrenal cortex |
| Anterior | Follicle-stimulating hormone (FSH) | Glycoprotein | Stimulates gamete production in gonads |
| Anterior | Luteinizing hormone (LH) | Glycoprotein | Stimulates androgen production by gonads |
| Posterior | Antidiuretic hormone (ADH) | Peptide | Stimulates water reabsorption by kidneys |
| Posterior | Oxytocin | Peptide | Stimulates uterine contractions during childbirth |
| Intermediate zone | Melanocyte-stimulating hormone | Peptide | 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).

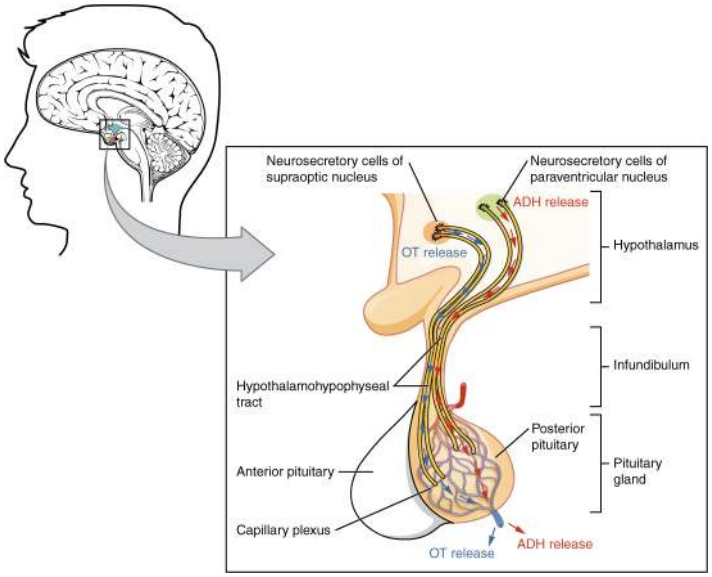



Figure 15.3.2: Posterior Pituitary. Neurosecretory cells in the hypothalamus release oxytocin (OT) or ADH into the posterior lobe of the pituitary gland. These hormones are stored or released into the blood via the capillary plexus.

The posterior pituitary gland does not produce hormones, but rather stores and secretes hormones produced by the hypothalamus. The paraventricular nuclei produce the hormone oxytocin, whereas the supraoptic nuclei produce 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)**. The target cells of ADH are located in the tubular cells of the kidneys. 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. ADH is also known as vasopressin because, in very high concentrations, it causes constriction of blood vessels, which increases blood pressure by increasing peripheral resistance. 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.

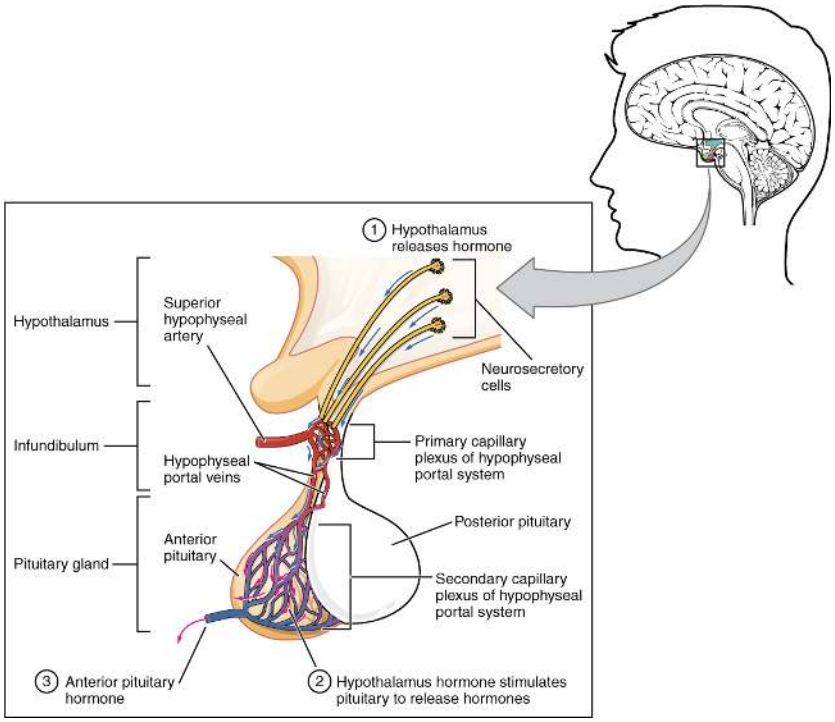



Figure 15.3.3: Anterior Pituitary. The anterior pituitary manufactures seven hormones. The hypothalamus produces separate hormones that stimulate or inhibit hormone production in the anterior pituitary. Hormones from the hypothalamus reach the anterior pituitary via the hypophyseal portal system.

The anterior pituitary produces seven hormones. These are the growth hormone (GH), thyroid-stimulating hormone (TSH), adrenocorticotropic hormone (ACTH), follicle-stimulating hormone (FSH), luteinizing hormone (LH), beta endorphin, 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 is anabolic; it promotes protein synthesis and tissue building through direct and indirect mechanisms (Figure 15.3.4). GH levels are controlled by the release of GHRH and GHIH (also known as somatostatin) from the hypothalamus.

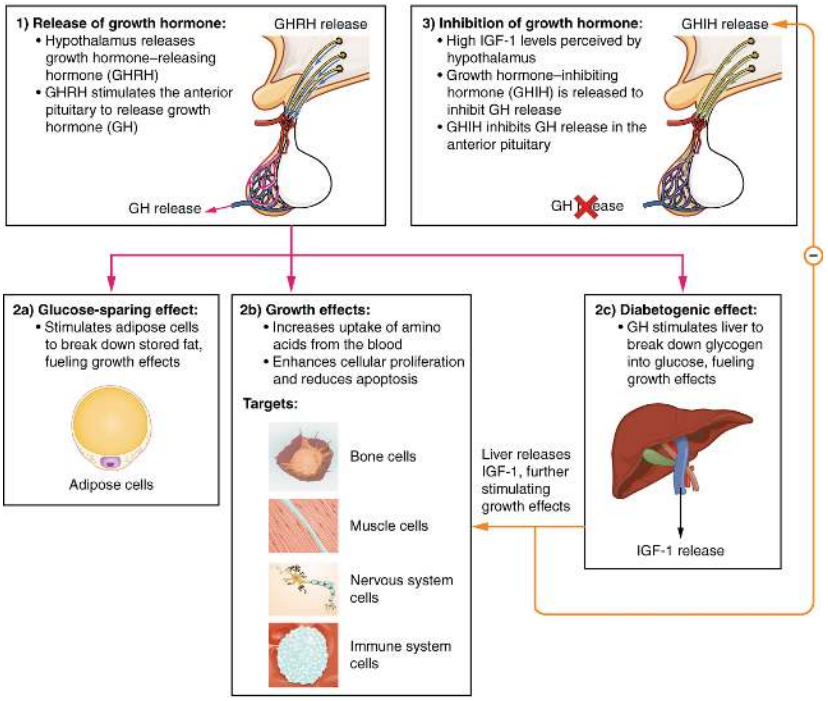



Figure **15.3.4**: Hormonal Regulation of Growth. Growth hormone (GH) directly accelerates the rate of protein synthesis in skeletal muscle and bones. Insulin-like growth factor 1 (IGF-1) is activated by growth hormone and indirectly supports the formation of new proteins in muscle cells and bone.

A glucose-sparing effect occurs when GH stimulates lipolysis, or the breakdown of adipose tissue, releasing fatty acids into the blood. As a result, many tissues switch from glucose to fatty acids as their main energy source, which means that less glucose is taken up from the bloodstream.

GH also initiates the diabetogenic effect in which GH stimulates the liver to break down glycogen to glucose, which is then deposited into the blood. The name “diabetogenic” is derived from the similarity in elevated blood glucose levels observed between individuals with untreated diabetes mellitus and individuals experiencing GH excess. Blood glucose levels rise as the result of a combination of glucose-sparing and diabetogenic effects.

GH indirectly mediates growth and protein synthesis by triggering the liver and other tissues to produce a group of proteins called **insulin-like growth factors (IGFs)**. These proteins enhance cellular proliferation and inhibit apoptosis, or programmed cell death. IGFs stimulate cells to increase their uptake of amino acids from the blood for protein synthesis. Skeletal muscle and cartilage cells are particularly sensitive to stimulation from IGFs.

Dysfunction of the endocrine system’s control of growth can result in several disorders. For example, **gigantism** is a disorder in children that is caused by the secretion of abnormally large amounts of GH, resulting in excessive growth. A similar condition in adults is **acromegaly**, a disorder that results in the growth of bones in the face, hands, and feet in response to excessive levels of GH in individuals who have stopped growing. Abnormally low levels of GH in children can cause growth impairment—a disorder called **pituitary dwarfism** (also known as growth hormone deficiency).

### 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 shortly, 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 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. A variety of stressors can also influence its release, 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 in males and the ovaries in females). Much of the development of the reproductive system occurs during puberty and is marked by the development of sex-specific characteristics in both male and female 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 women, 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 women and sperm in men. FSH also promotes follicular growth; these follicles then release estrogens in the female ovaries. **Luteinizing hormone (LH)** triggers ovulation in women, as well as the production of estrogens and progesterone by the ovaries. LH stimulates production of testosterone by the male 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 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 skin's melanocytes. 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 **15.3.5** is a summary of the pituitary hormones and their principal effects.

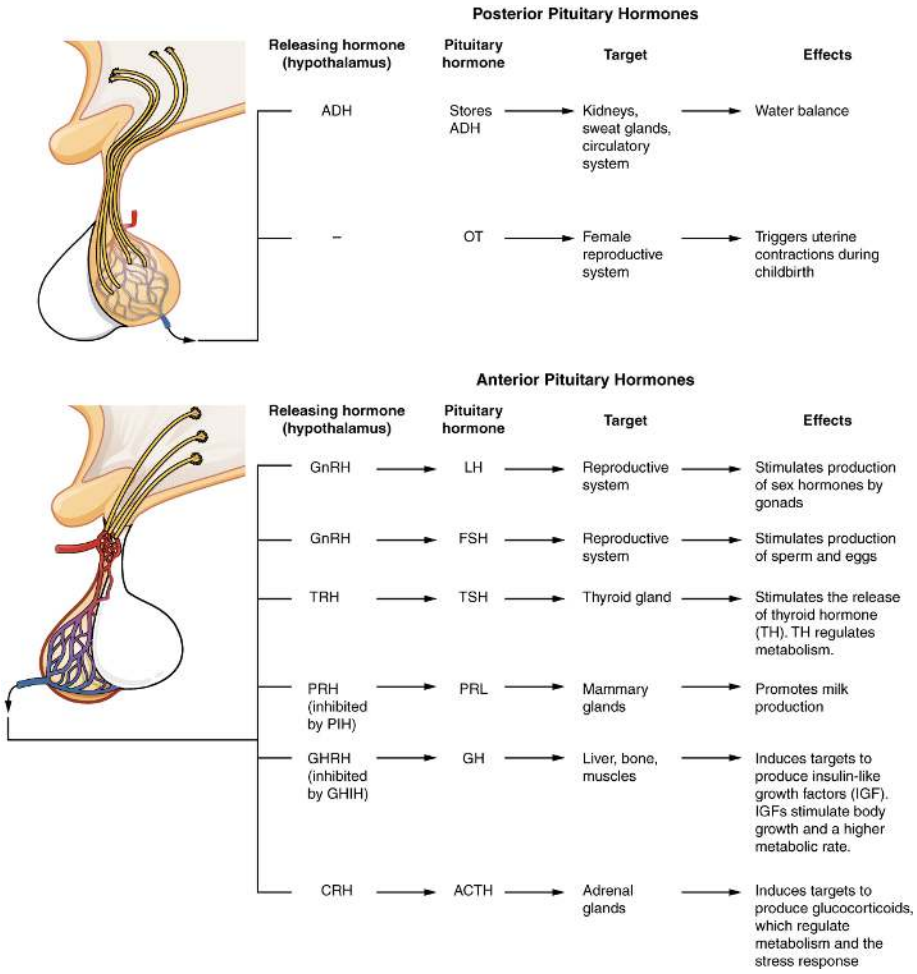



Figure 15.3.5: Major Pituitary Hormones. Major pituitary hormones and their target organs.

## Chapter 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 and antidiuretic hormone (ADH). The anterior lobe is connected to the hypothalamus by vasculature 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).

## Interactive Link Questions

Visit this link to watch an animation showing the role of the hypothalamus and the pituitary gland. Which hormone is released by the pituitary to stimulate the thyroid gland?

> Answer: Thyroid-stimulating hormone.

## 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: B

Q. Which of the following is an anterior pituitary hormone?

A. ADH

B. oxytocin

C. TSH

D. cortisol

Answer: C

Q. How many hormones are produced by the posterior pituitary?

A. 0

B. 1

C. 2

D. 6

Answer: A

Q. Which of the following hormones contributes to the regulation of the body's fluid and electrolyte balance?

A. adrenocorticotropic hormone

B. antidiuretic hormone

C. luteinizing hormone

D. all of the above

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.

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.

Q. Name the target tissues for prolactin.

A. The mammary glands are the target tissues for prolactin.

## Glossary

**acromegaly**
disorder in adults caused when abnormally high levels of GH trigger growth of bones in the face, hands, and feet

**adrenocorticotropic hormone (ACTH)**
anterior pituitary hormone that stimulates the adrenal cortex to secrete corticosteroid hormones (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

**gigantism**
disorder in children caused when abnormally high levels of GH prompt excessive growth

**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)

**insulin-like growth factors (IGF)**
protein that enhances cellular proliferation, inhibits apoptosis, and stimulates the cellular uptake of amino acids for protein synthesis

**luteinizing hormone (LH)**
anterior pituitary hormone that triggers ovulation and the production of ovarian hormones in females, and the production of testosterone in males

**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 males)

**pituitary dwarfism**

disorder in children caused when abnormally low levels of GH result in growth retardation

**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

## Contributors and Attributions

**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: The Thyroid Gland

**Learning Objectives**

- Describe the location and anatomy of the thyroid gland
- Identify the hormone produced by the parafollicular cells of the thyroid

A butterfly-shaped organ, the **thyroid gland** 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 are embedded with parathyroid glands, primarily on their posterior surfaces. The tissue of the thyroid gland is composed mostly of thyroid follicles. 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 hormones' essential and unique component: iodine.


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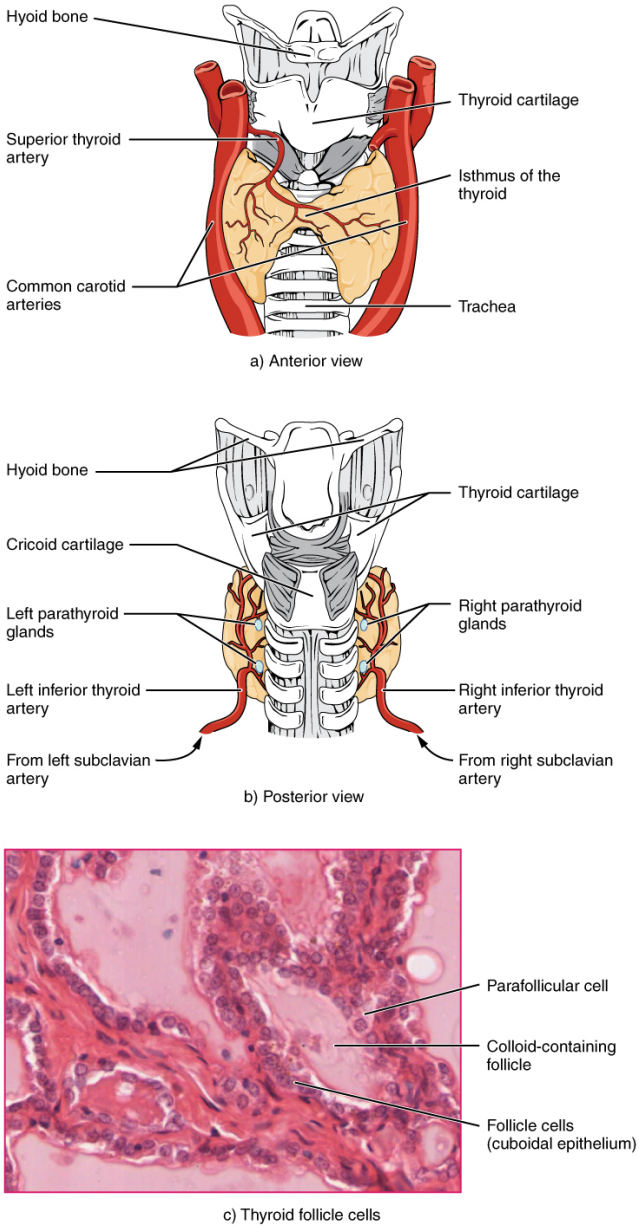



Figure **15.4.1**: Thyroid Gland. The thyroid gland is located in the neck where it wraps around the trachea. (a) Anterior view of the thyroid gland. (b) Posterior view of the thyroid gland. (c) The glandular tissue is composed primarily of thyroid follicles. The larger parafollicular cells often appear within the matrix of follicle cells. LM × 1332. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

## 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 mental retardation 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. (credit: "Almazi"/Wikimedia Commons)

In areas of the world with access to iodized salt, dietary deficiency is rare. Instead, 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 reduced mental activity. 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. The person may also develop a goiter.

## Calcitonin

The thyroid gland also secretes a hormone called **calcitonin** that is produced by the parafollicular cells (also called C cells) 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
- Increasing 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 | Chemical class | Effect |
|---|---|---|
| Thyroxine ($T_4$), triiodothyronine ($T_3$) | Amine | Stimulate basal metabolic rate |
| Calcitonin | Peptide | 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 organs involved in the regulation are the parathyroid glands.

## Chapter 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, cretinism, 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: 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: 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: C

Q. Iodide ions cross from the bloodstream into follicle cells via _____.

A. simple diffusion

B. facilitated diffusion

C. active transport

D. osmosis

Answer: C

## Critical Thinking Questions

Q. Explain why maternal iodine deficiency might lead to neurological impairment in the fetus.

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.

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: The Parathyroid Glands

**Learning Objectives**

- Describe the location and structure of the parathyroid glands
- Describe the hormonal control of blood calcium levels
- Discuss the physiological response of parathyroid dysfunction

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. The function of one type of parathyroid cells, the oxyphil cells, is not clear. The primary functional cells of the parathyroid glands are the chief cells. These epithelial cells produce and secrete the **parathyroid hormone (PTH)**, the major hormone involved in the regulation of blood calcium levels.

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.

When blood calcium levels are high, calcitonin is produced and secreted by the parafollicular cells of the thyroid gland. As discussed earlier, 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.

## Chapter 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 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: D

Q. Which of the following can result from hyperparathyroidism?

A. increased bone deposition

B. fractures

C. convulsions

D. all of the above

> Answer: B

## Critical Thinking Questions

Q. Describe the role of negative feedback in the function of the parathyroid gland.

> 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.

> 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

**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)

## Contributors and Attributions

**parathyroid hormone (PTH)**
peptide hormone produced and secreted by the parathyroid glands in response to low blood calcium levels

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# 15.6: The Adrenal Glands

**Learning Objectives**

- 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** are wedges of glandular and neuroendocrine tissue adhering to the top of the kidneys by a fibrous capsule (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.

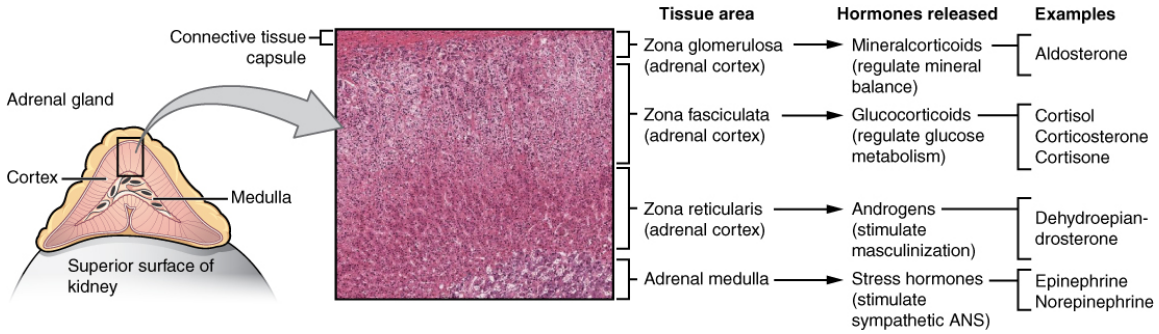



Figure 15.6.1: Adrenal Glands. Both adrenal glands sit atop the kidneys and are composed of an outer cortex and an inner medulla, all surrounded by a connective tissue capsule. The cortex can be subdivided into additional zones, all of which produce different types of hormones. LM × 204. (Micrograph 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 cortex itself is divided into three zones: the **zona glomerulosa**, the **zona fasciculata**, and the **zona reticularis**. Each region secretes its own set of hormones.

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. This pathway will be discussed in more detail below.

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 (SAM) 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 soon relieved, 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. Each of these regions produces different 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 and potassium 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. In adult women, they may contribute to the sex drive, but their function in adult men is not well understood. In post-menopausal women, 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. Derived from the amino acid tyrosine, they are chemically classified as catecholamines.

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 | Chemical class | Effect |
|---|---|---|---|
| Adrenal cortex | Aldosterone | Steroid | Increases blood $Na^+$ levels |
| Adrenal cortex | Cortisol, corticosterone, cortisone | Steroid | Increase blood glucose levels |
| Adrenal medulla | Epinephrine, norepinephrine | Amine | Stimulate fight-or-flight response |

## 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.

## Chapter 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.

## Interactive Link Questions

Visit this link to view an animation describing the location and function of the adrenal glands. Which hormone produced by the adrenal glands is responsible for mobilization of energy stores?

> Answer: Cortisol.

## 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 s not part of the fight-or-flight response?

A. pupil dilation

B. increased oxygen supply to the lungs

C. suppressed digestion

D. reduced mental activity

Answer: D

## Critical Thinking Questions

Q. What are the three regions of the adrenal cortex and what hormones do they produce?

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. If innervation to the adrenal medulla were disrupted, what would be the physiological outcome?

A. Damage to the innervation of the adrenal medulla would prevent the adrenal glands from responding to the hypothalamus during the fight-or-flight response. Therefore, the response would be reduced.

Q. Compare and contrast the short-term and long-term stress response.

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

**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: The Pineal Gland

**Learning Objectives**

- 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 amine hormone **melatonin**, which is derived from serotonin.

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.

## Chapter 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.

## Interactive Link Questions

Visit this link to view an animation describing the function of the hormone melatonin. What should you avoid doing in the middle of your sleep cycle that would lower melatonin?

Answer: Turning on the lights.

## 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.

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.

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: The Endocrine Pancreas

**Learning Objectives**

- 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 organ, most of which is located posterior to the bottom half of the stomach (Figure 15.8.1). Although it is primarily an exocrine gland, secreting a variety of digestive enzymes, the pancreas has an endocrine function. Its **pancreatic islets**—clusters of cells formerly known as the islets of Langerhans—secrete the hormones glucagon, insulin, somatostatin, and pancreatic polypeptide (PP).

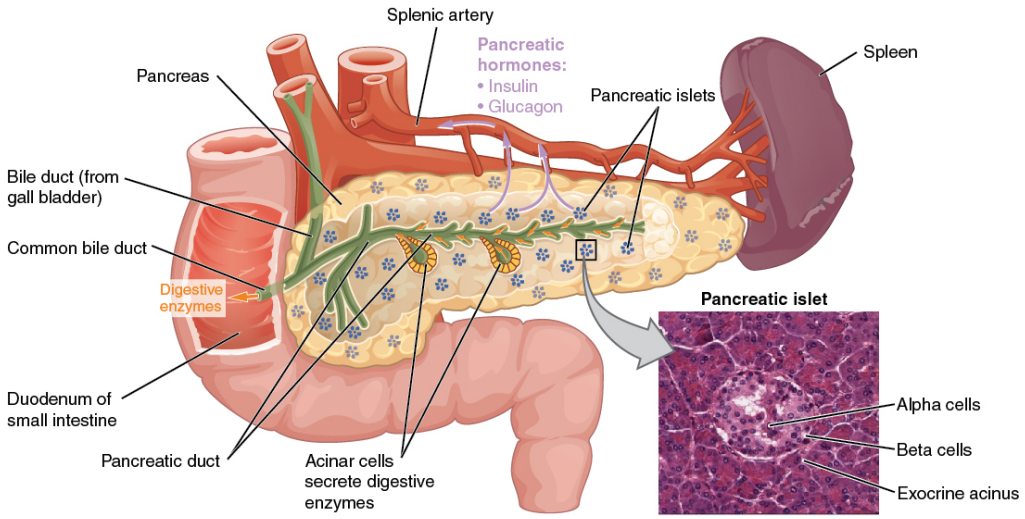



Figure 15.8.1: Pancreas. The pancreatic exocrine function involves the acinar cells secreting digestive enzymes that are transported into the small intestine by the pancreatic duct. Its endocrine function involves the secretion of insulin (produced by beta cells) and glucagon (produced by alpha cells) within the pancreatic islets. These two hormones regulate the rate of glucose metabolism in the body. The micrograph reveals pancreatic islets. LM × 760. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

## Cells and Secretions of the Pancreatic Islets

The pancreatic islets each contain four varieties of 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.

Table 1: Hormones of the Pancreas

| Associated hormones | Chemical class | Effect |
|---|---|---|
| Insulin (beta cells) | Protein | Reduces blood glucose levels |
| Glucagon (alpha cells) | Protein | Increases blood glucose levels |
| Somatostatin (delta cells) | Protein | Inhibits insulin and glucagon release |
| Pancreatic polypeptide (PP cells) | Protein | Role in appetite |

## 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.

*Visit this link to view an animation describing the role of insulin and the pancreas in diabetes.*

## Chapter 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.

## Interactive Link Questions

Visit this link to view an animation describing the location and function of the pancreas. What goes wrong in the function of insulin in type 2 diabetes?

Answer: Insulin is overproduced.

## 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: 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: B

## Critical Thinking Questions

Q. What would be the physiological consequence of a disease that destroyed the beta cells of the pancreas?

A. The beta cells produce the hormone insulin, which is important in the regulation of blood glucose levels. All insulin-dependent cells of the body require insulin in order to take up glucose from the bloodstream. Destruction of the beta cells would result in an inability to produce and secrete insulin, leading to abnormally high blood glucose levels and the disease called type 1 diabetes mellitus.

Q. Why is foot care extremely important for people with diabetes mellitus?

A. Excessive blood glucose levels damage the blood vessels and nerves of the body's extremities, increasing the risk for injury, infection, and tissue death. Loss of sensation to the feet means that a diabetic patient will not be able to feel foot trauma, such as from ill-fitting shoes. Even minor injuries commonly lead to infection, which , can progress to tissue death without proper care, requiring amputation.

## 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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# 15.9: Organs with Secondary Endocrine Functions

**Learning Objectives**

- Identify the organs with a secondary endocrine function, the hormone they produce, and its effects

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 peptide 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 and the initiation 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 adipose cells 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 adipose cells—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 other organs are summarized in Table 15.9.1.

Table 15.9.1: 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 |
| 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 |

## Chapter 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: 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: 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: 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: A

## Critical Thinking Questions

Q. Summarize the role of GI tract hormones following a meal.

A. 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, CCK stimulates the release of pancreatic digestive enzymes and bile from the gallbladder. Other GI tract hormones aid in glucose metabolism and other functions.

Q. Compare and contrast the thymus gland in infancy and adulthood.

A. 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.

## Glossary

**atrial natriuretic peptide (ANP)**

peptide hormone produced by the walls of the atria in response to high blood pressure, blood volume, or blood sodium that reduces the reabsorption of sodium and water in the kidneys and promotes vasodilation

**erythropoietin (EPO)**

protein hormone secreted in response to low oxygen levels that triggers the bone marrow to produce red blood cells

**leptin**

protein hormone secreted by adipose tissues in response to food consumption that promotes satiety

**thymosins**

hormones produced and secreted by the thymus that play an important role in the development and differentiation of T cells

**thymus**

organ that is involved in the development and maturation of T-cells and is particularly active during infancy and childhood

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# CHAPTER OVERVIEW

## 16: The Cardiovascular System - Blood

### Chapter Objectives

- 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 of platelets and explain the process of hemostasis
- Explain the significance of AB and Rh blood groups in blood transfusions
- Discuss a variety of blood disorders

16.1: Prelude to Blood
16.2: An Overview of Blood
16.3: Production of the Formed Elements
16.4: Erythrocytes
16.5: Leukocytes and Platelets

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# 16.1: Prelude to Blood

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—makes up the cardiovascular system. This chapter focuses on the medium of transport: blood.

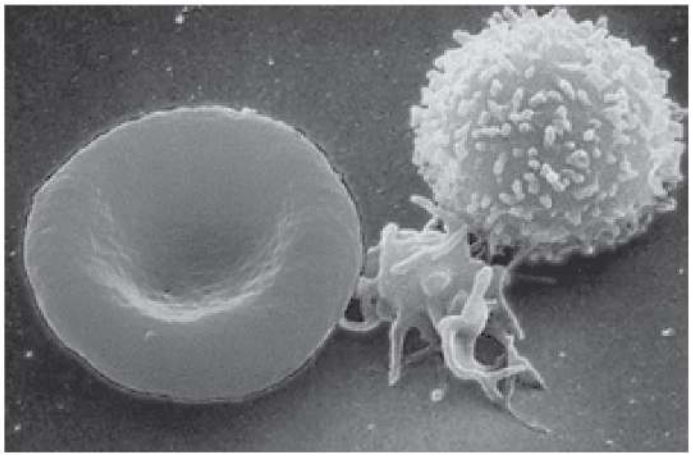


Figure 18.0.1: Blood Cells. A single drop of blood contains millions of red blood cells, white blood cells, and platelets. One of each type is shown here, isolated from a scanning electron micrograph.

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# 16.2: An Overview of Blood

**Learning Objectives**

- 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 **red blood cells (RBCs)**, **white blood cells (WBCs)**, and cell fragments called **platelets**. 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, which moves from the lungs to the heart, which then pumps it out to the rest of the body. Moreover, endocrine glands scattered throughout the body release their products, called hormones, into the bloodstream, which carries them to distant target cells. 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 WBCs protect the body from external threats, such as disease-causing bacteria that have entered the bloodstream in a wound. Other WBCs 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 the plasma, the fluid portion of the blood, interact to block the ruptured areas of the blood vessels involved. This protects the body from further blood loss.

### Maintenance of Homeostasis

Recall that 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, 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 RBCs, clinically known as erythrocytes, in a blood sample. It 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 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. These are the WBCs, clinically known as leukocytes, and the platelets, cell fragments also called thrombocytes. This layer 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, which constitutes the remainder of the sample.

The volume of erythrocytes after centrifugation 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, however, about 36–50 percent, according to gender and other factors. Normal hematocrit values for females range from 37 to 47, with a mean value of 41; for males, hematocrit ranges from 42 to 52, with a mean of 47. The percentage of other formed elements, the WBCs and platelets, is extremely small so it is not normally considered with the hematocrit. So the mean plasma percentage is the percent of blood that is not erythrocytes: for females, it is approximately 59 (or 100 minus 41), and for males, it is approximately 53 (or 100 minus 47).

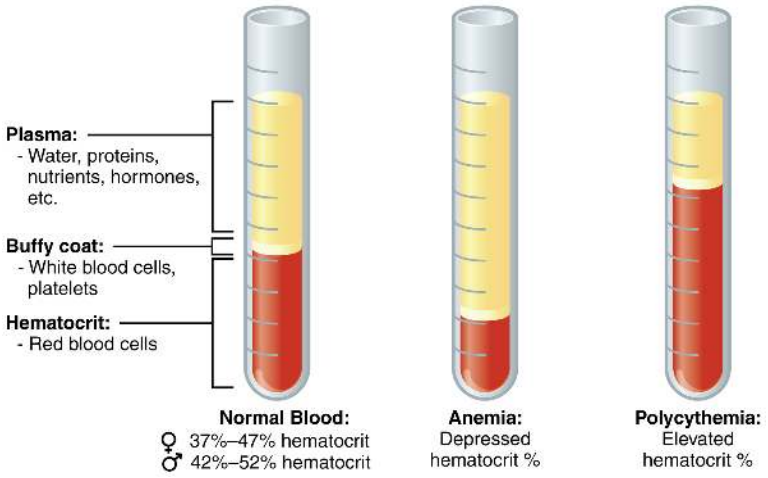



Figure **16.2.1**: Composition of Blood. The cellular elements of blood include a vast number of erythrocytes and comparatively fewer leukocytes and platelets. Plasma is the fluid in which the formed elements are suspended. A sample of blood spun in a centrifuge reveals that plasma is the lightest component. 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. Depressed and elevated hematocrit levels are shown for comparison.

## 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.

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; however, it can range from 7.35 to 7.45 in a healthy person. Blood is therefore somewhat more basic (alkaline) on a chemical scale than pure water, which has a pH of 7.0. Blood contains numerous buffers that actually

help to regulate pH.

Blood constitutes approximately 8 percent of adult body weight. Adult males typically average about 5 to 6 liters of blood. Females average 4–5 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 Figure 16.2.2.

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 fatty acids and steroid hormones. Recall that lipids are hydrophobic; however, their binding to albumin enables their transport 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, in clinical levels of 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. (Seek additional content for more information about immunoglobulins.) Globulins make up approximately 38 percent of the total plasma protein volume, in clinical levels of 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, in clinical levels of 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 nonprotein solutes combined contribute approximately 1 percent to the total volume of plasma.

| 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 | 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 | Transport gases, primarily oxygen and some carbon dioxide |
| | Leukocytes <1 percent Platelets <1 percent | Granular leukocytes: neutrophils eosinophils basophils | Red bone marrow | Nonspecific immunity |
| | | Agranular leukocytes: lymphocytes monocytes | Lymphocytes: bone marrow and lymphatic tissue | Lymphocytes: specific immunity |
| | | | Monocytes: red bone marrow | Monocytes: nonspecific immunity |
| | Platelets <1 percent | | Megakaryocytes: red bone marrow | Hemostasis |

Figure **16.2.2**: Major Blood Components.

### 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.

## Chapter 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 and 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.

## Interactive Link Questions

Visit this site for a list of normal levels established for many of the substances found in a sample of blood. Serum, one of the specimen types included, refers to a sample of plasma after clotting factors have been removed. What types of measurements are given for levels of glucose in the blood?

> Answer: There are values given for percent saturation, tension, and blood gas, and there are listings for different types of hemoglobin.

## 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: 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: 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: D

## Critical Thinking Questions

Q. A patient’s hematocrit is 42 percent. Approximately what percentage of the patient’s blood is plasma?

> 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 the formed elements as cells?

> 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.

> 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

**fibrinogen**
plasma protein produced in the liver and involved in blood clotting

**formed elements**
cellular 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

**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**
(also, thrombocytes) one of the formed elements of blood that consists of cell fragments broken off from megakaryocytes

**red blood cells (RBCs)**
(also, erythrocytes) one of the formed elements of blood that transports oxygen

## Contributors and Attributions

**white blood cells (WBCs)**
(also, leukocytes) one of the formed elements of blood that provides defense against disease agents and foreign materials

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# 16.3: Production of the Formed Elements

**Learning Objectives**

- 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 lower 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 divide and differentiate. One daughter cell remains a hemopoietic stem cell, allowing hemopoiesis to continue. The other daughter cell becomes either of two types of more specialized stem cells (Figure **16.3.1**):

- **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 monocytes and three forms of granular leukocytes: neutrophils, eosinophils, and basophils.

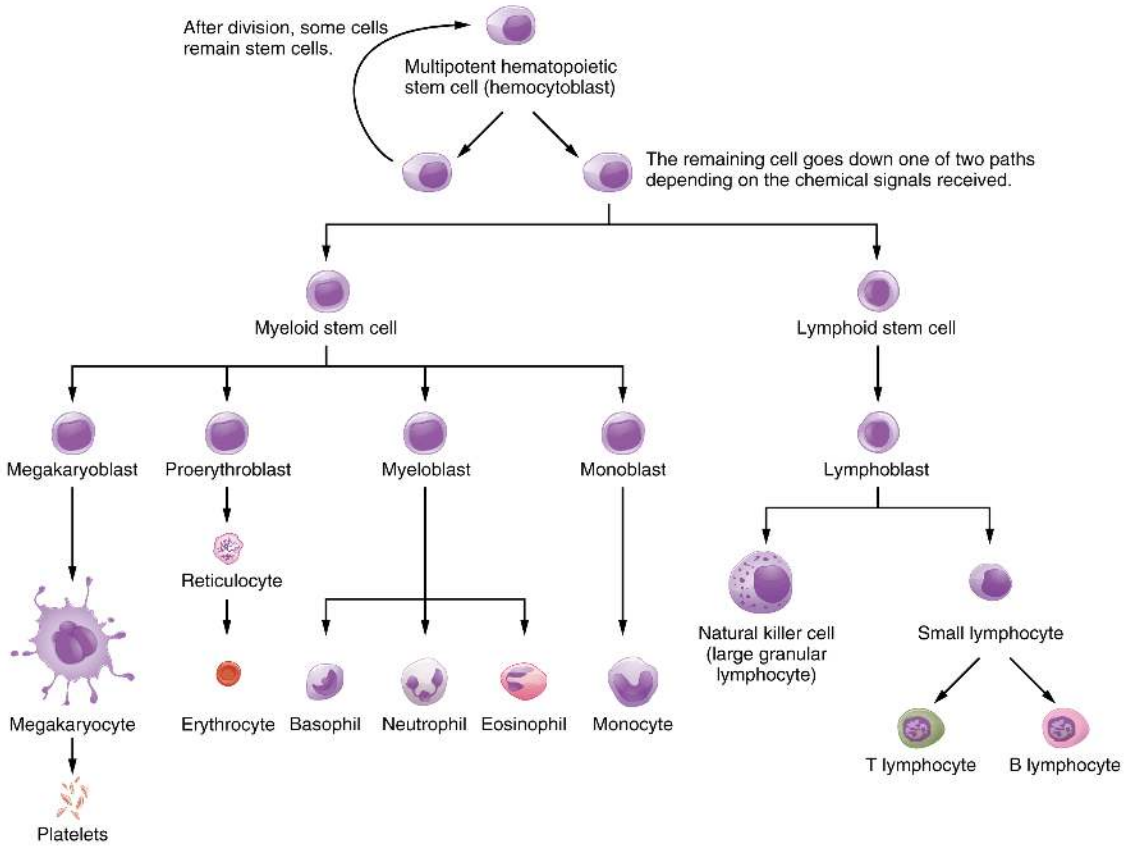



Figure **16.3.1**: Hematopoietic System of Bone Marrow. Hemopoiesis is the proliferation and differentiation of the formed elements of blood.

Lymphoid and myeloid stem cells do not immediately divide and differentiate into mature formed elements. As you can see in Figure **16.3.1**, 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.

## 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 a glycoprotein hormone 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**, another glycoprotein hormone, is produced by the liver and kidneys. It triggers the development of megakaryocytes into platelets.
- **Cytokines** are glycoproteins secreted by a wide variety of cells, including red bone marrow, leukocytes, macrophages, fibroblasts, and endothelial cells. They act locally as autocrine or paracrine factors, stimulating the proliferation of progenitor cells and helping 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 glycoproteins that act locally, as autocrine or paracrine factors. Some trigger the differentiation of myeloblasts into granular leukocytes, namely, neutrophils, eosinophils, and basophils. These are referred to as granulocyte CSFs. A different CSF induces the production of monocytes, called monocyte CSFs. Both granulocytes and monocytes are stimulated by GM-CSF; granulocytes, monocytes, platelets, and erythrocytes are stimulated by multi-CSF.

Synthetic forms of these hormones are often administered to patients with various forms of cancer who are receiving chemotherapy to revive their WBC 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.

EVERYDAY CONNECTIONS: Blood Doping

In its original intent, the term blood doping was used to describe the practice of injecting by transfusion supplemental RBCs into an individual, typically to enhance performance in a sport. Additional RBCs would deliver more oxygen to the tissues, providing extra aerobic capacity, clinically referred to as VO2 max. The source of the cells was either from the recipient (autologous) or from a donor with compatible blood (homologous). This practice was aided by the well-developed techniques of harvesting, concentrating, and freezing of the RBCs that could be later thawed and injected, yet still retain their functionality. These practices are considered illegal in virtually all sports and run the risk of infection, significantly increasing the viscosity of the blood and the potential for transmission of blood-borne pathogens if the blood was collected from another individual.

With the development of synthetic EPO in the 1980s, it became possible to provide additional RBCs by artificially stimulating RBC production in the bone marrow. Originally developed to treat patients suffering from anemia, renal failure, or cancer treatment, large quantities of EPO can be generated by recombinant DNA technology. Synthetic EPO is injected under the skin and can increase hematocrit for many weeks. It may also induce polycythemia and raise hematocrit to 70 or greater. This increased viscosity raises the resistance of the blood and forces the heart to pump more powerfully; in extreme cases, it has resulted in death. Other drugs such as cobalt II chloride have been shown to increase natural EPO gene expression. Blood doping has become problematic in many sports, especially cycling. Lance Armstrong, winner of seven Tour de France and many other cycling titles, was stripped of his victories and admitted to blood doping in 2013.

## 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 major 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.

## Chapter 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.

## Interactive Link Questions

Watch this video to see doctors discuss the dangers of blood doping in sports. What are the some potential side effects of blood doping?

> Answer: Side effects can include heart disease, stroke, pulmonary embolism, and virus transmission.

## 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: 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: 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: 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?

> 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.

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 proteins that act as autocrine or paracrine 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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# 16.4: Erythrocytes

**Learning Objectives**

- Describe the anatomy of erythrocytes
- Discuss the various steps in the lifecycle of an erythrocyte
- Explain the composition and function of hemoglobin

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 ($\mu$L) of blood, and females have approximately 4.8 million per $\mu$L. In fact, erythrocytes are estimated to make up about 25 percent of the total cells in the body. As you can imagine, they are quite small cells, with a mean diameter of only about 7–8 micrometers ($\mu$m) (Figure **16.4.1**). 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. Erythrocytes remain within the vascular network. Although leukocytes typically leave the blood vessels to perform their defensive functions, movement of erythrocytes from the blood vessels is abnormal.

| Formed element | Major subtypes | Numbers present per microliter (μL) and 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 disk; no nucleus; pale red color | Transport oxygen and some carbon dioxide between tissues and lungs | Lifespan of approximately 120 days |
| **Leukocytes (white blood cells)** | | 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 |
| | **Granulocytes including neutrophils, eosinophils, and basophils** | 4360 (1800–9950) | Abundant granules in cytoplasm; nucleus normally lobed | Nonspecific (innate) resistance to disease | Classified according to membrane-bound granules in cytoplasm |
| | 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; particularly 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 including 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 |
| | 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 (cellular immunity); B cells release antibodies (humoral immunity); natural killer cells are similar to 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 |

Figure **16.4.1**: Summary of Formed Elements in Blood.

## Shape and Structure of Erythrocytes

As an erythrocyte matures in the red bone marrow, it extrudes 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. Reticulocytes should comprise approximately 1–2 percent of the erythrocyte count and provide a rough estimate of the rate of RBC production, with abnormally low or high rates indicating deviations in the production of these cells. These remnants, primarily of networks (reticulum) of ribosomes, are quickly shed, however, and mature, circulating erythrocytes have few internal cellular structural components. Lacking mitochondria, for example, they rely on anaerobic respiration. This means that they do not utilize any of the oxygen they are transporting, so they can deliver it all to the tissues. They also lack endoplasmic reticula and do not synthesize proteins. Erythrocytes do, however, contain some structural proteins that help the blood cells maintain their unique

structure and enable them to change their shape to squeeze through capillaries. This includes the protein spectrin, a cytoskeletal protein element.

Erythrocytes are biconcave disks; that is, they are plump at their periphery and very thin in the center (Figure **16.4.2**). Since they lack most organelles, there is more interior space for the presence of the hemoglobin molecules that, as you will see shortly, 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.”

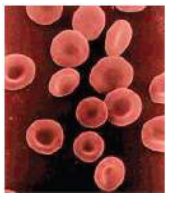


Figure **16.4.2**: Shape of Red Blood Cells. Erythrocytes are biconcave discs with very shallow centers. This shape optimizes the ratio of surface area to volume, facilitating gas exchange. It also enables them to fold up as they move through narrow blood vessels.

## 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 1 and 2, and beta 1 and 2 (Figure18.3.3.a). Each of these globin molecules is bound to a red pigment molecule called **heme**, which contains an ion of iron ($Fe^{2+}$) (Figure18.3.3.b).

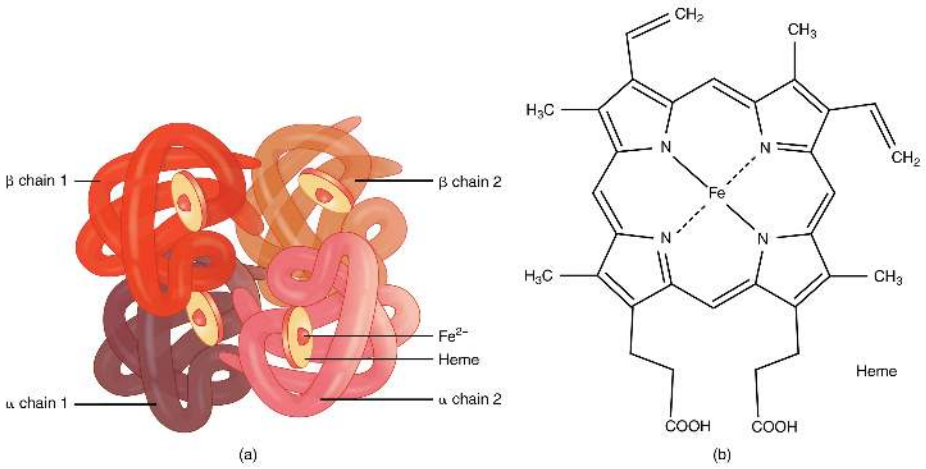



Figure **16.4.3**: Hemoglobin. (a) A molecule of hemoglobin contains four globin proteins, each of which is bound to one molecule of the iron-containing pigment heme. (b) A single erythrocyte can contain 300 million hemoglobin molecules, and thus more than 1 billion oxygen molecules.

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 (see Figure **16.4.3**.b).

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 ion. 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.

Changes in the levels of RBCs can have significant effects on the body's ability to effectively deliver oxygen to the tissues. Ineffective hematopoiesis results in insufficient numbers of RBCs and results in one of several forms of anemia. An overproduction of RBCs 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.

In patients with insufficient hemoglobin, the tissues may not receive sufficient oxygen, resulting in another form of anemia. 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. Clinically this value is commonly referred to simply as "percent sat."

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 volume, and thus serve as ideal sites for receptors that determine oxygen saturation. 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 within the kidney secrete EPO, thereby increasing erythrocyte production and restoring 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.

## Disorders of Erythrocytes

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 number of RBCs or hemoglobin is deficient, 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. Anemia can be broken down into three major groups: those caused by blood loss, those caused by faulty or decreased RBC production, and those caused by excessive destruction of RBCs. Clinicians often use two groupings in diagnosis: The kinetic approach focuses on evaluating the production, destruction, and removal of RBCs, whereas the morphological approach examines the RBCs themselves, paying particular emphasis to their size. 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 RBCs. The effects of the various anemias are widespread, because reduced numbers of RBCs 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 nonsteroidal anti-inflammatory drugs 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 RBC production include sickle cell anemia, iron deficiency anemia, vitamin deficiency anemia, and diseases of the 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 **16.4.5**). 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 **16.4.5**: 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. (credit: Janice Haney Carr)

- 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 B12 and folate.
  - Megaloblastic anemia involves a deficiency of vitamin B12 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 B12 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 RBCs and hemoglobin. If myeloid stem cells are defective or replaced by cancer cells, there will be insufficient quantities of RBCs produced.
  - Aplastic anemia is the condition in which there are deficient numbers of RBC stem cells. 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 RBCs 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 RBC 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 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 elderly patients those over 60 years of age.

## Chapter Review

The most abundant formed elements in blood, erythrocytes are red, biconcave disks 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 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 RBCs or hemoglobin, whereas polycythemia is an excess of RBCs.

## 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: 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: 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: D

Q. Aging and damaged erythrocytes are removed from the circulation by _____.

A. myeoblasts

B. monocytes

C. macrophages

D. mast cells

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: 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?

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.

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

**ferritin**
protein-containing storage form of iron found in the bone marrow, liver, and spleen

**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

**hemosiderin**
protein-containing storage form of iron found in the bone marrow, liver, and spleen

**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 RBCs that take on a characteristic sickle shape

**thalassemia**
inherited blood disorder in which maturation of RBCs does not proceed normally, leading to abnormal formation of hemoglobin and the destruction of RBCs

## Contributors and Attributions

**transferrin**
plasma protein that binds reversibly to iron and distributes it throughout the body

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# 16.5: Leukocytes and Platelets

**Learning Objectives**

- 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

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. Platelets are essential for the repair of blood vessels when damage to them has occurred; they also provide growth factors for healing and repair. See [link] for a summary of leukocytes and platelets.

## Characteristics of Leukocytes

Although leukocytes and erythrocytes both originate from hematopoietic stem cells in the 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 $\mu$L. They are also larger than erythrocytes and are the only formed elements that are complete cells, possessing a nucleus and organelles. And 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 simply a highway they travel and soon exit to reach their true destination. When they arrive, they are often given distinct names, such as macrophage or microglia, depending on their function. As shown in Figure **16.5.1**, 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 fixed positions in lymphatic tissue, bone marrow, the spleen, the thymus, or other organs. Others will move about through the tissue spaces very much like amoebas, 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.

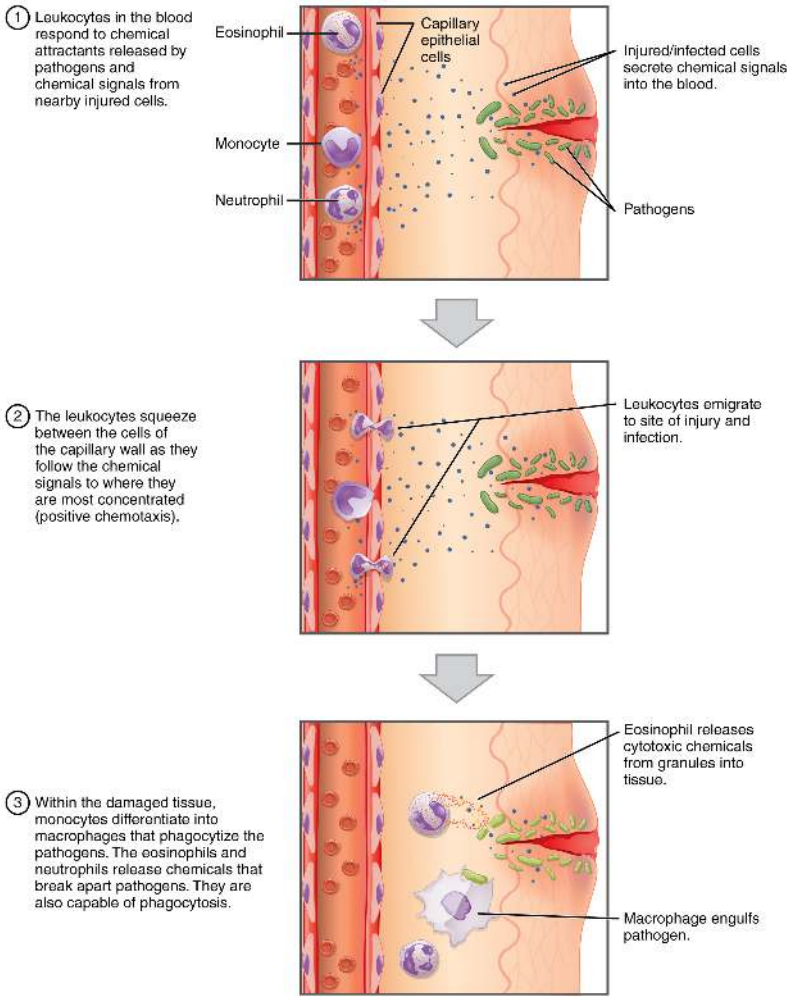



Figure 16.5.1: Emigration. Leukocytes exit the blood vessel and then move through the connective tissue of the dermis toward the site of a wound. Some leukocytes, such as the eosinophil and neutrophil, are characterized as granular leukocytes. They release chemicals from their granules that destroy pathogens; they are also capable of phagocytosis. The monocyte, an agranular leukocyte, differentiates into a macrophage that then phagocytizes the pathogens.

## 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** contain abundant granules within the cytoplasm. They include neutrophils, eosinophils, and basophils (you can view their lineage from myeloid stem cells in [link]).
- While granules are not totally lacking in **agranular leukocytes**, they are far fewer and less obvious. Agranular leukocytes include monocytes, which mature into macrophages that are phagocytic, and lymphocytes, which arise from the lymphoid stem cell line.

### Granular Leukocytes

We will consider the granular leukocytes 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 16.5.2).

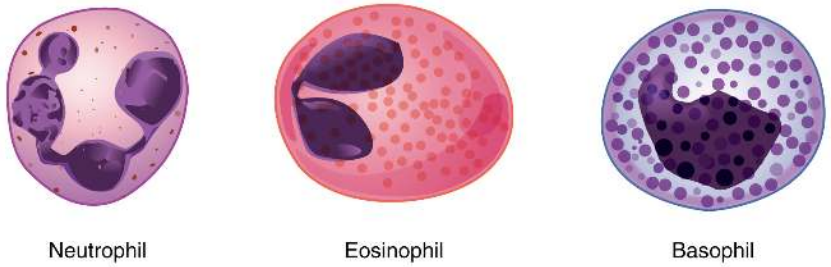



Figure **16.5.2**: Granular Leukocytes. A neutrophil has small granules that stain light lilac and a nucleus with two to five lobes. An eosinophil's granules are slightly larger and stain reddish-orange, and its nucleus has two to three lobes. A basophil has large granules that stain dark blue to purple and a two-lobed nucleus.

The most common of all the leukocytes, **neutrophils** will normally comprise 50–70 percent of total leukocyte count. They are 10–12 $\mu$m 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 **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 total leukocyte count. They are also 10–12 $\mu$m 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 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 when antibodies bind to the target and form an antigen-antibody complex. High counts of eosinophils are typical of patients experiencing allergies, parasitic worm infestations, and some autoimmune diseases. 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 $\mu$m 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. 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 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 (see [link]).

**Lymphocytes** are the only formed element of blood that arises from lymphoid stem cells. Although they form initially in the 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 essential for 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 $\mu$m and have a smaller nucleus-to-cytoplasm ratio and more granules. The smaller cells are typically 6–9 $\mu$m with a larger volume of nucleus to cytoplasm, creating a "halo" effect. A few cells may fall outside these ranges, at 14–17 $\mu$m. 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 "nonself" cells include 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. 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 live for many years. B cells undergo a maturation process in the bone marrow, whereas T cells undergo maturation in the 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, although 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 $\mu$m and indented or horseshoe-shaped nuclei. Macrophages are monocytes that have left the circulation and 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 occupy fixed locations, whereas others wander through the tissue fluid.

Abnormally high counts of monocytes are associated with viral or fungal infections, tuberculosis, and some forms of leukemia and other chronic diseases. Abnormally low counts are typically caused by suppression of the bone marrow.

## Disorders of 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

You may occasionally see platelets referred to as **thrombocytes**, but because this name suggests they are a type of cell, it is not accurate. 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 [link]) and are large, typically 50–100 $\mu$m in diameter, and contain an enlarged, lobed nucleus. As noted earlier, thrombopoietin, a glycoprotein secreted by the kidneys and liver, stimulates the proliferation of megakaryoblasts, which mature into megakaryocytes. These remain within bone marrow tissue (Figure **16.5.3**) 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 megakaryocyte releases 2000–3000 platelets during its lifespan. Following platelet release, megakaryocyte remnants, which are little more than a cell nucleus, are consumed by macrophages.

Platelets are relatively small, 2–4 $\mu$m in diameter, but numerous, with typically 150,000–160,000 per $\mu$L of blood. 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. 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. They 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.

## Disorders of 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.

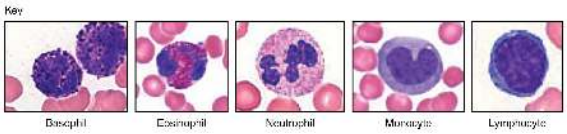



Figure **16.5.4**: Leukocytes. (Micrographs provided by the Regents of University of Michigan Medical School © 2012)

View University of Michigan Webscopes at histology.med.umich.edu/medic...nd-bone-marrow and explore the blood slides in greater detail. The Webscope feature allows you to move the slides as you would with a mechanical stage. You can increase and decrease the magnification. There is a chance to review each of the leukocytes individually after you have attempted to identify them from the first two blood smears. In addition, there are a few multiple choice questions.

Are you able to recognize and identify the various formed elements? You will need to do this is a systematic manner, scanning along the image. The standard method is to use a grid, but this is not possible with this resource. Try constructing a simple table with each leukocyte type and then making a mark for each cell type you identify. Attempt to classify at least 50 and perhaps as many as 100 different cells. Based on the percentage of cells that you count, do the numbers represent a normal blood smear or does something appear to be abnormal?

## Chapter 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 with myeloid stem cells, as do the agranular monocytes. The other agranular leukocytes, NK cells, B cells, and T cells, 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.

## Interactive Link Questions

Figure Are you able to recognize and identify the various formed elements? You will need to do this is a systematic manner, scanning along the image. The standard method is to use a grid, but this is not possible with this resource. Try constructing a simple

table with each leukocyte type and then making a mark for each cell type you identify. Attempt to classify at least 50 and perhaps as many as 100 different cells. Based on the percentage of cells that you count, do the numbers represent a normal blood smear or does something appear to be abnormal?

Answer: Figure This should appear to be a normal blood smear.

## 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: 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: 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: 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: A

Q. Thrombocytes are more accurately called _____.

A. clotting factors

B. megakaryoblasts

C. megakaryocytes

D. platelets

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?

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?

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

**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

**granular leukocytes**
leukocytes with abundant granules in their cytoplasm; specifically, neutrophils, eosinophils, and basophils

**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

**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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# CHAPTER OVERVIEW

## 17: The Cardiovascular System - The Heart

### Chapter Objectives

- Identify and describe the interior and exterior parts of the human heart
- Describe the path of blood through the cardiac circuits
- Describe the size, shape, and location of the heart
- Compare cardiac muscle to skeletal and smooth muscle
- Explain the cardiac conduction system
- Describe the process and purpose of an electrocardiogram
- Explain the cardiac cycle
- Calculate cardiac output
- Describe the effects of exercise on cardiac output and heart rate
- Name the centers of the brain that control heart rate and describe their function
- Identify other factors affecting heart rate
- Describe fetal heart development

In this chapter, you will explore the remarkable pump that propels the blood into the vessels. There is no single better word to describe the function of the heart other than “pump,” since its contraction develops the pressure that ejects blood into the major vessels: the aorta and pulmonary trunk. From these vessels, the 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.

17.1: Prelude to The Heart
17.2: Heart Anatomy
17.3: Cardiac Muscle

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# 17.1: Prelude to The Heart

In this chapter, you will explore the remarkable pump that propels the blood into the vessels. There is no single better word to describe the function of the heart other than “pump,” since its contraction develops the pressure that ejects blood into the major vessels: the aorta and pulmonary trunk. From these vessels, the 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. (credit: Patrick J. Lynch)

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# 17.2: Heart Anatomy

**Learning Objectives**

- 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
- Relate the structure of the heart to its function as a pump
- Compare systemic circulation to pulmonary circulation
- Identify the veins and arteries of the coronary circulation system
- Trace the pathway of oxygenated and deoxygenated blood thorough 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 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. In order to understand how that happens, it is necessary to understand the anatomy and physiology of the heart.

## Location of the Heart

The human heart is located within the thoracic cavity, medially between the lungs in the space known as the mediastinum. 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 by a tough membrane known as the pericardium, or pericardial sac, and sits in its own space called the **pericardial cavity**. 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 right side of the heart is deflected anteriorly, and the left side is deflected posteriorly. 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**.

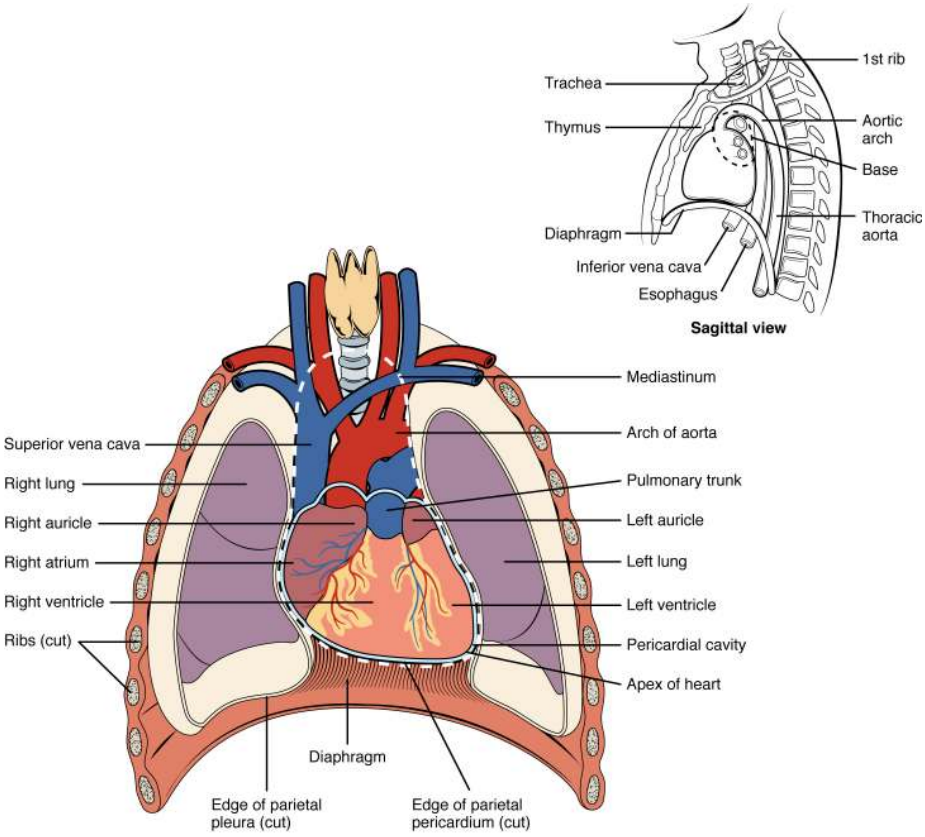



Figure **17.2.1**: Position of the Heart in the Thorax. The heart is located within the thoracic cavity, medially between the lungs in the mediastinum. It is about the size of a fist, is broad at the top, and tapers toward the base.

## EVERYDAY CONNECTION: CPR

The position of the heart in the torso between the vertebrae and sternum (see Figure **17.2.2** 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. By applying pressure with the flat portion of one hand on the sternum in the area between the line at T4 and T9 (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.

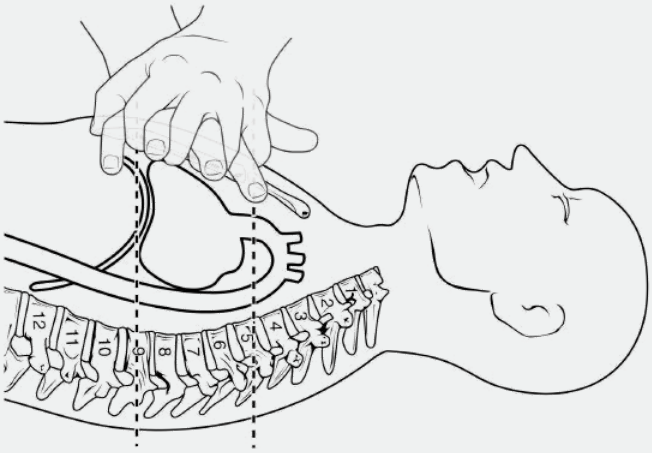


Figure **17.2.2**: CPR Technique. If the heart should stop, CPR can maintain the flow of blood until the heart resumes beating. By applying pressure to the sternum, the blood within the heart will be squeezed out of the heart and into the circulation. Proper positioning of the hands on the sternum to perform CPR would be between the lines at T4 and T9.

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 website 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 nonathletes. 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 the condition 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 (plural = atria) and the left atrium, 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 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 leads toward the lungs and bifurcates into the left and right **pulmonary arteries**. These vessels in turn branch many times 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 left atrium, which pumps the blood into the left ventricle, which in turn pumps oxygenated blood into the aorta and on to the many branches of the systemic circuit. Eventually, these vessels will lead to the 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 to 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**).

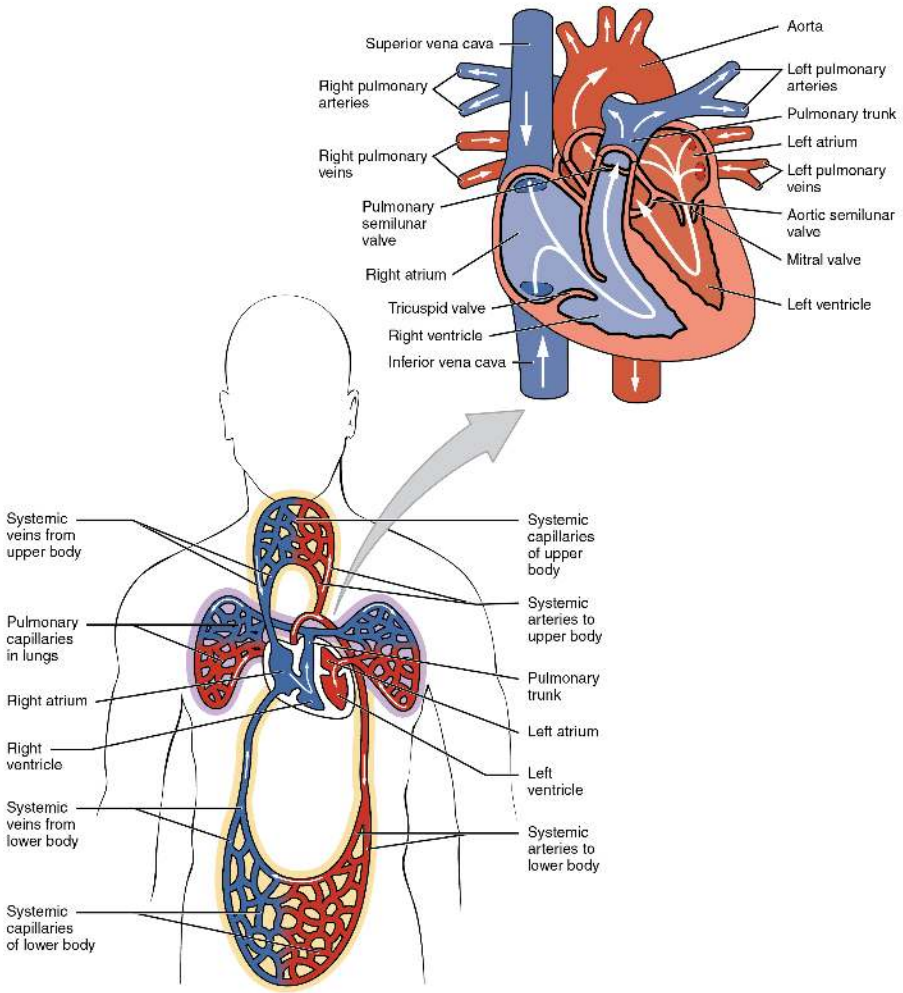



Figure **17.2.3**: Dual System of the Human Blood Circulation. Blood flows from the right atrium to the right ventricle, where it is pumped into the pulmonary circuit. The blood in the pulmonary artery branches is low in oxygen but relatively high in carbon dioxide. Gas exchange occurs in the pulmonary 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.

## 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 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 connective tissue that protects the heart and maintains its position in the thorax. 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 pericardium.

In most organs within the body, visceral serous membranes such as the epicardium are microscopic. However, in the case of the heart, it is not a microscopic layer but rather a macroscopic layer, consisting of a simple squamous epithelium called a

**mesothelium**, reinforced with loose, irregular, or areolar connective tissue that attaches to the pericardium. This 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.

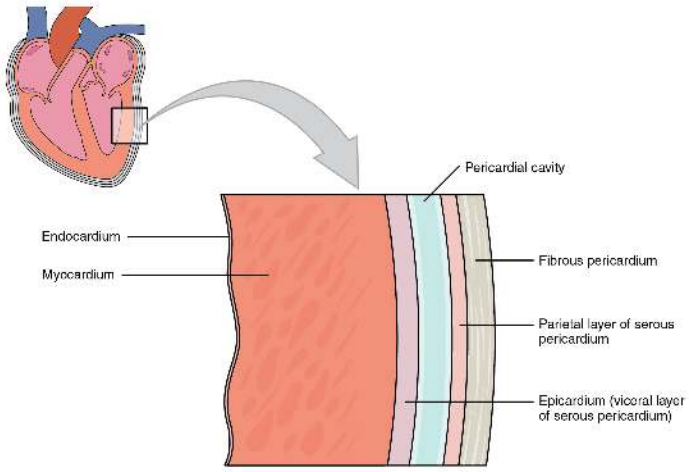



Figure **17.2.4**: Pericardial Membranes and Layers of the Heart Wall. The pericardial membrane that surrounds the heart consists of three layers and the pericardial cavity. The heart wall also consists of three layers. The pericardial membrane and the heart wall share the epicardium.

### 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 the atria near the superior surface of the heart, one on each side, called an **auricle**—a name that means “ear like”—because its shape resembles the external ear of a human (Figure). 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 is a series of fat-filled grooves, each of which is known as a **sulcus** (plural = sulci), along the superior surfaces of the heart. 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.

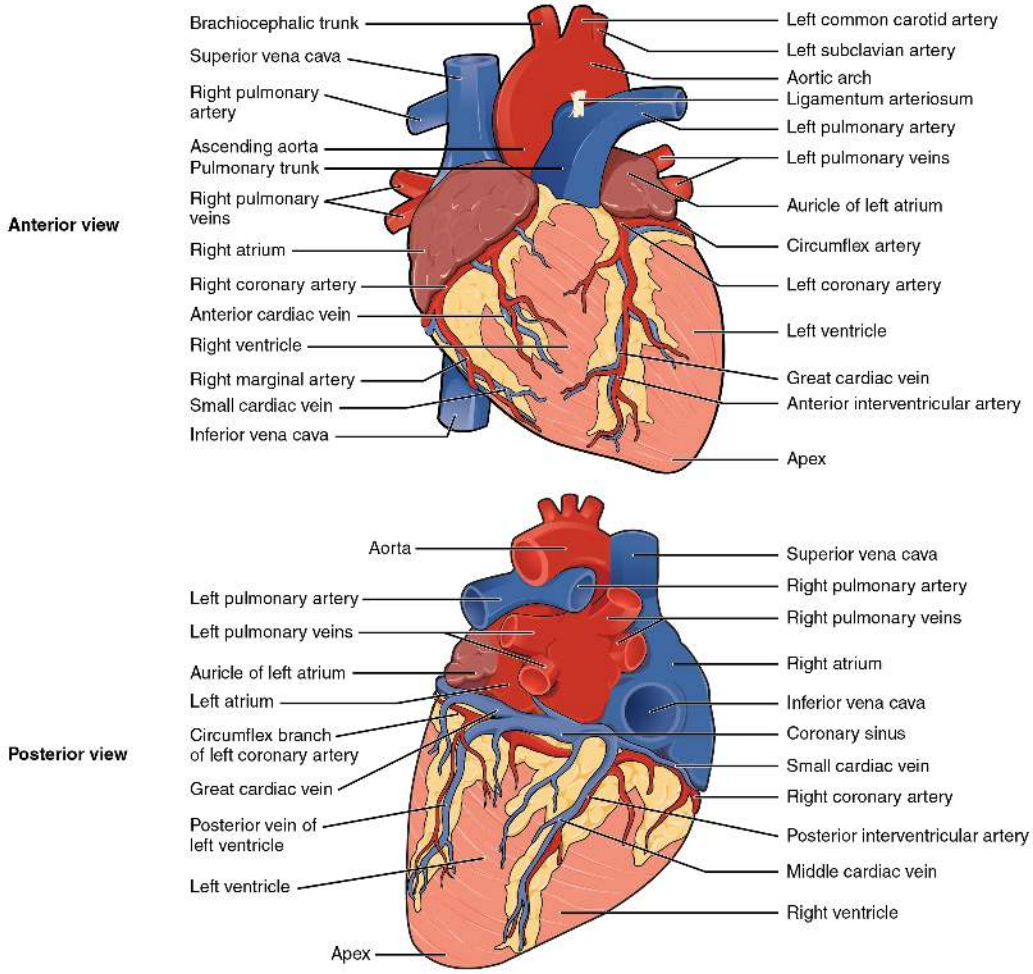



Figure **17.2.5**: External Anatomy of the Heart. Inside the pericardium, the surface features of the heart are visible.

## 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. It is built upon a framework of collagenous fibers, plus the blood vessels that supply the myocardium and the nerve fibers that help regulate the heart. 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 around the chambers of the heart. They form a figure 8 pattern around the atria and around the bases 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 than a simple linear pattern would. Figure **17.2.6** illustrates the arrangement of muscle cells.

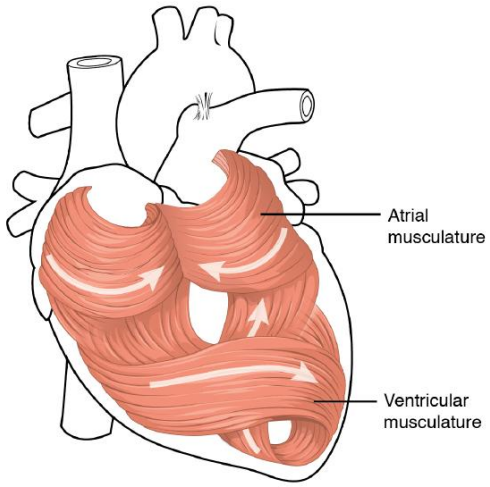



Figure **17.2.6**: Heart Musculature. The swirling pattern of cardiac muscle tissue contributes significantly to the heart's ability to pump blood effectively.

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.

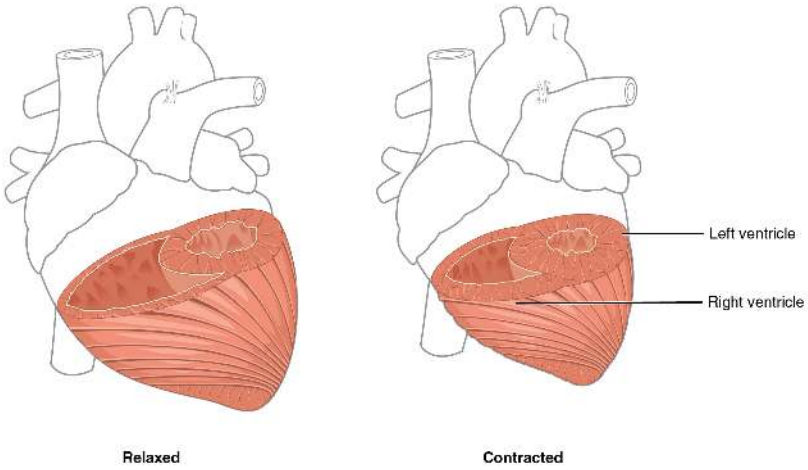



Figure **17.2.7**: Differences in Ventricular Muscle Thickness. The myocardium in the left ventricle is significantly thicker than that of the right ventricle. Both ventricles pump the same amount of blood, but the left ventricle must generate a much greater pressure to overcome greater resistance in 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.

The innermost layer of the heart wall, the **endocardium**, is joined to the myocardium with a thin layer of 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**).

Once regarded as a simple lining layer, recent evidence indicates that the endothelium of the endocardium and the coronary capillaries may play active roles in regulating the contraction of the muscle within the myocardium. The endothelium may also regulate the growth patterns of the cardiac muscle cells throughout life, and the endothelins it secretes create an environment in the surrounding tissue fluids that regulates ionic concentrations and states of contractility. Endothelins are potent vasoconstrictors and, in a normal individual, establish a homeostatic balance with other vasoconstrictors and vasodilators.

## Internal Structure 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.

### 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 bicupid and tricuspid valves; the interatrial septum is not visible, since its location is covered by the aorta and pulmonary trunk. Since these openings and valves structurally weaken the atrioventricular septum, the remaining tissue is heavily reinforced with dense connective tissue called 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 an important boundary in the heart electrical conduction system.

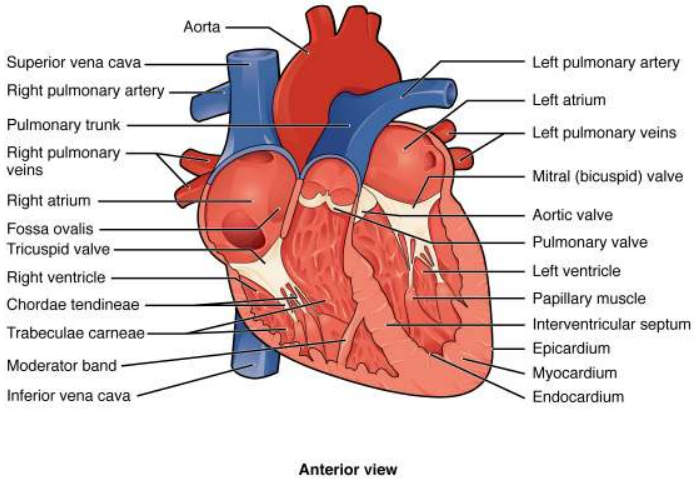



Figure 17.2.8: Internal Structures of the Heart. This anterior view of the heart shows the four chambers, the major vessels and their early branches, as well as the valves. The presence of the pulmonary trunk and aorta covers the interatrial septum, and the atrioventricular septum is cut away to show the atrioventricular valves.

### 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 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, the remnant of the fetal shunt called the ductus arteriosus. If severe, this condition drastically restricts blood flow through the 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**.

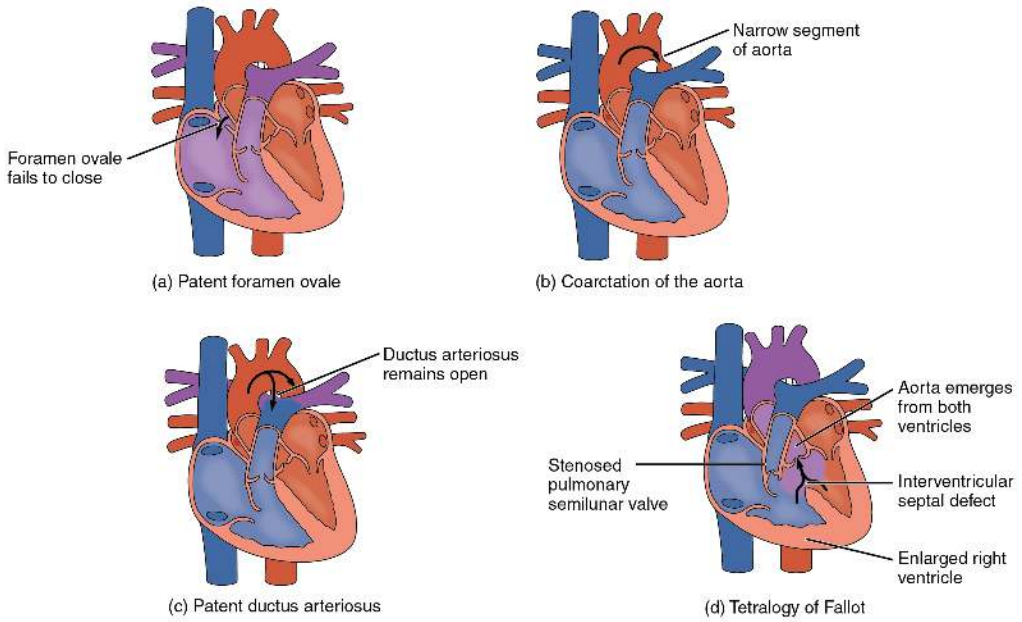



Figure 17.2.9: Congenital Heart Defects. (a) A patent foramen ovale defect is an abnormal opening in the interatrial septum, or more commonly, a failure of the foramen ovale to close. (b) Coarctation of the aorta is an abnormal narrowing of the aorta. (c) A patent ductus arteriosus is the failure of the ductus arteriosus to close. (d) Tetralogy of Fallot includes an abnormal opening in the interventricular septum.

## 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** that drains the heart myocardium 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. 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**. 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, preventing venous flow from stopping 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 atrium and 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** that extends from the inferior ventricular surface. 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 papillary muscles also contract, 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 17.2.10 shows papillary muscles and chordae tendineae attached to the tricuspid valve.

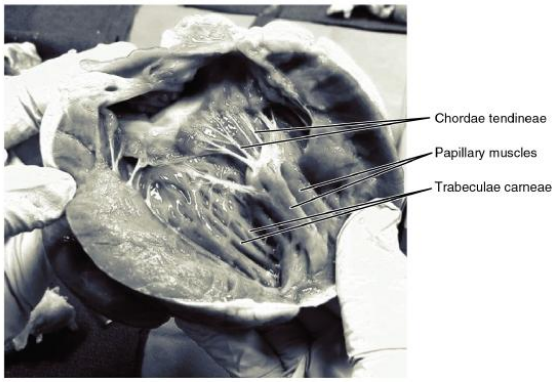



Figure 17.2.10: Chordae Tendineae and Papillary Muscles. In this frontal section, you can see papillary muscles attached to the tricuspid valve on the right as well as the mitral valve on the left via chordae tendineae. (credit: modification of work by "PV KS"/flickr.com)

The walls of the ventricle are lined with **trabeculae carneae**, ridges of cardiac muscle covered by endocardium. 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 it 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.

### Left Atrium

After exchange of gases in the pulmonary capillaries, blood returns to the left atrium high in oxygen via one of the four pulmonary veins. While the left atrium does not contain pectinate muscles, it does have an auricle that includes these 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 opening 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 on the left—the anterior and posterior—as opposed to three on the right.

The left ventricle is the major pumping chamber for the systemic circuit; it ejects blood into the aorta through the aortic semilunar valve.

### 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 17.2.11). 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 connective tissue. The flaps are connected by chordae tendineae to the papillary muscles, which control the opening and closing of the valves.

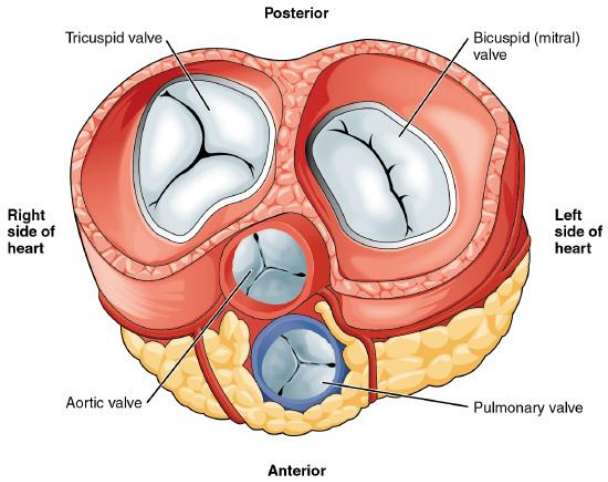



Figure **17.2.11**: Heart Valves. With the atria and major vessels removed, all four valves are clearly visible, although it is difficult to distinguish the three separate cusps of the tricuspid valve.

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 or the right semilunar valve. The pulmonary valve is comprised of three small flaps of endothelium reinforced with connective tissue. When the ventricle relaxes, the pressure differential causes blood to flow back into the ventricle from the pulmonary trunk. This flow of blood fills the pocket-like flaps of the pulmonary valve, causing the valve to close and producing an audible sound. Unlike the atrioventricular valves, there are no papillary muscles or chordae tendineae associated with the pulmonary valve.

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**. Structurally, this valve consists of two cusps, known as the anterior medial cusp and the posterior medial cusp, compared to the three cusps of the tricuspid valve. In a clinical setting, the valve is referred to as the mitral valve, rather than the bicuspid valve. The two cusps of the mitral valve are attached by chordae tendineae to two papillary muscles that project from the wall of the ventricle.

At the base of the aorta is the aortic semilunar valve, or the **aortic valve**, which prevents backflow from the aorta. It normally is composed of three flaps. When the ventricle relaxes and blood attempts to flow back into the ventricle from the aorta, blood will fill the cusps of the valve, causing it to close and producing an audible sound.

In Figure19.1.12.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. Figure19.1.12.b shows a frontal view. Although only the left side of the heart is illustrated, the process is virtually identical on the right.

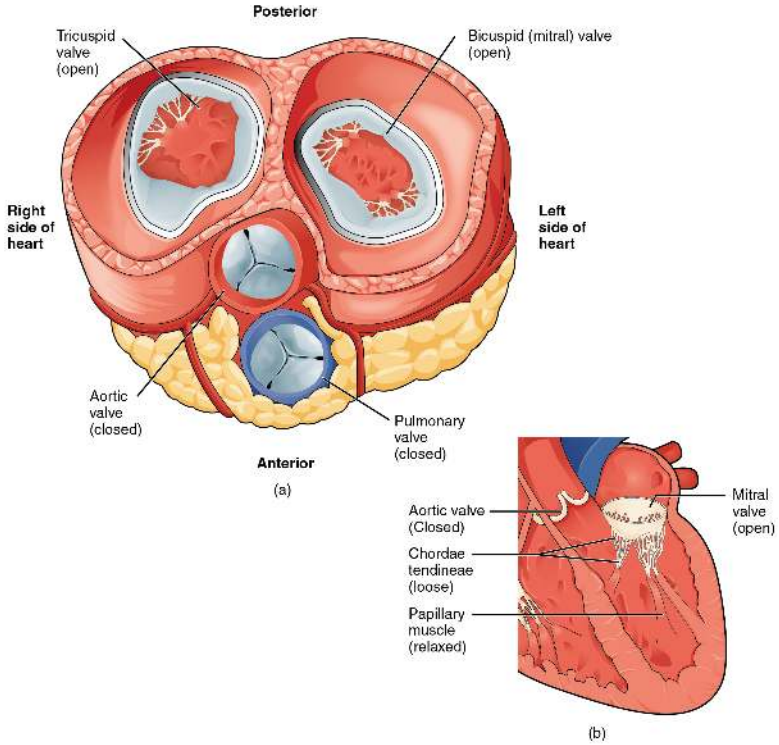



Figure **17.2.12**: Blood Flow from the Left Atrium to the Left Ventricle. (a) A transverse section through the heart illustrates the four heart valves. The two atrioventricular valves are open; the two semilunar valves are closed. The atria and vessels have been removed. (b) A frontal section through 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.

Figure **17.2.13**.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 Figure19.1.13.b.

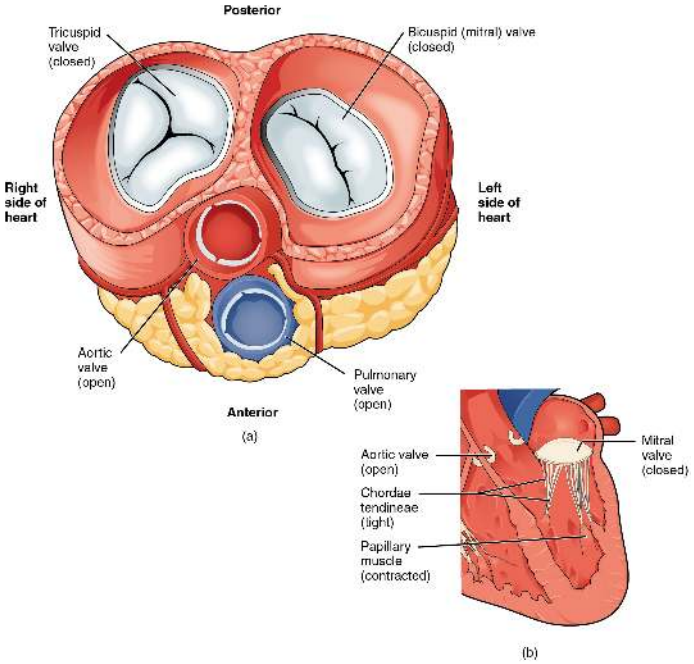



Figure **17.2.13**: Blood Flow from the Left Ventricle into the Great Vessels. (a) A transverse section through the heart illustrates the four heart valves during ventricular contraction. The two atrioventricular valves are closed, but the two semilunar valves are open. The atria and vessels have been 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.

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 backflow causes the cusps of the tricuspid and mitral (bicuspid) valves to close. These valves are tied down to the papillary muscles by chordae tendineae. 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 **17.2.12**.b). However, as the myocardium of the ventricle contracts, so do the papillary muscles. This creates tension on the chordae tendineae (see Figure19.1.13.b), helping to hold the cusps of the atrioventricular valves in place and preventing them from being blown back into the atria.

The aortic and pulmonary semilunar valves lack the chordae tendineae and papillary muscles associated with the atrioventricular valves. Instead, they consist of pocket-like folds of endocardium reinforced with additional connective tissue. When the ventricles relax and the change in pressure forces the blood toward the ventricles, the blood presses against these cusps and seals the openings.

QR Code representing a URL

*Visit this site to observe an echocardiogram of actual heart valves opening and closing. 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?*

## 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.

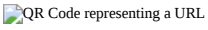



*Visit this site for a free download, including excellent animations and audio of heart sounds.*

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.




*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 $49,410 as of May 2010, according to the U.S. Bureau of Labor Statistics. Growth within the field is fast, projected at 29 percent from 2010 to 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).

QR Code representing a URL

*Visit this site for more information on cardiovascular technologists/technicians.*

## Coronary Circulation

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 artery 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. The **circumflex artery** arises from the left coronary artery and follows the coronary sulcus to the left. Eventually, it will fuse with the small branches of the right coronary artery. The larger **anterior interventricular artery**, also known as the left anterior descending artery (LAD), is the second major branch arising from the left coronary artery. It 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 heart conduction 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 gives rise to 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 interventricular septum and portions of both ventricles. Figure **17.2.14** presents views of the coronary circulation from both the anterior and posterior views.

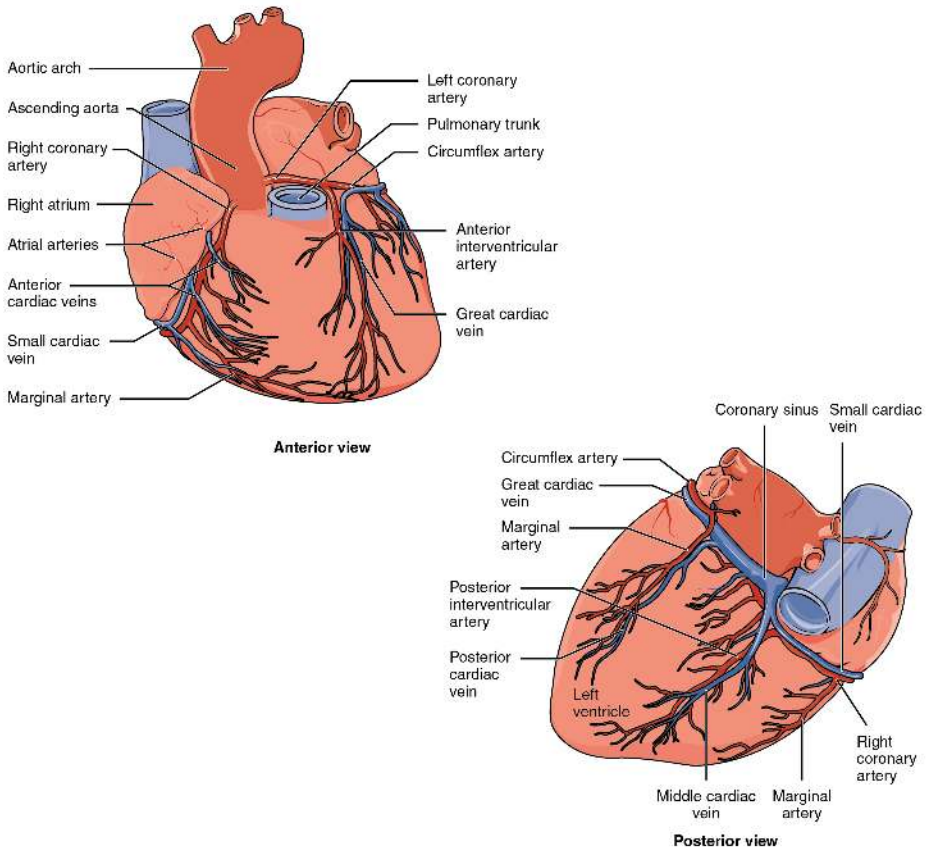



Figure **17.2.14**: Coronary Circulation. The anterior view of the heart shows the prominent coronary surface vessels. The posterior view of the heart shows the prominent coronary surface vessels.

## DISEASES 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 (palpations), 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 **17.2.14**). 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.

### DISEASES 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 **17.2.15** 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.

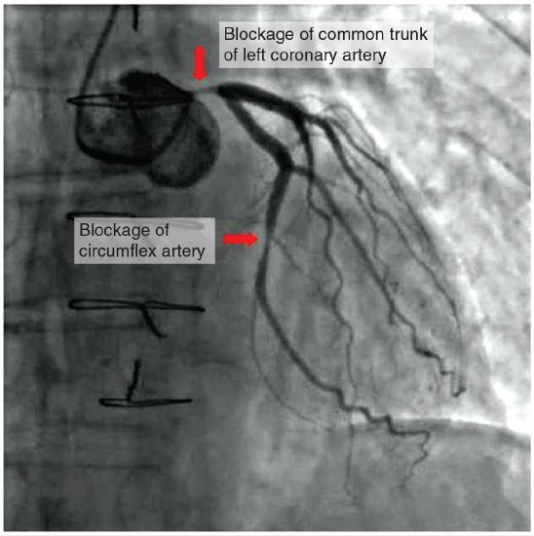



Figure **17.2.15**: Atherosclerotic Coronary Arteries. In this coronary angiogram (X-ray), the dye makes visible two occluded coronary arteries. Such blockages can lead to decreased blood flow (ischemia) and insufficient oxygen (hypoxia) delivered to the cardiac tissues. If uncorrected, this can lead to cardiac muscle death (myocardial infarction).

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.

## Chapter 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 capsule and an inner parietal pericardium lined with a 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 valve is located at the base of the pulmonary trunk, and the left semilunar valve is located at the base of the aorta. 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.

## Interactive Link Questions

Visit this site to observe an echocardiogram of actual heart valves opening and closing. 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: 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.

## 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. endocardium

> 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 _____ layer secretes chemicals that help to regulate ionic environments and strength of contraction and serve as powerful vasoconstrictors.

A. pericardial sac

B. endocardium

C. myocardium

D. epicardium

Answer: B

Q. The myocardium would be the thickest in the _____.

A. left atrium

B. left ventricle

C. right atrium

D. right ventricle

Answer: B

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 how the valves keep the blood moving in one direction.

A. When the ventricles contract and pressure begins to rise in the ventricles, there is an initial tendency for blood to flow back (regurgitate) to the atria. However, the papillary muscles also contract, placing tension on the chordae tendineae and holding the atrioventricular valves (tricuspid and mitral) in place to prevent the valves from prolapsing and being forced back into the atria. The semilunar valves (pulmonary and aortic) lack chordae tendineae and papillary muscles, but do not face the same pressure gradients as do the atrioventricular valves. As the ventricles relax and pressure drops within the ventricles, there is a tendency for the blood to flow backward. However, the valves, consisting of reinforced endothelium and connective tissue, fill with blood and seal off the opening preventing the return of blood.

Q. Why is the pressure in the pulmonary circulation lower than in the systemic circulation?

A. The pulmonary circuit consists of blood flowing to and from the lungs, whereas the systemic circuit carries blood to and from the entire body. The systemic circuit is far more extensive, consisting of far more vessels and offers much greater resistance to the flow of blood, so the heart must generate a higher pressure to overcome this resistance. This can be seen in the thickness of the myocardium in the ventricles.

## 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

**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 superior 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

**circumflex artery**
branch of the left coronary artery that follows coronary sulcus

**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

**coronary veins**

vessels that drain the heart and generally parallel the large surface arteries

**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

**epicardial coronary arteries**

surface arteries of the heart that generally follow the sulci

**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

**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

**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

**left atrioventricular valve**

(also, mitral valve or bicuspid valve) valve located between the left atrium and ventricle; consists of two flaps of tissue

**marginal arteries**
branches of the right coronary artery that supply blood to the superficial portions of the right ventricle

**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)

**middle cardiac vein**
vessel that parallels and drains the areas supplied by the posterior interventricular artery; drains into the great cardiac vein

**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 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

**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

**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

**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

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# 17.3: Cardiac Muscle

**Learning Objectives**

- Describe the structure of cardiac muscle
- Identify and describe the components of the conducting system that distributes electrical impulses through the heart
- Compare the effect of ion movement on membrane potential of cardiac conductive and contractile cells
- Relate characteristics of an electrocardiogram to events in the cardiac cycle
- Identify blocks that can interrupt the cardiac cycle

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**. Neither smooth nor skeletal muscle can do this. Even though cardiac muscle has autorhythmicity, heart rate is modulated by the endocrine and nervous systems.

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 atria and ventricles. Contractile cells conduct impulses and are responsible for contractions that pump blood through the body. The **myocardial conducting cells** (1 percent of the cells) form the conduction system of the heart. Except for Purkinje cells, they are generally much smaller than the contractile cells and have few of the myofibrils or filaments needed for contraction. Their function is similar in many respects to neurons, although they are specialized muscle cells. Myocardial conduction cells initiate and propagate the action potential (the electrical impulse) that travels throughout the heart and triggers the contractions that propel the blood.

## Structure of Cardiac Muscle

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 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 contractions of the heart. Typically, cardiomyocytes have a single, central nucleus, but two or more nuclei may be found in some cells.

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 (Figure 17.3.1.b). The sarcolemmas from adjacent cells bind together at the intercalated discs. They consist of desmosomes, specialized linking proteoglycans, tight junctions, and large numbers of gap junctions that allow the passage of ions between the cells and help to synchronize the contraction (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.

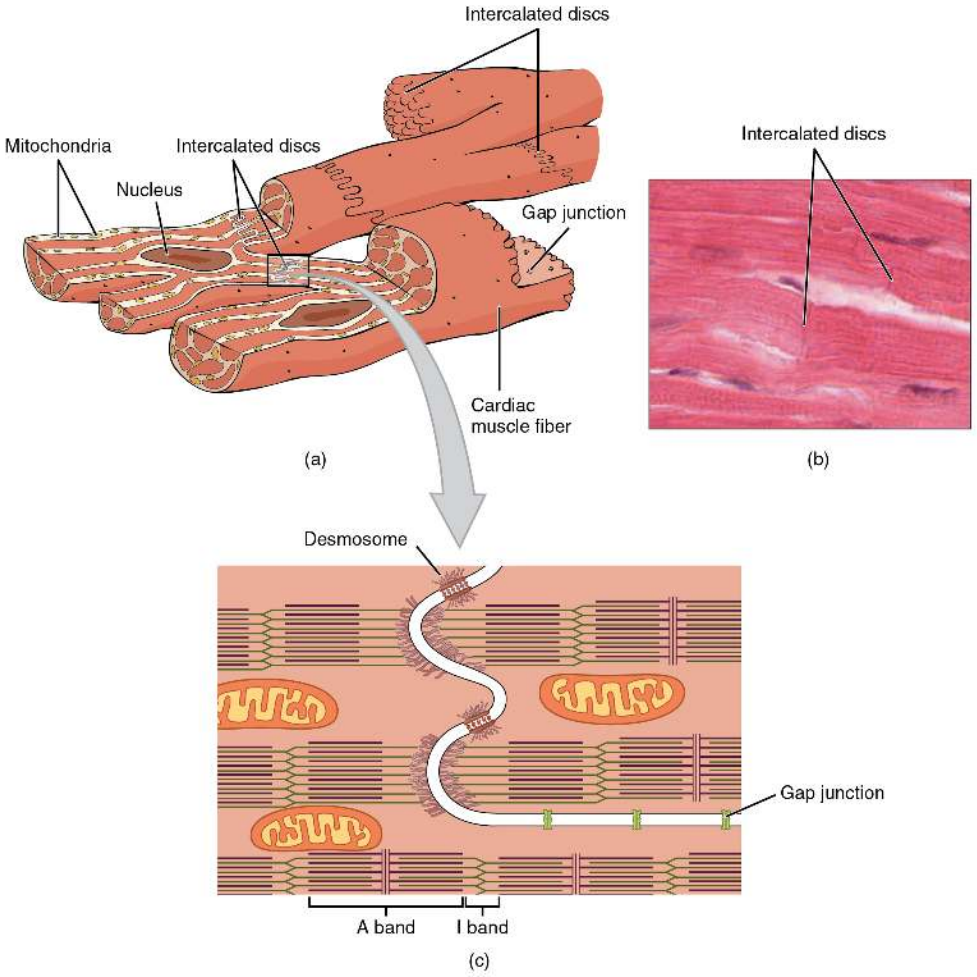



Figure **17.3.1**: Cardiac Muscle. (a) Cardiac muscle cells have myofibrils composed of myofilaments arranged in sarcomeres, T tubules to transmit the impulse from the sarcolemma to the interior of the cell, numerous mitochondria for energy, and intercalated discs that are found at the junction of different cardiac muscle cells. (b) A photomicrograph of cardiac muscle cells shows the nuclei and intercalated discs. (c) An intercalated disc connects cardiac muscle cells and consists of desmosomes and gap junctions. LM × 1600. (Micrograph provided by the Regents of the University of Michigan Medical School © 2012)

Cardiac muscle undergoes aerobic respiration patterns, primarily metabolizing lipids and carbohydrates. Myoglobin, lipids, and glycogen are all stored within the cytoplasm. Cardiac muscle cells undergo twitch-type contractions with long refractory periods followed by brief relaxation periods. The relaxation is essential so the heart can fill with blood for the next cycle. The refractory period is very long to prevent the possibility of tetany, a condition in which muscle remains involuntarily contracted. In the heart, tetany is not compatible with life, since it would prevent the heart from pumping blood.

EVERYDAY CONNECTION

**Repair and Replacement**

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 MI, dead cells are often replaced by patches of scar tissue. 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.

## Conduction System of the Heart

If embryonic heart cells are separated into a Petri dish and kept alive, each is capable of generating its own electrical impulse followed by contraction. When two independently beating embryonic cardiac muscle cells are placed together, the cell with the higher inherent rate sets the pace, and the impulse spreads from the faster to the slower cell to trigger a contraction. As more cells are joined together, the fastest cell continues to assume control of the rate. A fully developed adult heart maintains the capability of generating its own electrical impulse, triggered by the fastest cells, as part of the cardiac conduction system. The components of the cardiac conduction system include the sinoatrial node, the atrioventricular node, the atrioventricular bundle, the atrioventricular bundle branches, and the Purkinje cells (Figure **17.3.2**).

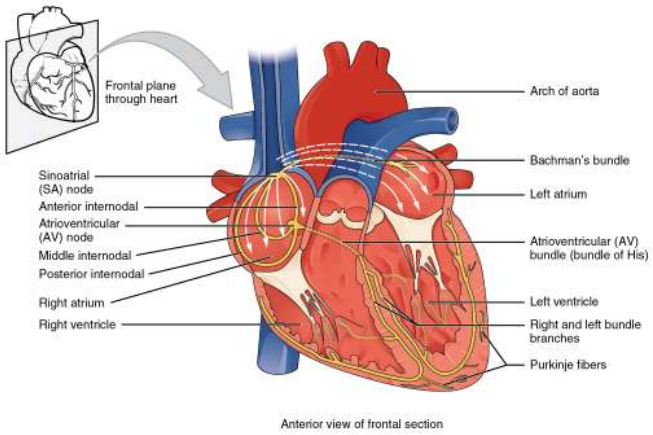



Figure **17.3.2**: Conduction System of the Heart. Specialized conducting components of the heart include the sinoatrial node, the internodal pathways, the atrioventricular node, the atrioventricular bundle, the right and left bundle branches, and the Purkinje fibers.

### Sinoatrial (SA) Node

Normal cardiac rhythm is established by the **sinoatrial (SA) node**, a specialized clump of myocardial conducting cells located in the superior and posterior walls of the right atrium in close proximity to the orifice of the superior vena cava. The SA node has the highest inherent rate of depolarization and 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) that lead directly from the SA node to the next node in the conduction system, the atrioventricular node (see Figure **17.3.2**). The impulse takes approximately 50 ms (milliseconds) 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 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.

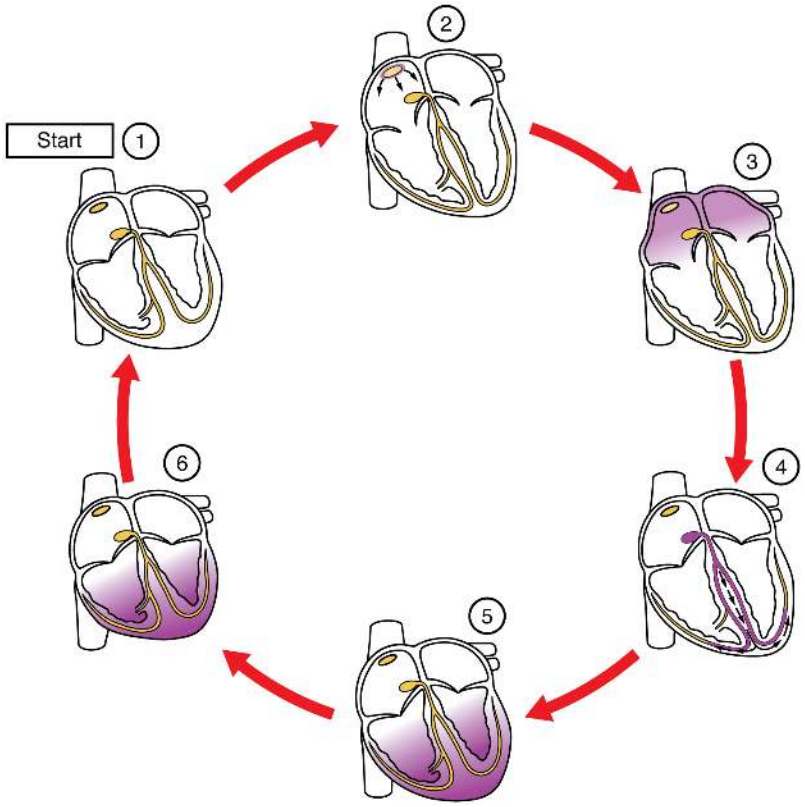



Figure **17.3.3**: Cardiac Conduction. (1) The sinoatrial (SA) node and the remainder of the conduction system are at rest. (2) The SA node initiates the action potential, which sweeps across the atria. (3) After reaching the atrioventricular node, there is a delay of approximately 100 ms that allows 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.

The electrical event, the wave of depolarization, is the trigger for muscular contraction. The wave of depolarization 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 conductive cells, located in the inferior portion of the right atrium within the atrioventricular septum. The septum prevents the impulse from spreading directly to the ventricles without passing through the AV node. There is a critical pause before the AV node depolarizes and transmits the 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 Purkinje Fibers

Arising from the AV node, the **atrioventricular bundle**, or **bundle of His**, proceeds through the interventricular septum before dividing into two **atrioventricular bundle branches**, commonly called the left and right bundle branches. The left bundle branch has two fascicles. 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 Purkinje fibers (see Figure **17.3.3**, step 4). This passage takes approximately 25 ms.

The **Purkinje fibers** are additional myocardial conductive 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. The Purkinje fibers have 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 depolarization of the ventricles is approximately 225 ms.

## Chapter Review

The heart is regulated by both neural and endocrine control, yet it is capable of initiating its own action potential followed by muscular contraction. The conductive cells within the heart establish the heart rate and transmit it through the myocardium. The 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 of His, bundle branches, and Purkinje fibers. The action potential for the conductive cells consists of a prepotential phase with a slow influx of $Na^+$ followed by a rapid influx of $Ca^{2+}$ and outflux of $K^+$. Contractile cells have an action potential with an extended plateau phase that results in an extended refractory period to allow complete contraction for the heart to pump blood effectively. Recognizable points on the ECG include the P wave that corresponds to atrial depolarization, the QRS complex that corresponds to ventricular depolarization, and the T wave that corresponds to ventricular repolarization.

## Review Questions

Q. Which of the following is unique to cardiac muscle cells?

A. Only cardiac muscle contains a sarcoplasmic reticulum.

B. Only cardiac muscle has gap junctions.

C. Only cardiac muscle is capable of autorhythmicity

D. Only cardiac muscle has a high concentration of mitochondria.

> Answer: C

Q. Which component of the heart conduction system would have the slowest rate of firing?

A. atrioventricular node

B. atrioventricular bundle

C. bundle branches

D. Purkinje fibers

> Answer: D

## Critical Thinking Questions

Q. How do gap junctions and intercalated disks aid contraction of the heart?

> A. Gap junctions within the intercalated disks allow impulses to spread from one cardiac muscle cell to another, allowing sodium, potassium, and calcium ions to flow between adjacent cells, propagating the action potential, and ensuring coordinated contractions.

## 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 depolarization of the atria

**pacemaker**
cluster of specialized myocardial cells known as the SA node that initiates the sinus rhythm

**prepotential depolarization**
(also, spontaneous depolarization) mechanism that accounts for the autorhythmic property of cardiac muscle; the membrane potential increases as sodium ions diffuse through the always-open sodium ion channels and causes the electrical potential to rise

**Purkinje fibers**
specialized myocardial conduction 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 depolarization of the ventricles and includes, as a component, the repolarization of the atria

**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

**spontaneous depolarization**
(also, prepotential depolarization) the mechanism that accounts for the autorhythmic property of cardiac muscle; the membrane potential increases as sodium ions diffuse through the always-open sodium ion channels and causes the electrical potential to rise

**T wave**
component of the electrocardiogram that represents the repolarization of the ventricles

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# CHAPTER OVERVIEW

## 18: The Cardiovascular System - Blood Vessels and Circulation

### Learning Objectives

- Compare and contrast the anatomical structure of arteries, arterioles, capillaries, venules, and veins
- Accurately describe the forces that account for capillary exchange
- List the major factors affecting blood flow, blood pressure, and resistance
- Describe how blood flow, blood pressure, and resistance interrelate
- Discuss how the neural and endocrine mechanisms maintain homeostasis within the blood vessels
- 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

18.1: Introduction to the Cardiovascular System - Blood Vessels and Circulation
18.2: Structure of Blood Vessels
18.3: Circulatory Pathways

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# 18.1: Introduction to the Cardiovascular System - Blood Vessels and Circulation

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 bodily system are threatened.



Figure 20.0.1: 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. (credit: Colin Davis)

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# 18.2: Structure of Blood Vessels

**Learning Objectives**

- 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
- Describe the basic structure of a capillary bed, from the supplying metarteriole to the venule into which it drains
- Explain the structure and function of venous valves in the large veins of the extremities

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.

Arteries and veins transport blood in two distinct circuits: the systemic circuit and the pulmonary circuit (Figure 18.2.1). Systemic arteries provide blood rich in oxygen to the body's tissues. 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. In contrast, in the pulmonary circuit, 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.

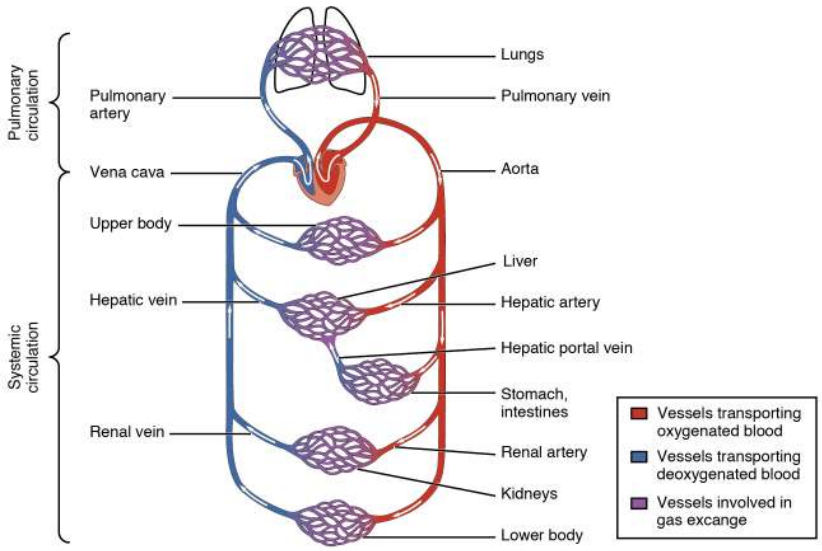



Figure 18.2.1: Cardiovascular Circulation. The pulmonary circuit moves blood from the right side of the heart to the lungs and back to the heart. The systemic circuit moves blood from the left side of the heart to the head and body and returns it to the right side of the heart to repeat the cycle. The arrows indicate the direction of blood flow, and the colors show the relative levels of oxygen concentration.

## Shared Structures

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.

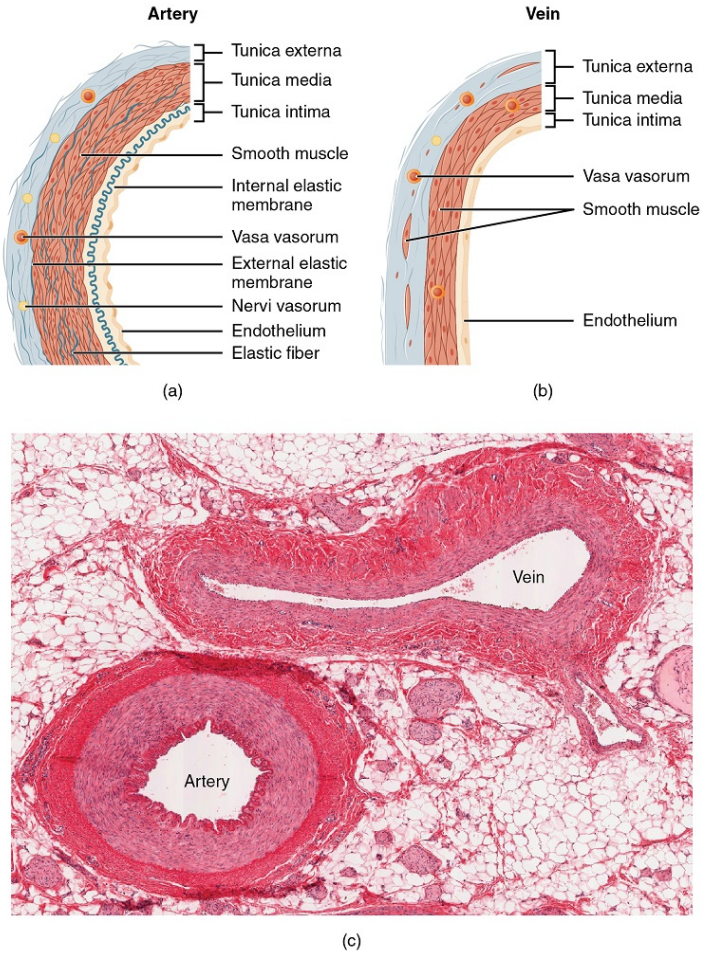



Figure **18.2.2**: Structure of Blood Vessels. (a) Arteries and (b) veins share the same general features, but the walls of arteries are much thicker because of the higher pressure of the blood that flows through them. (c) A micrograph shows the relative differences in thickness. LM × 160. (Micrograph 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 collagenous 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 (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 its 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; the term tunic is also used for some modern garments. From the most interior layer to the outer, these tunics are the tunica intima, the tunica media, and the tunica externa (Figure **18.2.2**). Table compares and contrasts the tunics of the arteries and veins.

Table **18.2.1**: Comparison of Tunics in Arteries and Veins

| | Arteries | Veins |
|---|---|---|
| **General Apperance** | Thick walls with small lumens<br>Generally appear rounded | Thin walls with large lumens<br>Generally appear flattened |
| **Tunica Intima** | Endothelium usually appears wavy due to constriction of smooth muscle<br>Internal elastic membrane present in larger vessels | Endothelium appears smooth<br>Internal elastic membrane absent |
| **Tunica media** | Normally the thickest layer in arteries<br>Smooth muscle cells and elastic fibers predominate (the proportions of these vary with distance from the heart)<br>External elastic membrane present in larger vessels | Normally thinner than the tunica externa<br>Smooth muscle cells and collagenous fibers predominate<br>Nervi vasorum and vasa vasorum present<br>External elastic membrane absent |
| **Tunica externa** | Normally thinner than the tunica media in all but the largest arteries<br>Collagenous and elastic fibers<br>Nervi vasorum and vasa vasorum present | Normally the thickest layer in veins<br>Collagenous and smooth fibers predominate<br>Some smooth muscle fibers<br>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 collagenous 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 collagenous fibers to provide additional strength.

In larger arteries, there is also a thick, distinct layer of elastic fibers 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 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). 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 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. These are generally all sympathetic fibers, although some trigger vasodilation and others induce vasoconstriction, depending upon the nature of the neurotransmitter and receptors located on the target cell. Parasympathetic stimulation does trigger vasodilation as well as erection during sexual arousal in the external genitalia of both sexes. Nervous control over vessels tends to be more generalized than the specific targeting of individual blood vessels. Local controls, discussed later, account for this phenomenon. (Seek additional content for more information on these dynamic aspects of the autonomic nervous system.) Hormones and local chemicals also control blood vessels. Together, these neural and chemical mechanisms reduce or increase blood flow in response to changing body conditions, from exercise to hydration. Regulation of both blood flow and blood pressure is discussed in detail later in this chapter.

The smooth muscle layers of the tunica media are supported by a framework of collagenous fibers that also binds the tunica media to the inner and outer tunics. Along with the collagenous 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 connective tissue composed primarily of collagenous 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 (the stroke volume) 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 enables it to accept a large volume of blood from the heart and conduct it to smaller branches.

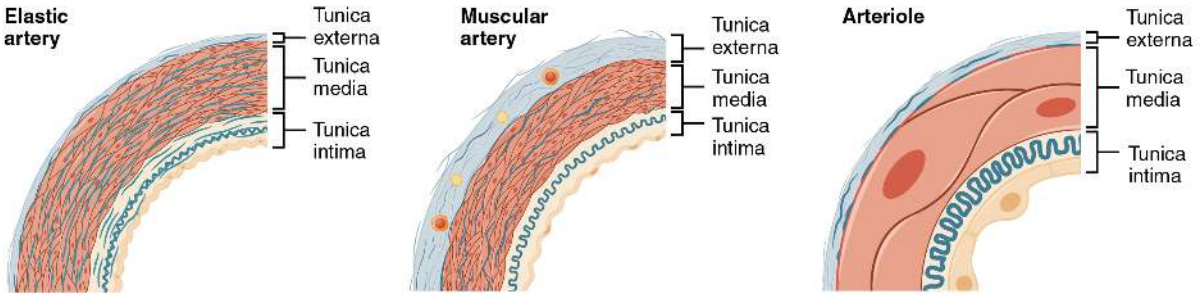



Figure 18.2.3: Types of Arteries and Arterioles. Comparison of the walls of an elastic artery, a muscular artery, and an arteriole is shown. In terms of scale, the diameter of an arteriole is measured in micrometers compared to millimeters for elastic and muscular arteries.

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. 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. 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 (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.

## Capillaries

A **capillary** is a microscopic channel that supplies blood to the tissues themselves, 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. There is some variation in wall structure: In a large capillary, several endothelial cells bordering each other may line the lumen; 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, allowing substances to pass through. There are three major types of capillaries, which differ according to their degree of "leakiness:" continuous, fenestrated, and sinusoid capillaries (Figure 18.2.4).

### 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.

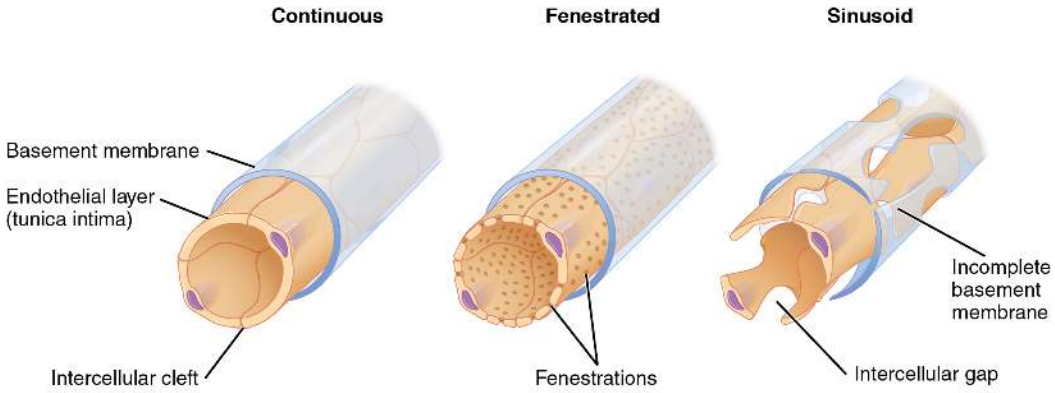



Figure **18.2.4**: Types of Capillaries. The three major types of capillaries: continuous, fenestrated, and sinusoid.

### 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, however, 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. 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 not unlike 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 of 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 to 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.

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 **18.2.5**). 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, an **arteriovenous anastomosis** may bypass the capillary bed and lead 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.

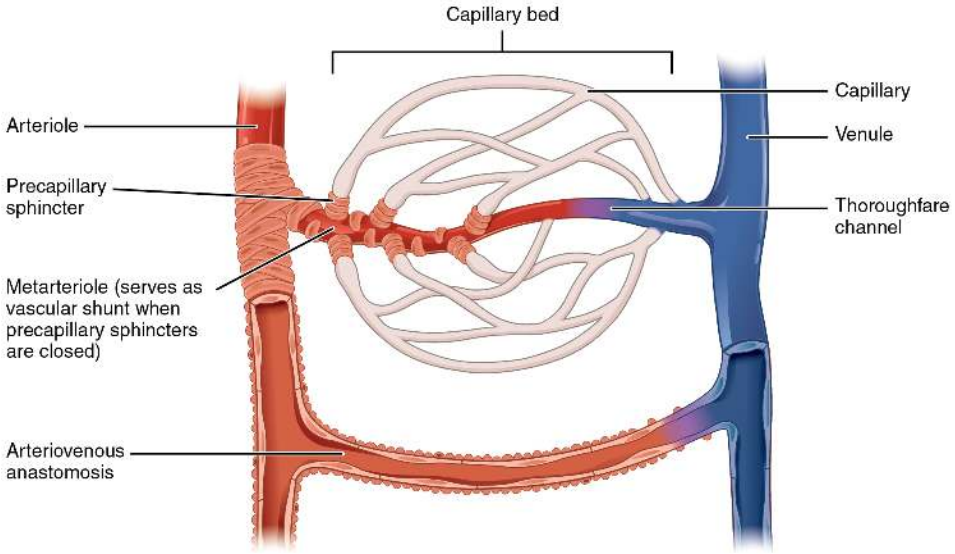



Figure **18.2.5**: Capillary Bed. In a capillary bed, arterioles give rise to metarterioles. Precapillary sphincters located at the junction of a metarteriole with a capillary regulate blood flow. A thoroughfare channel connects the metarteriole to a venule. An arteriovenous anastomosis, which directly connects the arteriole with the venule, is shown at the bottom.

## Venules

A **venule** is an extremely small vein, generally 8–100 micrometers in diameter. Postcapillary venules join multiple capillaries exiting from a capillary bed. Multiple venules join to form veins. The walls of venules consist of endothelium, a thin middle layer with a few muscle cells and elastic fibers, plus an outer layer of connective tissue fibers that constitute a very thin tunica externa (Figure). 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 through 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 **18.2.6**). 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. Table compares the features of arteries and veins.

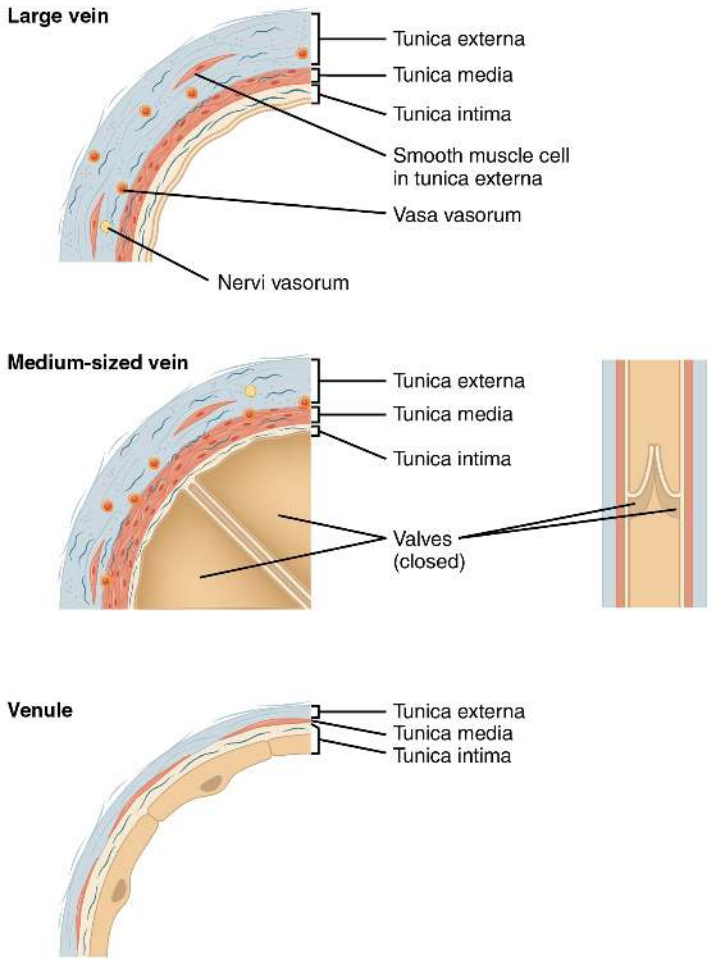



Figure **18.2.6**: Comparison of Veins and Venules. Many veins have valves to prevent back flow of blood, whereas venules do not. In terms of scale, the diameter of a venule is measured in micrometers compared to millimeters for veins.

Table **18.2.2**: Comparison 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<br>Lower in pulmonary arteries | Lower in systemic veins<br>Higher in pulmonary veins |
| Valves | Not present | Present most commonly in limbs and in veins inferior to the heart |

## 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 **18.2.7**: Varicose Veins. Varicose veins are commonly found in the lower limbs. (credit: Thomas Kriese)

Edema may be accompanied by varicose veins, especially in the superficial veins of the legs (Figure 20.1.7). 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 **18.2.8**). 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**.

| | | |
|---|---|---|
| Systemic circulation<br>84% | Systemic veins<br>64% | Large veins<br>18% |
| | | Large venous networks (liver, bone marrow, and integument)<br>21% |
| | | Venules and medium-sized veins<br>25% |
| | Systemic arteries<br>13% | Arterioles<br>2% |
| | | Muscular arteries<br>5% |
| | | Elastic arteries<br>4% |
| | | Aorta<br>2% |
| | Systemic capillaries<br>7% | Systemic capillaries<br>7% |
| Pulmonary circulation<br>9% | Pulmonary veins<br>4% | |
| | Pulmonary capillaries<br>2% | |
| | Pulmonary arteries<br>3% | |
| Heart<br>7% | | |

Figure **18.2.8**: Distribution of Blood Flow.

When blood flow needs to be redistributed to other portions of the body, the vasomotor center located in the medulla oblongata sends sympathetic stimulation to the smooth muscles in the walls of the veins, causing constriction—or in this case, venoconstriction. Less dramatic than the vasoconstriction seen in smaller arteries and arterioles, venoconstriction may be likened to a "stiffening" of the vessel wall. This increases pressure on the blood within the veins, speeding its return to the heart. As you will note in Figure **18.2.8**, approximately 21 percent of the venous blood is located in venous networks within the liver, bone marrow, and integument. This volume of blood is referred to as **venous reserve**. Through venoconstriction, this "reserve" volume of blood can get back to the heart more quickly for redistribution to other parts of the circulation.

### CAREER CONNECTION: Vascular Surgeons and Technicians

Vascular surgery is a specialty in which the physician deals primarily with diseases of the vascular portion of the cardiovascular system. This includes repair and replacement of diseased or damaged vessels, removal of plaque from vessels, minimally invasive procedures including the insertion of venous catheters, and traditional surgery. Following completion of medical school, the physician generally completes a 5-year surgical residency followed by an additional 1 to 2 years of vascular specialty training. In the United States, most vascular surgeons are members of the Society of Vascular Surgery.

Vascular technicians are specialists in imaging technologies that provide information on the health of the vascular system. They may also assist physicians in treating disorders involving the arteries and veins. This profession often overlaps with cardiovascular technology, which would also include treatments involving the heart. Although recognized by the American Medical Association, there are currently no licensing requirements for vascular technicians, and licensing is voluntary. Vascular technicians typically have an Associate's degree or certificate, involving 18 months to 2 years of training. The United States Bureau of Labor projects this profession to grow by 29 percent from 2010 to 2020.

## Chapter 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.

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. Arteries, arterioles, venules, and veins are composed of three tunics known as the tunica intima, tunica media, and tunica externa. Capillaries have only a tunica intima layer. 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 influenced by vasoconstriction and vasodilation in their walls.

## Review Questions

Q. The endothelium is found in the _____.

A. tunica intima

B. tunica media

C. tunica externa

D. lumen

Answer: A

Q. Nervi vasorum control _____.

A. vasoconstriction

B. vasodilation

C. capillary permeability

D. both vasoconstriction and vasodilation

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. collagenous fibers

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: B

Q. An especially leaky 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: C

## Critical Thinking Questions

Q. Arterioles are often referred to as resistance vessels. Why?

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. Cocaine use causes vasoconstriction. Is this likely to increase or decrease blood pressure, and why?

A. Vasoconstriction causes the lumens of blood vessels to narrow. This increases the pressure of the blood flowing within the vessel.

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?

A. This is a venule.

## 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

**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

**precapillary sphincters**

circular rings of smooth muscle that surround the entrance to a capillary and regulate blood flow into that capillary

**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

**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

**Learning Objectives**

- Identify the vessels through which blood travels within the pulmonary circuit, beginning from the right ventricle of the heart and ending at the left atrium
- 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. Figure **18.3.1** summarizes these relationships.

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.

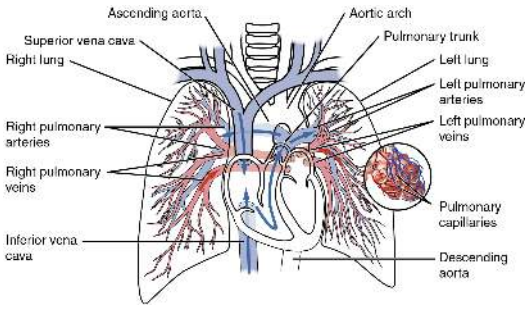



Figure **18.3.2**: Pulmonary Circuit. Blood exiting from the right ventricle flows into the pulmonary trunk, which bifurcates into the two pulmonary arteries. These vessels branch to supply blood to the pulmonary capillaries, where gas exchange occurs within the lung alveoli. Blood returns via the pulmonary veins to the left atrium.

Table **18.3.1**: 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 **18.3.3**).

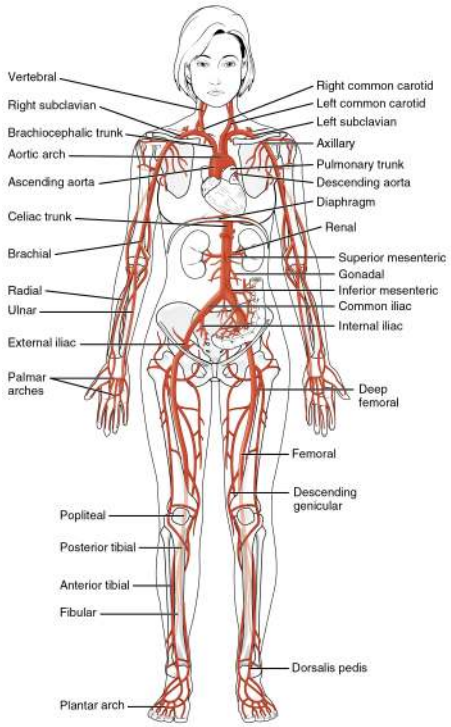



Figure **18.3.3**: Systemic Arteries. The major systemic arteries shown here deliver oxygenated blood throughout the body.

## The Aorta

The **aorta** is the largest artery in the body (Figure **18.3.4**). 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 **18.3.4** for an illustration of the ascending aorta, the aortic arch, and the initial segment of the descending aorta plus major branches; Table **18.3.2** summarizes the structures of the aorta.

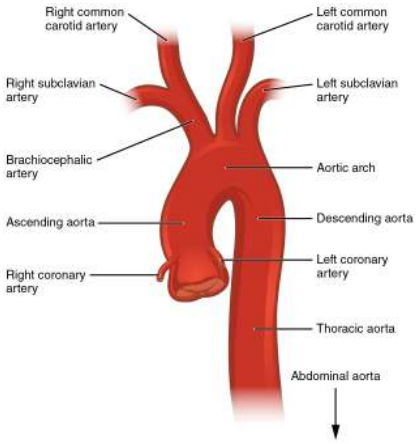



Figure 18.3.4: Aorta. The aorta has distinct regions, including the ascending aorta, aortic arch, and the descending aorta, which includes the thoracic and abdominal regions.

Table 18.3.2: 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 Figure20.5.4), 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. (Seek additional content for more detail on cardiac circulation.)

## 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 18.3.5).

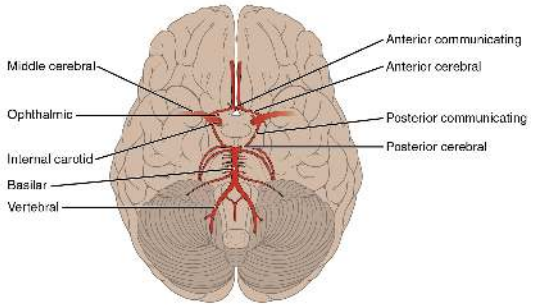



Figure 18.3.6: Arteries Serving the Brain. This inferior view shows the network of arteries serving the brain. The structure is referred to as the arterial circle or circle of Willis.

| 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 |
| 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 |

| Aortic Arch Branches and Brain Circulation | |
|---|---|
| Vessel | Description |
| | 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 18.3.7). 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 lists the arteries of the thoracic region.

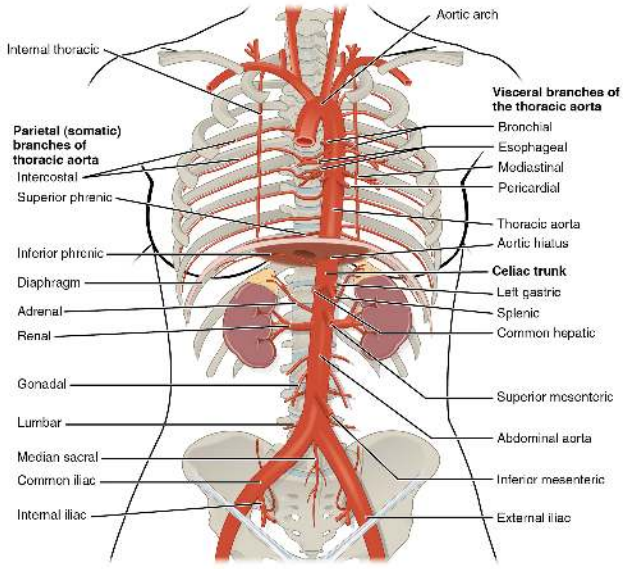



Figure 18.3.7: Arteries of the Thoracic and Abdominal Regions. The thoracic aorta gives rise to the arteries of the visceral and parietal branches.

| 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 18.3.7). 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 18.3.8 shows the distribution of the major branches of the aorta into the thoracic and abdominal regions. Figure 18.3.9 shows the distribution of the major branches of the common iliac arteries. Table summarizes the major branches of the abdominal aorta.

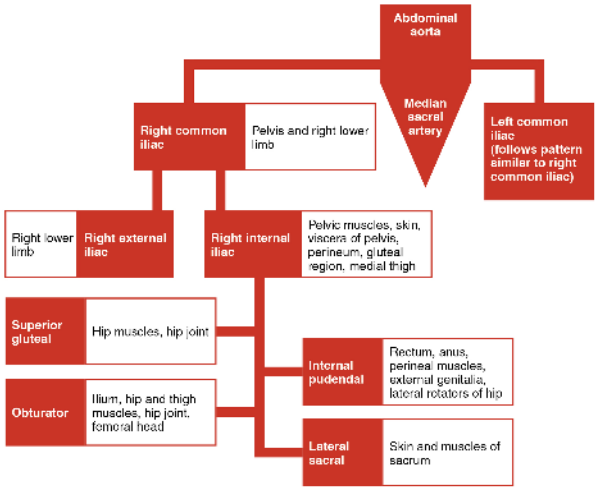



Figure 18.3.9: Major Branches of the Iliac Arteries. The flow chart summarizes the distribution of the major branches of the common iliac arteries into the pelvis and lower limbs. The left side follows a similar pattern to the right.

| Vessels of 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 |
| 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 |

| Vessels of the Abdominal Aorta | |
|---|---|
| Vessel | Description |
| 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 **18.3.10**). 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 **18.3.11** shows the distribution of systemic arteries from the heart into the upper limb. Table summarizes the arteries serving the upper limbs.

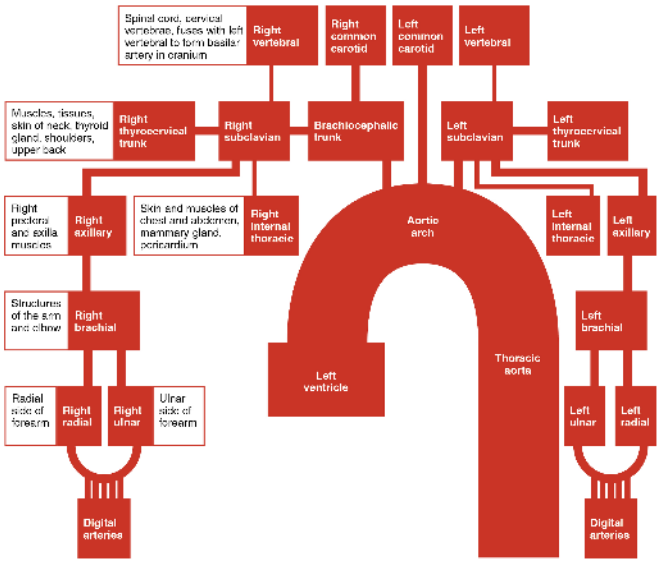



Figure **18.3.11**: Major Arteries of the Upper Limb. The flow chart summarizes the distribution of the major arteries from the heart into the upper limb.

| 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 |
| 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 18.3.12). 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 18.3.13 shows the distribution of the major systemic arteries in the lower limb. Table summarizes the major systemic arteries discussed in the text.

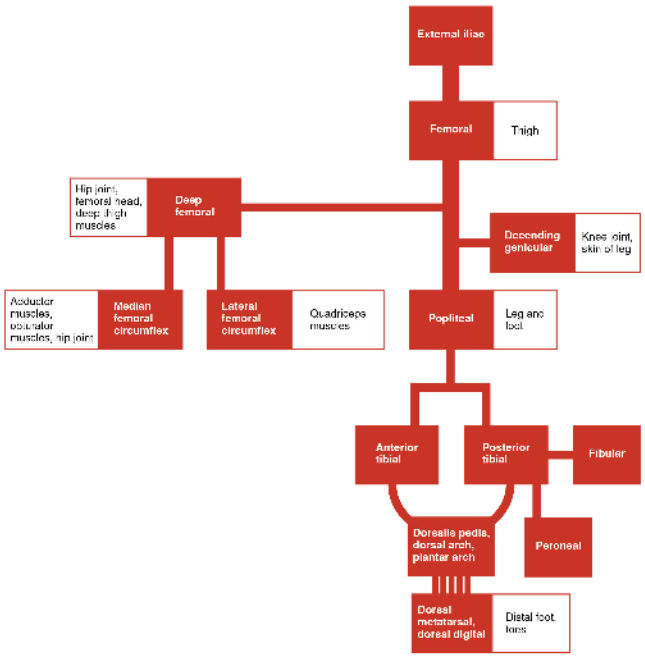



Figure 18.3.13: Systemic Arteries of the Lower Limb. The flow chart summarizes the distribution of the systemic arteries from the external iliac artery into the lower limb.


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| 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 |
| 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

QR Code representing a URL

*Visit this site for a brief online summary of the veins.*

Figure **18.3.14**: Major Systemic Veins of the Body. The major systemic veins of the body are shown here in an anterior view.

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 18.3.15). 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 summarizes the veins of the thoracic region that flow into the superior vena cava.

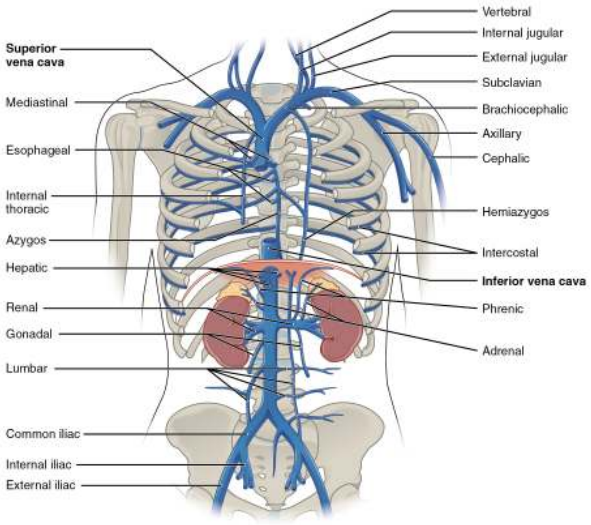



Figure 18.3.15: Veins of the Thoracic and Abdominal Regions. Veins of the thoracic and abdominal regions drain blood from the area above the diaphragm, returning it to the right atrium via the superior vena cava.

| 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 18.3.16). 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 summarizes the major veins of the head and neck.

| 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 **18.3.16**). 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 summarizes the major veins of the brain.

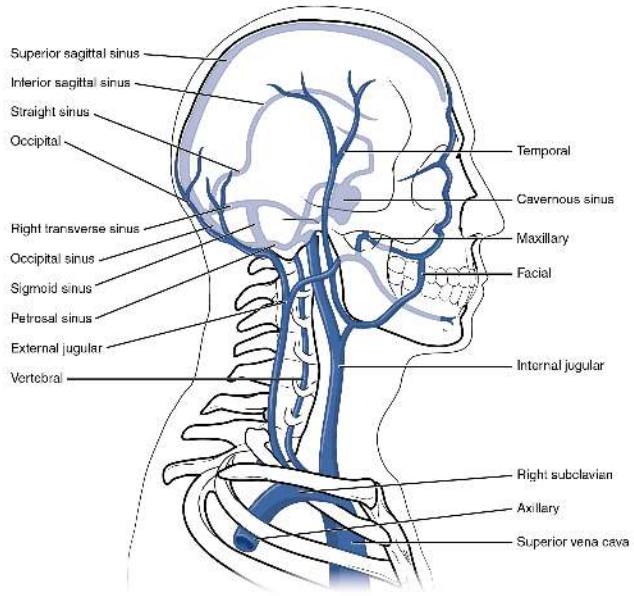



Figure **18.3.16**: Veins of the Head and Neck. This left lateral view shows the veins of the head and neck, including the intercranial sinuses.

| 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 **18.3.17**). 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 18.3.18. Table summarizes the veins of the upper limbs.

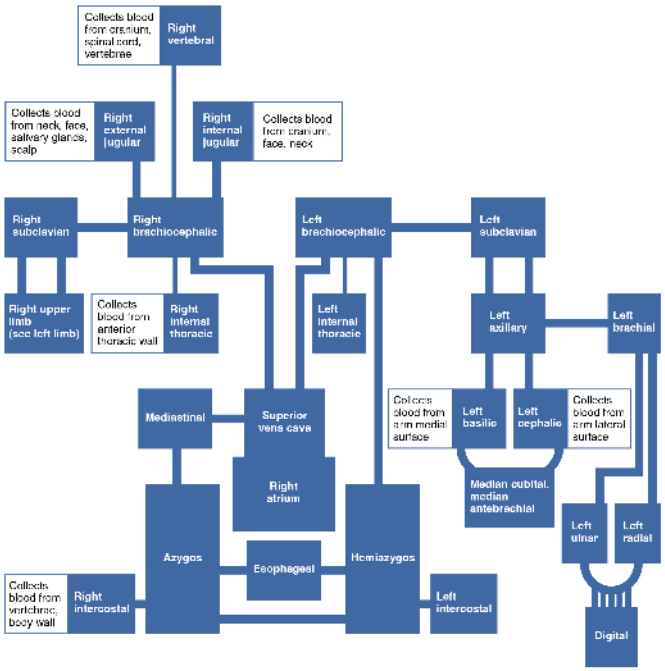



Figure 18.3.18: Veins Flowing into the Superior Vena Cava. The flow chart summarizes the distribution of the veins flowing into the superior vena cava.

| 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 18.3.15). 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 **18.3.19** provides a flow chart of the veins flowing into the inferior vena cava. Table summarizes the major veins of the abdominal region.

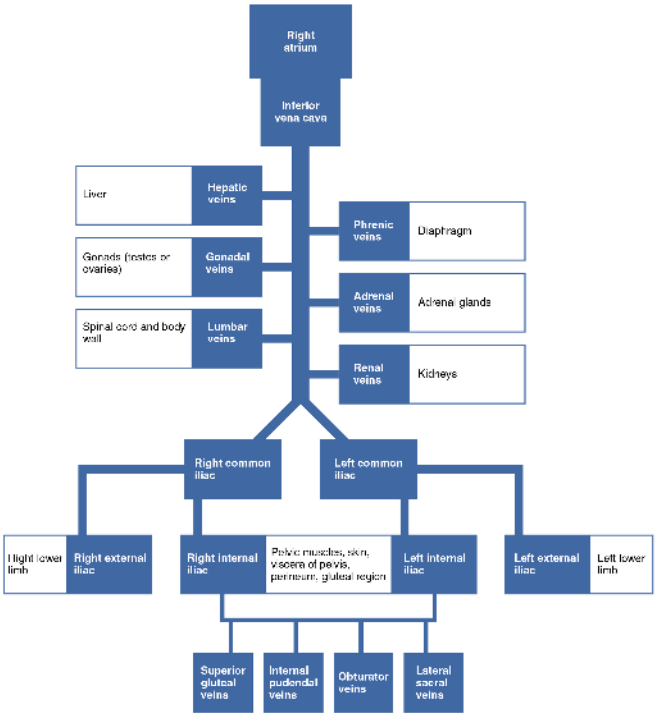



Figure **18.3.19**: Venous Flow into Inferior Vena Cava. The flow chart summarizes veins that deliver blood to the inferior vena cava.

| 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 18.3.20). 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 and the fibular 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 popliteal 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 to 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 upper 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 18.3.21 is a flow chart of veins flowing into the lower limb. Table summarizes the major veins of the lower limbs.

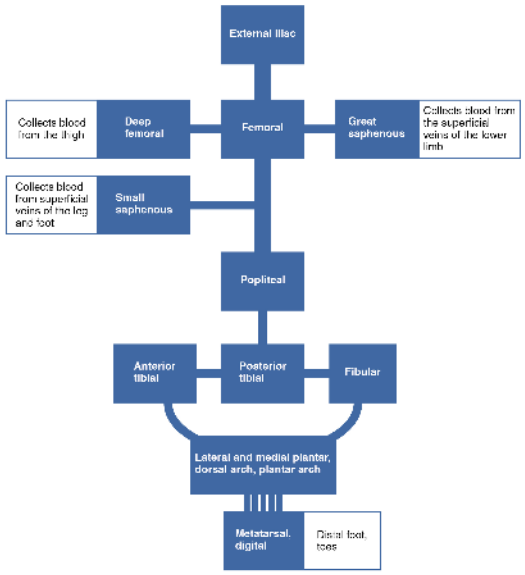



Figure 18.3.21: Major Veins of the Lower Limb. The flow chart summarizes venous flow from the lower limb.

| 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 popliteal 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 |
| 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 18.3.22). Portal systems begin and end in capillaries. 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. You saw the only other portal system with the hypothalamic-hypophyseal portal vessel in the endocrine chapter.

The hepatic portal system consists of the hepatic portal vein and the veins that drain into it. 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.

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.

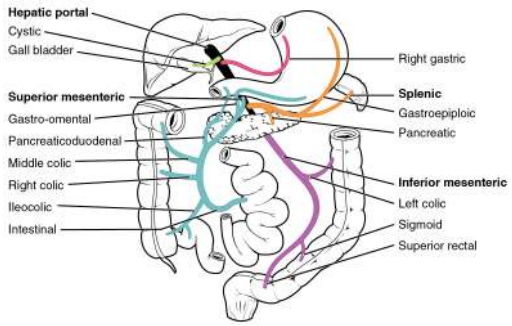



Figure 18.3.22: Hepatic Portal System. The liver receives blood from the normal systemic circulation via the hepatic artery. It also receives and processes blood from other organs, delivered via the veins of the hepatic portal system. All blood exits the liver via the hepatic vein, which delivers the blood to the inferior vena cava. (Different colors are used to help distinguish among the different vessels in the system.)

## Chapter 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: 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: 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: 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: D

Q. The hepatic portal system delivers blood from the digestive organs to the _____.

A. liver

B. hypothalamus

C. spleen

D. left atrium

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.

A. The right ventricle of the heart pumps oxygen-depleted blood to the pulmonary arteries.

Q. What organs do the gonadal veins drain?

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?

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 popliteal 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 fibular and 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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# CHAPTER OVERVIEW

## 19: The Lymphatic and Immune System

19.1: Introduction
19.2: Anatomy of the Lymphatic and Immune Systems

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# 19.1: Introduction

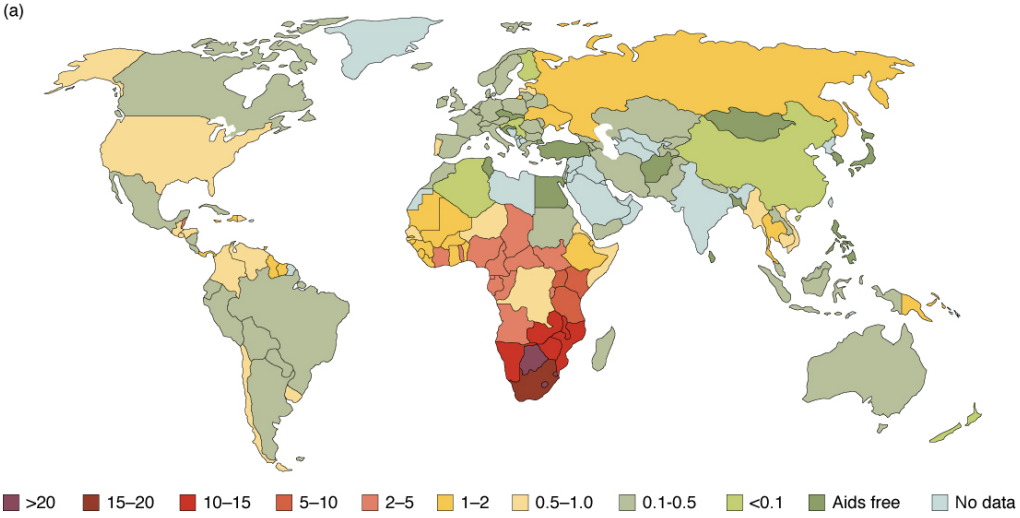
In June 1981, the Centers for Disease Control and Prevention (CDC), in Atlanta, Georgia, published a report of an unusual cluster of five patients in Los Angeles, California. All five were diagnosed with a rare pneumonia caused by a fungus called *Pneumocystis jirovecii* (formerly known as *Pneumocystis 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). Although nearly 100 percent fatal in those with active HIV infections in the early years, the development of anti-HIV drugs has transformed HIV infection into a chronic, manageable disease and not the certain death sentence it once was. One positive outcome resulting from the emergence of HIV disease was that the public's attention became focused as never before on the importance of having a functional and healthy immune system.

(a)




(b)

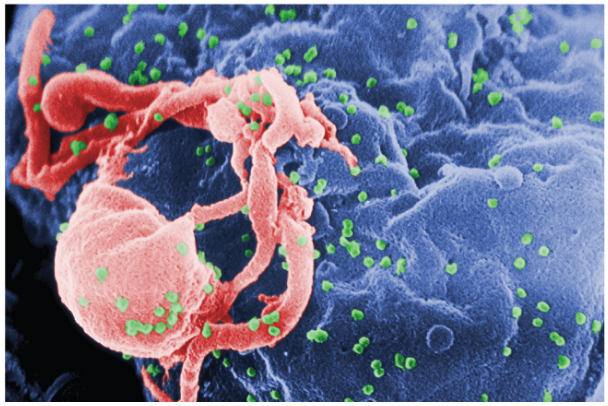


Figure 19.1.1: The Worldwide AIDS Epidemic. (a) As of 2008, more than 15 percent of adults were infected with HIV in certain African countries. This grim picture had changed little by 2012. (b) In this scanning electron micrograph, HIV virions (green particles) are budding off the surface of a macrophage (pink structure). (credit b: C. Goldsmith)

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# 19.2: Anatomy of the Lymphatic and Immune Systems

**Learning Objectives**

- Describe the structure and function of the lymphatic tissue (lymph fluid, vessels, ducts, and organs)
- Describe the structure and function of the primary and secondary lymphatic organs
- Discuss the cells of the immune system, how they function, and their relationship with the lymphatic system

The **immune system** is the complex collection of cells and organs that destroys or neutralizes pathogens that would otherwise cause disease or death. The lymphatic system, for most people, is associated with the immune system to such a degree that the two systems are virtually indistinguishable. The **lymphatic system** is the system of vessels, cells, and organs that carries excess fluids to the bloodstream and filters pathogens from the blood. The swelling of lymph nodes during an infection and the transport of lymphocytes via the lymphatic vessels are but two examples of the many connections between these critical organ systems.

## Functions of the Lymphatic System

A major function of the lymphatic system is to drain body fluids and return them to the bloodstream. Blood pressure causes leakage of fluid from the 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? This is where the lymphatic system comes into play. It drains the excess fluid and empties it back into the bloodstream via a series of vessels, trunks, and ducts. **Lymph** is the term used to describe interstitial fluid once it has entered the lymphatic system. When the lymphatic system is damaged in some way, such as by being blocked by cancer cells or destroyed by injury, protein-rich interstitial fluid accumulates (sometimes “backs up” from the lymph vessels) in the tissue spaces. This inappropriate accumulation of fluid referred to as lymphedema may lead to serious medical consequences.

As the vertebrate immune system evolved, the network of lymphatic vessels became convenient avenues for transporting the cells of the immune system. Additionally, the transport of dietary lipids and fat-soluble vitamins absorbed in the gut uses this system.

Cells of the immune system not only use lymphatic vessels to make their way from interstitial spaces back into the circulation, but they also use lymph nodes as major staging areas for the development of critical immune responses. A **lymph node** is one of the small, bean-shaped organs located throughout the lymphatic system.

*Visit this website for an overview of the lymphatic system. What are the three main components of the lymphatic system?*

## Structure of the Lymphatic System

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. Along the way, the lymph travels through the lymph nodes, which are commonly found near the groin, armpits, neck, chest, and abdomen. Humans have about 500–600 lymph nodes throughout the body (Figure 19.2.1).

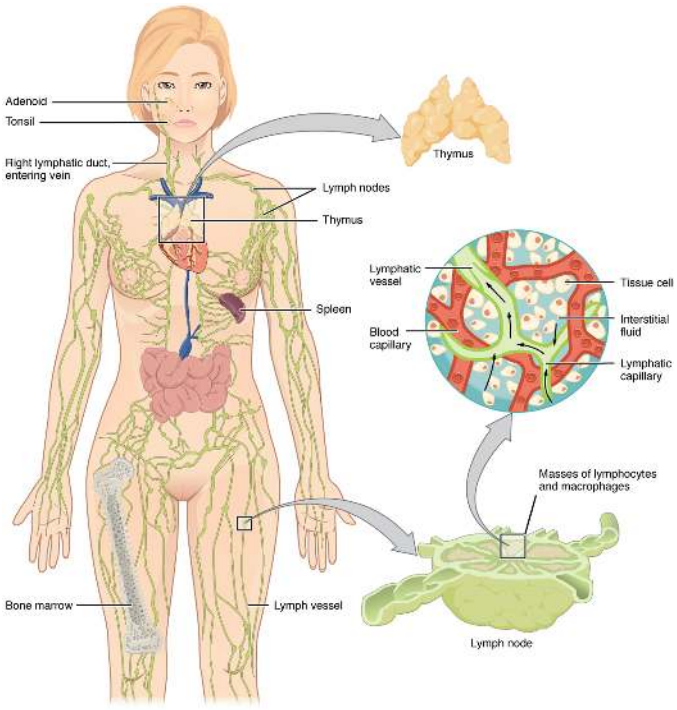



Figure 19.2.1: Anatomy of the Lymphatic System. Lymphatic vessels in the arms and legs convey lymph to the larger lymphatic vessels in the torso.

A major distinction between the lymphatic and cardiovascular systems in humans is that lymph is not actively pumped by the heart, but is forced through the vessels by the movements of the body, the contraction of skeletal muscles during body movements, and breathing. One-way valves (semi-lunar valves) in lymphatic vessels keep the lymph moving toward the heart. Lymph flows from the lymphatic capillaries, through lymphatic vessels, and then is dumped into the circulatory system via the lymphatic ducts located at the junction of the jugular and subclavian veins in the neck.

## 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 interlaced among the arterioles and venules of the circulatory system in the soft connective tissues of the body (Figure 19.2.2). Exceptions are the central nervous system, bone marrow, bones, teeth, and the cornea of the eye, which do not contain lymph vessels.

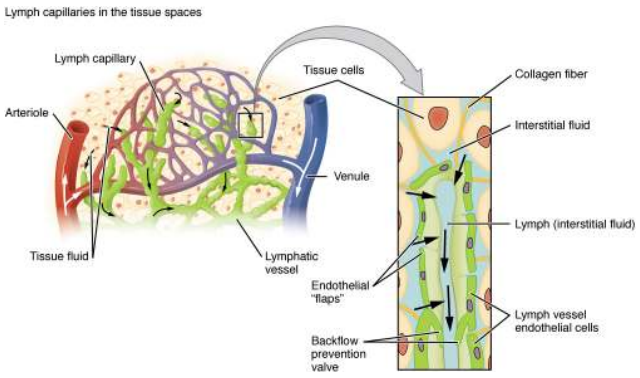



Figure 19.2.2: Lymphatic Capillaries. Lymphatic capillaries are interlaced with the arterioles and venules of the cardiovascular system. Collagen fibers anchor a lymphatic capillary in the tissue (inset). Interstitial fluid slips through spaces between the overlapping endothelial cells that compose the lymphatic capillary.

Lymphatic capillaries are formed by a one cell-thick layer of endothelial cells and represent the open end of the system, allowing interstitial fluid to flow into them via overlapping cells (see Figure 19.2.2). When interstitial pressure is low, the endothelial flaps close to prevent “backflow.” As interstitial pressure increases, the spaces between the cells open up, allowing the fluid to enter.

Entry of fluid into lymphatic capillaries is also enabled by the collagen filaments that anchor the capillaries to surrounding structures. As interstitial pressure increases, the filaments pull on the endothelial cell flaps, opening up them even 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 system, eventually entering the liver and then the bloodstream.

### Larger Lymphatic Vessels, Trunks, and Ducts

The lymphatic capillaries empty into larger lymphatic vessels, which are similar to veins in terms of their three-tunic structure and the presence of valves. 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 19.2.2).

The superficial and deep lymphatics eventually merge to form larger lymphatic vessels known as **lymphatic trunks**. On the right side of the body, the right sides of the head, thorax, and right upper limb drain lymph fluid into the right subclavian vein via the right lymphatic duct (Figure 19.2.3). On the left side of the body, the remaining portions of the body drain into the larger thoracic duct, which drains into the left subclavian vein. 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.

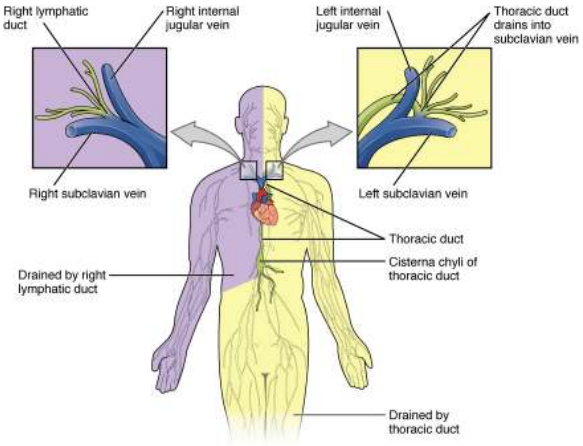



Figure 19.2.3: Major Trunks and Ducts of the Lymphatic System. The thoracic duct drains a much larger portion of the body than does the right lymphatic duct.

The overall drainage system of the body is asymmetrical (see Figure 19.2.3). The **right lymphatic duct** receives lymph from only the upper right side of the body. The lymph from the rest of the body enters the bloodstream through the **thoracic duct** via all the remaining lymphatic trunks. 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.

## Primary Lymphoid Organs and Lymphocyte Development

Understanding the differentiation and development of B and T cells is critical to the understanding of the adaptive immune response. It is 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, spleen, and thymus gland. The lymphoid organs are where lymphocytes mature, proliferate, and are selected, which enables them to attack pathogens without harming the cells of the body.

### Bone Marrow

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 bone marrow takes over most hematopoietic functions, although the final stages of the differentiation of some cells may take place in other organs. The red **bone marrow** is a loose collection of cells where hematopoiesis occurs, and the yellow bone marrow is a site of energy storage, which consists largely of fat cells (Figure 19.2.5). 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 **19.2.5**: Bone Marrow. Red bone marrow fills the head of the femur, and a spot of yellow bone marrow is visible in the center. The white reference bar is 1 cm.

## Thymus

The **thymus** gland is a bilobed organ found in the space between the sternum and the aorta of the heart (Figure **19.2.6**). Connective tissue holds the lobes closely together but also separates them and forms a capsule.

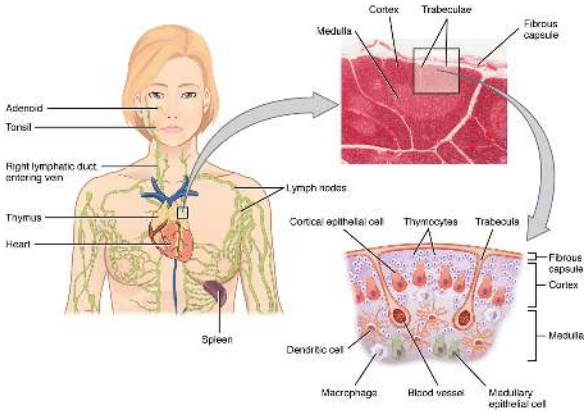



Figure **19.2.6**: Location, Structure, and Histology of the Thymus. The thymus lies above the heart. The trabeculae and lobules, including the darkly staining cortex and the lighter staining medulla of each lobule, are clearly visible in the light micrograph of the thymus of a newborn. LM × 100. (Micrograph provided by the Regents of the University of Michigan Medical School © 2012)

View the University of Michigan WebScope to explore the tissue sample in greater detail.

The connective tissue capsule further divides the thymus into lobules via extensions called trabeculae. The outer region of the organ is known as the cortex and contains large numbers of thymocytes with some epithelial cells, macrophages, and dendritic cells (two types of phagocytic cells that are derived from monocytes). The cortex is densely packed so it stains more intensely than the rest of the thymus (see Figure **19.2.6**). The medulla, where thymocytes migrate before leaving the thymus, contains a less dense collection of thymocytes, epithelial cells, and dendritic cells.

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 disease 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 at birth, 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.

## Secondary Lymphoid Organs and their Roles in Active 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, but have yet to encounter an antigen to respond to. In addition to circulating in the blood and lymph, lymphocytes concentrate in secondary lymphoid organs, which include the lymph nodes, spleen, and lymphoid nodules. All of these tissues have many features in common, including the following:

- The presence of lymphoid follicles, the sites of the formation of lymphocytes, with specific B cell-rich and T cell-rich areas
- An internal structure of reticular fibers with associated fixed macrophages
- **Germinal centers**, which are the sites of 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

Lymph nodes function to remove debris and pathogens from the lymph, and are thus sometimes referred to as the “filters of the lymph” (Figure 19.2.7). 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 that pass through, thereby removing them from the body. The lymph node is also the site of adaptive immune responses mediated by T cells, B cells, and accessory cells of the adaptive immune system. Like the thymus, the bean-shaped lymph nodes are surrounded by a tough capsule of connective tissue and are separated into compartments by trabeculae, the 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.

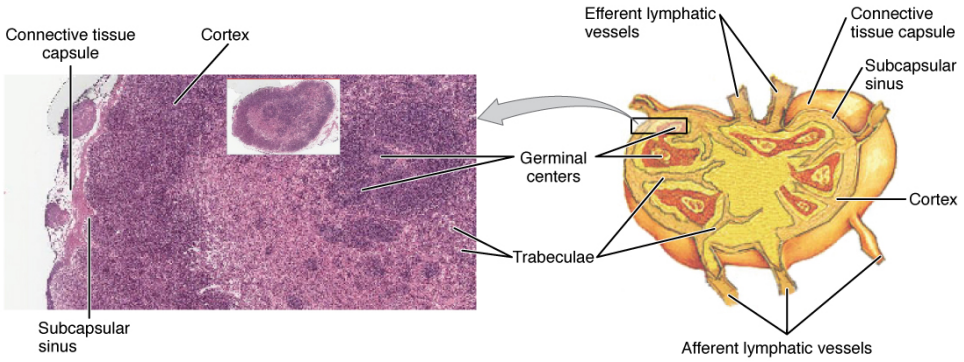



Figure 19.2.7: Structure and Histology of a Lymph Node. Lymph nodes are masses of lymphatic tissue located along the larger lymph vessels. The micrograph of the lymph nodes shows a germinal center, which consists of rapidly dividing B cells surrounded by a layer of T cells and other accessory cells. LM × 128. (Micrograph provided by the Regents of the University of Michigan Medical School © 2012)

View the University of Michigan WebScope to explore the tissue sample in greater detail.

The major routes into the lymph node are via **afferent lymphatic vessels** (see Figure 19.2.7). Cells and lymph fluid that leave the lymph node may do so by another set of vessels known as the **efferent lymphatic vessels**. Lymph enters the lymph node via the subcapsular sinus, which is occupied by dendritic cells, macrophages, and reticular fibers. Within the cortex of the lymph node are lymphoid follicles, which consist of germinal centers of rapidly dividing B cells surrounded by a layer of T cells and other accessory cells. As the lymph continues to flow through the node, it enters the medulla, which consists of medullary cords of B cells and plasma cells, and the medullary sinuses where the lymph collects before leaving the node via the efferent lymphatic vessels.

## Spleen

In addition to the lymph nodes, the **spleen** is a major secondary lymphoid organ (Figure 19.2.8). It is about 12 cm (5 in) long and is attached to the lateral border of the stomach via the gastrosplenic ligament. The spleen is a fragile organ without a strong capsule, and is dark red due to its extensive vascularization. The spleen is sometimes called the “filter of the blood” because of its extensive vascularization and the presence of macrophages and dendritic cells that remove microbes and other materials from the blood, including dying red blood cells. The spleen also functions as the location of immune responses to blood-borne pathogens.

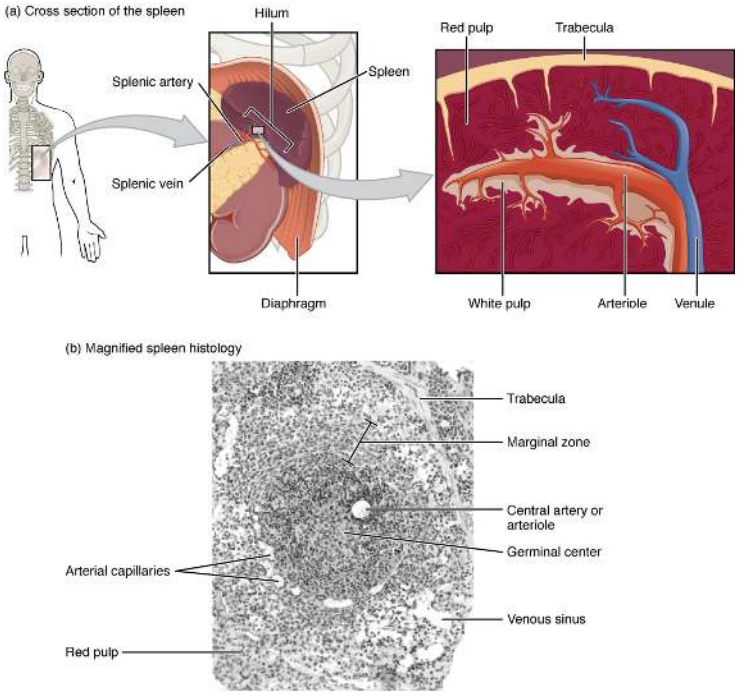



Figure 19.2.8: Spleen. (a) The spleen is attached to the stomach. (b) A micrograph of spleen tissue shows the germinal center. The marginal zone is the region between the red pulp and white pulp, which sequesters particulate antigens from the circulation and presents these antigens to lymphocytes in the white pulp. EM × 660. (Micrograph provided by the Regents of the University of Michigan Medical School © 2012)

The spleen is also divided by trabeculae of connective tissue, and within each splenic nodule is an area of red pulp, consisting of mostly red blood cells, and white pulp, which resembles the lymphoid follicles of the lymph nodes. Upon entering the spleen, the splenic artery splits into several arterioles (surrounded by white pulp) and eventually into sinusoids. Blood from the capillaries subsequently collects in the venous sinuses and leaves via the splenic vein. The red pulp consists of reticular fibers with fixed macrophages attached, free macrophages, and all of the other cells typical of the blood, including some lymphocytes. The white pulp surrounds a central arteriole and consists of germinal centers of dividing B cells surrounded by T cells and accessory cells,

including macrophages and dendritic cells. Thus, the red pulp primarily functions as a filtration system of the blood, using cells of the relatively nonspecific immune response, and white pulp is where adaptive T and B cell responses are mounted.

## Lymphoid Nodules

The other lymphoid tissues, the **lymphoid nodules**, have a simpler architecture than the spleen and lymph nodes in that they consist of a dense cluster of lymphocytes without a surrounding fibrous capsule. These nodules are located in 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 19.2.9). The tonsil located at the back of the throat, the pharyngeal tonsil, is sometimes referred to as the adenoid when swollen. Such swelling 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. These structures, which accumulate all sorts of materials taken into the body through eating and breathing, actually "encourage" pathogens to penetrate deep into the tonsillar tissues where they are acted upon by numerous lymphoid follicles and eliminated. 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.

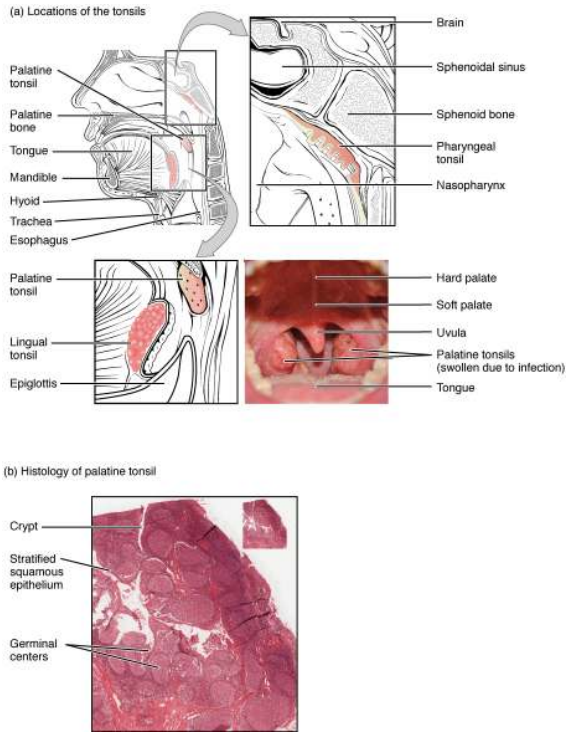



Figure 19.2.9: Locations and Histology of the Tonsils. (a) The pharyngeal tonsil is located on the roof of the posterior superior wall of the nasopharynx. The palatine tonsils lay on each side of the pharynx. (b) A micrograph shows the palatine tonsil tissue. LM × 40. (Micrograph provided by the Regents of the University of Michigan Medical School © 2012)

View the University of Michigan WebScope to explore the tissue sample in greater detail.

**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 19.2.10). 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.

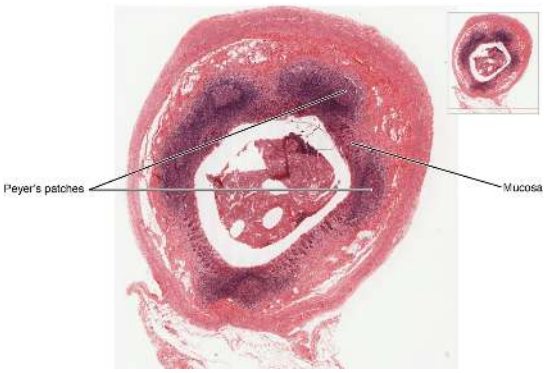



Figure **19.2.10**: Mucosa-associated Lymphoid Tissue (MALT) Nodule. LM × 40. (Micrograph provided by the Regents of the University of Michigan Medical School © 2012)

**Bronchus-associated lymphoid tissue (BALT)** consists of lymphoid follicular structures with an overlying epithelial layer found along the bifurcations of the bronchi, and between bronchi and arteries. They also have the typically less-organized structure of other lymphoid nodules. These tissues, in addition to the tonsils, are effective against inhaled pathogens.

## Chapter Review

The lymphatic system is a series of vessels, ducts, and trunks that remove interstitial fluid from the tissues and return it the blood. The lymphatics are also used to transport dietary lipids and cells of the immune system. Cells of the immune system all come from the hematopoietic system of the bone marrow. Primary lymphoid organs, the bone marrow and thymus gland, are the locations where lymphocytes of the adaptive immune system proliferate and mature. Secondary lymphoid organs are site in which mature lymphocytes congregate to mount immune responses. Many immune system cells use the lymphatic and circulatory systems for transport throughout the body to search for and then protect against pathogens.

## Interactive Link Questions

Visit this website for an overview of the lymphatic system. What are the three main components of the lymphatic system?

> Answer: The three main components are the lymph vessels, the lymph nodes, and the lymph.

Visit this website to learn about the many different cell types in the immune system and their very specialized jobs. What is the role of the dendritic cell in infection by HIV?

> Answer: The dendritic cell transports the virus to a lymph node.

## Review Questions

Q. Which of the following cells is phagocytic?

A. plasma cell

B. macrophage

C. B cell

D. NK cell

> Answer: B

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: A

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: C

Q. Which of the following cells would be most active in early, antiviral immune responses the first time one is exposed to pathogen?

A. macrophage

B. T cell

E. neutrophil

D. natural killer cell

> Answer: D

Q. Which of the lymphoid nodules is most likely to see food antigens first?

A. tonsils

B. Peyer's patches

C. bronchus-associated lymphoid tissue

D. mucosa-associated lymphoid tissue

> Answer: A

## Critical Thinking Questions

Q. Describe the flow of lymph from its origins in interstitial fluid to its emptying into the venous bloodstream.

> A. The lymph enters through lymphatic capillaries, and then into larger lymphatic vessels. The lymph can only go in one direction due to valves in the vessels. The larger lymphatics merge to form trunks that enter into the blood via lymphatic ducts.

## Glossary

**adaptive immune response**
relatively slow but very specific and effective immune response controlled by lymphocytes

**afferent lymphatic vessels**
lead into a lymph node

**antibody**
antigen-specific protein secreted by plasma cells; immunoglobulin

**antigen**
molecule recognized by the receptors of B and T lymphocytes

**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

**bone marrow**
tissue found inside bones; the site of all blood cell differentiation and maturation of B lymphocytes

**bronchus-associated lymphoid tissue (BALT)**
lymphoid nodule associated with the respiratory tract

**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

**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

**immune system**
series of barriers, cells, and soluble mediators that combine to response to infections of the body with pathogenic organisms

**innate immune response**
rapid but relatively nonspecific immune response

**lymph**
fluid contained within the lymphatic system

**lymph node**
one of the bean-shaped organs found associated with the lymphatic vessels

**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

**lymphocytes**
white blood cells characterized by a large nucleus and small rim of cytoplasm

**lymphoid nodules**
unencapsulated patches of lymphoid tissue found throughout the body

**mucosa-associated lymphoid tissue (MALT)**
lymphoid nodule associated with the mucosa

**naïve lymphocyte**
mature B or T cell that has not yet encountered antigen for the first time

**natural killer cell (NK)**
cytotoxic lymphocyte of innate immune response

**plasma cell**
differentiated B cell that is actively secreting antibody

**primary lymphoid organ**
site where lymphocytes mature and proliferate; red bone marrow and thymus gland

**right lymphatic duct**
drains lymph fluid from the upper right side of body into the right subclavian vein

**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)

**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

**thoracic duct**
large duct that drains lymph from the lower limbs, left thorax, left upper limb, and the left side of the head

**thymocyte**
immature T cell found in the thymus

**thymus**
primary lymphoid organ; where T lymphocytes proliferate and mature

**tonsils**
lymphoid nodules associated with the nasopharynx

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# CHAPTER OVERVIEW

## 20: The Respiratory System

The respiratory system consists of specific organs and structures used for the process of respiration in an organism. The respiratory system is involved in the intake and exchange of oxygen and carbon dioxide between an organism and the environment.


20.1: Prelude to the Respiratory System

20.2: Organs and Structures of the Respiratory System

20.3: The Lungs


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# 20.1: Prelude to the Respiratory System

**Chapter Objectives**

- 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
- Outline the process of gas exchange
- Summarize the process of oxygen and carbon dioxide transport within the respiratory system
- Create a flow chart illustrating how respiration is controlled
- Discuss how the respiratory system responds to exercise
- 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. 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.



***Figure 22.0.1: Mountain Climbers.*** *The thin air at high elevations can strain the human respiratory system. (credit: "bortescristian"/flickr.com)*

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# 20.2: Organs and Structures of the Respiratory System

**Learning Objectives**

- List the structures that make up the respiratory system
- Describe how the respiratory system processes oxygen and $CO_2$
- Compare and contrast the functions of upper respiratory tract with the lower respiratory tract

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**).

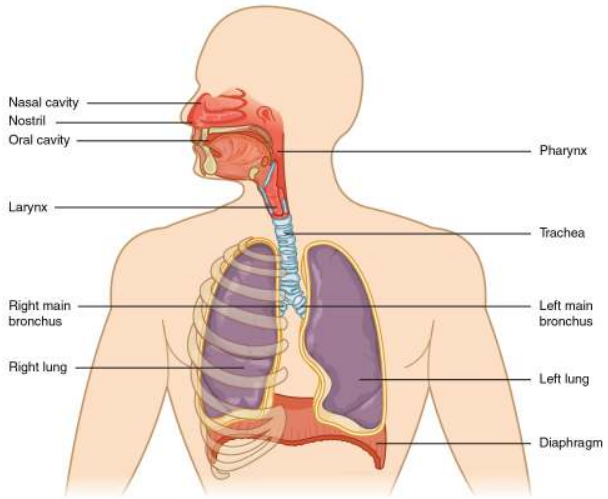



Figure **20.2.1**: Major Respiratory Structures. The major respiratory structures span the nasal cavity to the diaphragm.

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. The gas exchange occurs in 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 major 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 length of the nose. The **apex** is the tip of the nose. On either side of the apex, the nostrils are formed by the alae (singular = ala). An **ala** is a cartilaginous structure that forms the lateral side of each **naris** (plural = nares), or nostril opening. The **philtrum** is the concave surface that connects the apex of the nose to the upper lip.

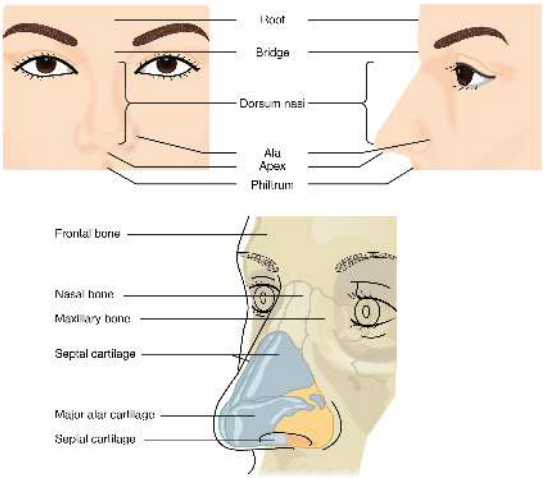



Figure **20.2.2**: Nose. This illustration shows features of the external nose (top) and skeletal features of the nose (bottom).

Underneath the thin skin of the nose are its skeletal features (see Figure, lower illustration). While the root and bridge of the nose consist of bone, the protruding portion of the nose is composed of cartilage. As a result, when looking at a skull, the nose is missing. The **nasal bone** is one of a pair of bones that lies under the root and bridge of the nose. The nasal bone articulates superiorly with the frontal bone and laterally with the maxillary bones. Septal cartilage is flexible hyaline cartilage connected to the nasal bone, forming the dorsum nasi. The **alar cartilage** consists of the apex of the nose; it surrounds the naris.

The nares open into the nasal cavity, which is separated into left and right sections by the nasal septum (Figure **20.2.3**). The **nasal septum** is formed anteriorly by a portion of the septal cartilage (the flexible portion you can touch with your fingers) and posteriorly by the perpendicular plate of the ethmoid bone (a cranial bone located just posterior to the nasal bones) and the thin vomer bones (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. The inferior conchae are separate bones, whereas the superior and middle conchae are portions of the ethmoid bone. Conchae serve to increase the surface area of the nasal cavity and to disrupt the flow of air as it enters the nose, causing air to bounce along the epithelium, where it is cleaned and warmed. The conchae and **meatuses** also conserve water and prevent dehydration of the nasal epithelium by trapping water during exhalation. 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 bone. The soft palate at the posterior portion of the nasal cavity consists of muscle tissue. Air exits the nasal cavities via the internal nares and moves into the pharynx.

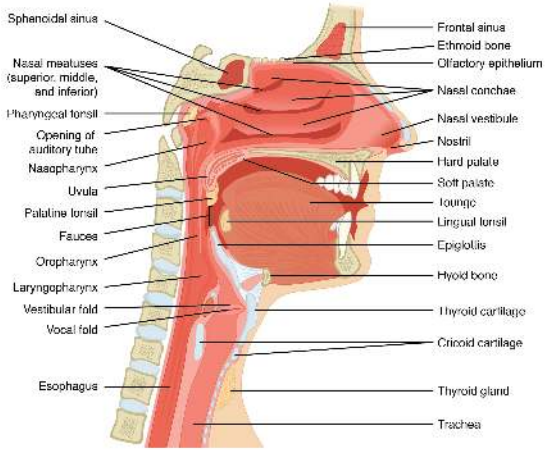



Figure **20.2.3**: Upper Airway.

Several bones that help form the walls of the nasal cavity have air-containing spaces called the paranasal sinuses, which serve to warm and humidify incoming air. Sinuses are lined with a mucosa. Each **paranasal sinus** is named for its associated bone: frontal sinus, maxillary sinus, sphenoidal sinus, and ethmoidal sinus. The sinuses produce mucus and lighten the weight of the skull.

The nares and anterior portion of the nasal cavities are lined with mucous membranes, containing sebaceous glands and hair follicles that serve to prevent the passage of large debris, such as dirt, through the nasal cavity. An olfactory epithelium used to detect odors is found deeper in the nasal cavity.

The conchae, meatuses, and paranasal sinuses are lined by **respiratory epithelium** composed of pseudostratified ciliated columnar epithelium (Figure 20.2.4). The 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. This moist epithelium functions to warm and humidify incoming air. 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.

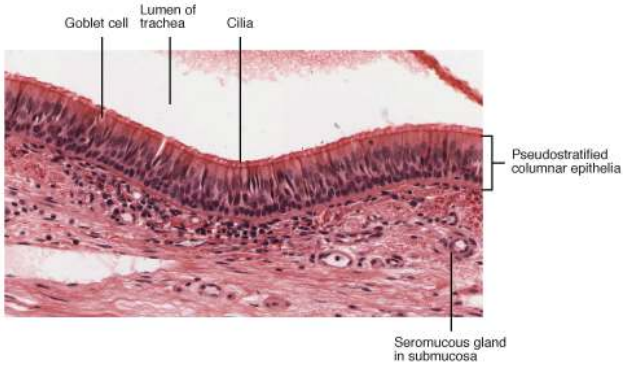



Figure 20.2.4: Pseudostratified Ciliated Columnar Epithelium. Respiratory epithelium is pseudostratified ciliated columnar epithelium. Seromucous glands provide lubricating mucus. LM × 680. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

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View the University of Michigan WebScope at 141.214.65.171/Histology/Basi....svs/view.apml? to explore the tissue sample in greater detail.

## 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).

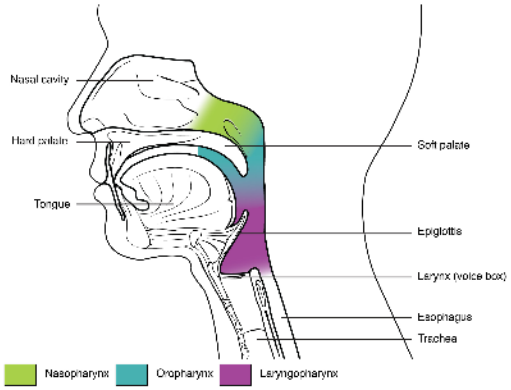



Figure 20.2.5: Divisions of the Pharynx. The pharynx is divided into three regions: the nasopharynx, the oropharynx, and the laryngopharynx.

The **nasopharynx** is flanked by the conchae of the nasal cavity, and it serves only as an airway. At the top of the nasopharynx are the pharyngeal tonsils. A **pharyngeal tonsil**, also called an adenoid, is an aggregate of lymphoid reticular tissue similar to a lymph node that lies at the superior portion of the nasopharynx. 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 tonsils are large in children, but interestingly, tend 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 often lead to ear infections.

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. As the nasopharynx becomes the oropharynx, the epithelium changes from pseudostratified ciliated columnar epithelium to 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 and posterior to the larynx. It continues the route for ingested material and air until its inferior end, where the digestive and respiratory systems diverge. The stratified squamous epithelium of the oropharynx is continuous with the laryngopharynx. Anteriorly, the laryngopharynx opens into the larynx, whereas posteriorly, it enters the esophagus.

## 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 (Figure **20.2.6**). The structure of the larynx is formed by several pieces of cartilage. Three large cartilage pieces—the thyroid cartilage (anterior), epiglottis (superior), and cricoid cartilage (inferior)—form the major structure of the larynx. The **thyroid cartilage** is the largest piece of cartilage that makes up 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 ring, with a wide posterior region and a thinner anterior region. Three smaller, paired cartilages—the arytenoids, corniculates, and cuneiforms—attach to the epiglottis and the vocal cords and muscle that help move the vocal cords to produce speech.

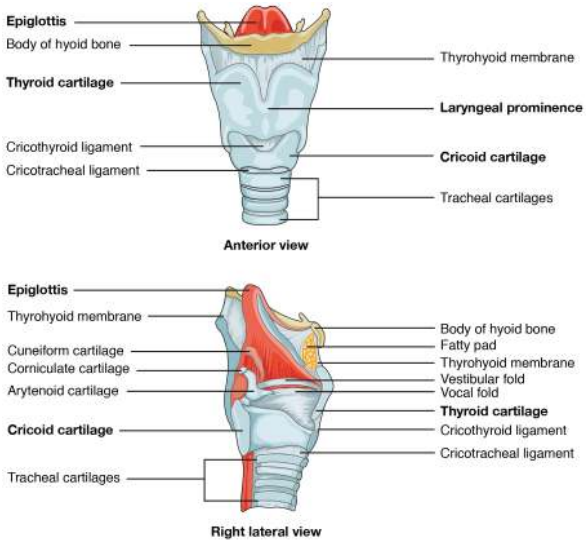



Figure **20.2.6**: Larynx. The larynx extends from the laryngopharynx and the hyoid bone to the trachea.

The **epiglottis**, attached to the thyroid cartilage, is a very flexible piece of elastic cartilage that covers the opening of the trachea (see Figure **20.2.3**). When in the "closed" position, the unattached end of the epiglottis rests on the glottis. The **glottis** is composed of the vestibular folds, the true vocal cords, and the space between these folds (Figure **20.2.7**). A **vestibular fold**, or false vocal cord, is one of a pair of folded sections of mucous membrane. A **true vocal cord** 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 are free, allowing oscillation 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.

The act of swallowing causes the pharynx and larynx to lift upward, allowing the pharynx to expand and the epiglottis of the larynx to swing downward, closing the opening to the trachea. These movements produce a larger area for food to pass through, while preventing food and beverages from entering the trachea.

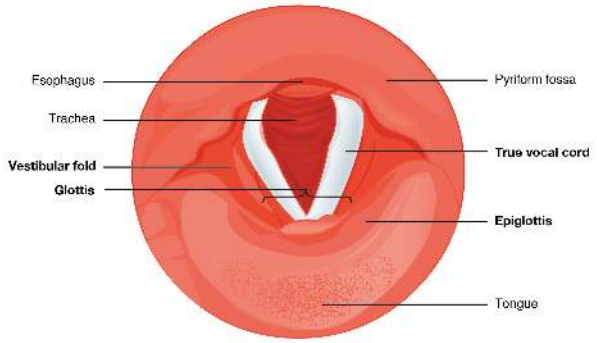



Figure 20.2.7: Vocal Cords. The true vocal cords and vestibular folds of the larynx are viewed inferiorly from the laryngopharynx.

Continuous with the laryngopharynx, the superior portion of the larynx is lined with stratified squamous epithelium, transitioning into pseudostratified ciliated 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. The cilia beat the mucus upward towards the laryngopharynx, where it can be swallowed down the esophagus.

## Trachea

The trachea (windpipe) extends from the larynx toward the lungs (Figure 20.2.8.a). The **trachea** is formed by 16 to 20 stacked, C-shaped pieces of hyaline cartilage that are connected by dense connective tissue. The **trachealis muscle** and elastic connective tissue together form the **fibroelastic membrane**, a flexible membrane that closes the posterior surface of the trachea, connecting the C-shaped cartilages. The fibroelastic membrane allows the trachea to stretch and expand slightly during inhalation and exhalation, whereas the rings of cartilage provide structural support and prevent the trachea from collapsing. In addition, the trachealis muscle can be contracted to force air through the trachea during exhalation. The trachea is lined with pseudostratified ciliated columnar epithelium, which is continuous with the larynx. The esophagus borders the trachea posteriorly.

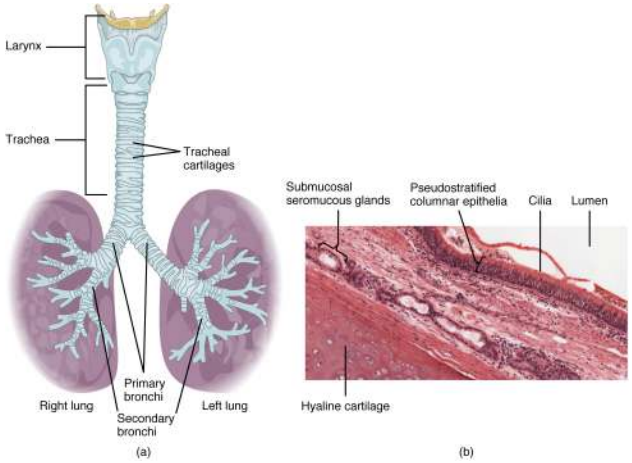



Figure 20.2.8: Trachea. (a) The tracheal tube is formed by stacked, C-shaped pieces of hyaline cartilage. (b) The layer visible in this cross-section of tracheal wall tissue between the hyaline cartilage and the lumen of the trachea is the mucosa, which is composed of pseudostratified ciliated columnar epithelium that contains goblet cells. LM × 1220. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

## Bronchial Tree

The trachea branches into the right and left primary **bronchi** at the carina. These bronchi are also lined by pseudostratified ciliated columnar epithelium containing mucus-producing goblet cells (Figure 20.2.8.b). The carina is a raised structure that contains specialized nervous tissue that induces violent coughing if a foreign body, such as food, is present. Rings of cartilage, similar to those of the trachea, support the structure of the bronchi and prevent their collapse. The primary bronchi enter the lungs at the

hilum, a concave region where blood vessels, lymphatic vessels, and nerves also enter the lungs. The bronchi continue to branch into bronchial a tree. A **bronchial tree** (or respiratory tree) is the collective term used for these multiple-branched bronchi. 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.

A **bronchiole** branches from the tertiary bronchi. Bronchioles, which are about 1 mm in diameter, further branch until they become the tiny terminal bronchioles, which lead to the structures of gas exchange. There are more than 1000 terminal bronchioles in each lung. The muscular walls of the bronchioles do not contain cartilage like those of the bronchi. This muscular wall can change the size of the tubing to increase or decrease airflow through the tube.

## 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 20.2.9), which then leads to an alveolar duct, opening into a cluster of alveoli.

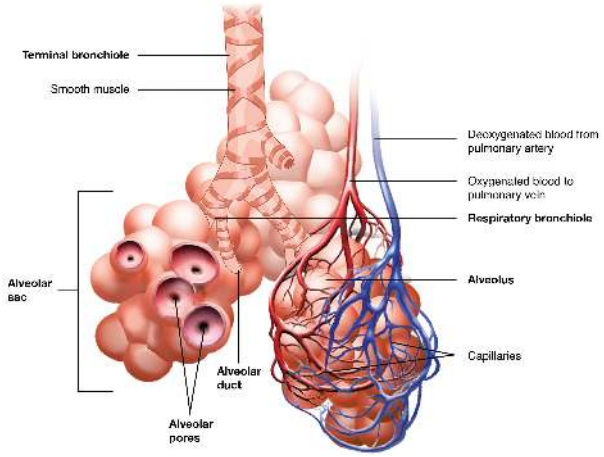



Figure 20.2.9: Respiratory Zone. Bronchioles lead to alveolar sacs in the respiratory zone, where gas exchange occurs.

### Alveoli

An **alveolar duct** is a tube composed of smooth muscle and connective tissue, which opens into a cluster of alveoli. An **alveolus** is one of the many small, grape-like sacs that are attached to the alveolar ducts.

An **alveolar sac** is a cluster of many individual alveoli that are responsible for gas exchange. An alveolus is approximately 200 µm in diameter with elastic walls that allow the alveolus to stretch during air intake, which greatly increases the surface area available for gas exchange. Alveoli are connected to their neighbors by **alveolar pores**, which help maintain equal air pressure throughout the alveoli and lung (Figure 20.2.10).

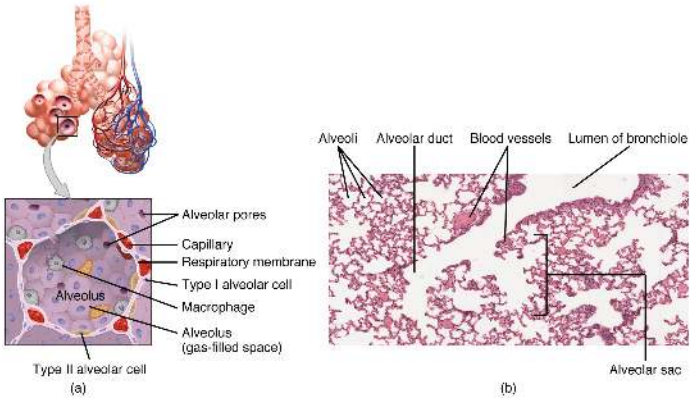



Figure 20.2.10: Structures of the Respiratory Zone. (a) The alveolus is responsible for gas exchange. (b) A micrograph shows the alveolar structures within lung tissue. LM × 178. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

The alveolar wall consists of three major cell types: type I alveolar cells, type II alveolar cells, and alveolar macrophages. A **type I alveolar cell** is a squamous epithelial cell of the alveoli, which constitute up to 97 percent of the alveolar surface area. These cells are about 25 nm thick and are highly permeable to gases. A **type II alveolar cell** is interspersed among the type I cells and secretes **pulmonary surfactant**, a substance composed of phospholipids and proteins that reduces the surface tension of the alveoli. 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.

DISEASES 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 **20.2.11**). Cells of the immune system, such as eosinophils and mononuclear cells, 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.

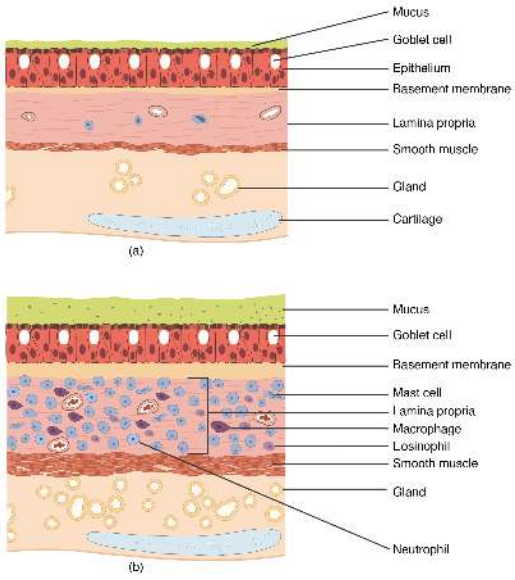



Figure **20.2.11**: Normal and Bronchial Asthma Tissues. (a) Normal lung tissue does not have the characteristics of lung tissue during (b) an asthma attack, which include thickened mucosa, increased mucus-producing goblet cells, and eosinophil infiltrates.

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.

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*Visit this site to learn more about what happens during an asthma attack. What are the three changes that occur inside the airways during an asthma attack?*

## Chapter 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, 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 borders the oropharynx, trachea, and esophagus. The respiratory zone includes the structures of the lung that are directly involved in gas exchange: the terminal bronchioles and alveoli.

The lining of the conducting zone is composed mostly of pseudostratified ciliated columnar epithelium with goblet cells. The mucus traps pathogens and debris, whereas beating cilia move the mucus superiorly 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.

## Interactive Link Questions

Visit this site to learn more about what happens during an asthma attack. What are the three changes that occur inside the airways during an asthma attack?

> Answer: Inflammation and the production of a thick mucus; constriction of the airway muscles, or bronchospasm; and an increased sensitivity to allergens.

## 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: A

Q. Which of the following structures is *not* part of the bronchial tree?

A. alveoli

B. bronchi

C. terminal bronchioles

D. respiratory bronchioles

Answer: C

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.

A. The pharynx has three major regions. The first region is the nasopharynx, which is connected to the posterior nasal cavity and functions as an airway. 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.

Q. If a person sustains an injury to the epiglottis, what would be the physiological result?

A. 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.

A. 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 nares

**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

**bronchus**
tube connected to the trachea that branches into many subsidiaries and provides a passageway for air to enter and leave the lungs

**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 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

**naris**
(plural = nares) opening of the nostrils

**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

**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

**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

**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

**Learning Objectives**

- Describe the overall function of the lung
- Summarize the blood flow pattern associated with the lungs
- Outline the anatomy of the blood supply to the lungs
- Describe the pleura 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 surface of the left lung, and it 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.

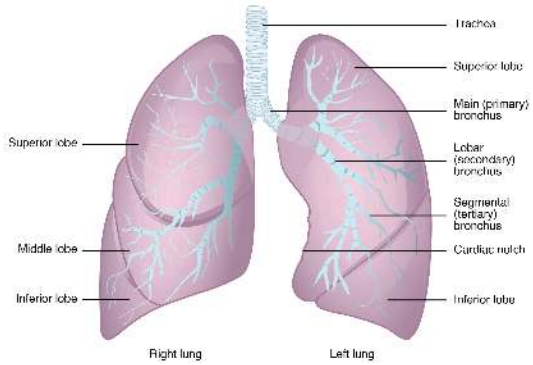



Figure 20.3.1: Gross Anatomy of the Lungs.

Each lung is composed of smaller units called lobes. Fissures separate these lobes from each other. The right lung consists of three lobes: the superior, middle, and inferior lobes. The left lung consists of two lobes: the superior and inferior lobes. 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 the both the parasympathetic and sympathetic nervous systems provides an important level of control through dilation and constriction of the airway.

### 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 artery** is an artery that arises from the pulmonary trunk and carries

deoxygenated, arterial blood to the alveoli. The 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 arteries 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.

## Pleura of the Lungs

Each lung is enclosed within a cavity that is surrounded by the pleura. The pleura (plural = pleurae) is a serous membrane that surrounds the 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.

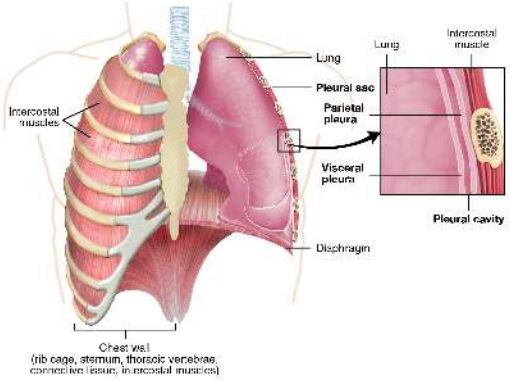



Figure 20.3.2: Parietal and Visceral Pleurae of the Lungs.

The pleurae perform two major functions: They produce pleural fluid and create cavities that separate the major organs. **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.

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.

## Chapter 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. 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 the bronchodilation and bronchoconstriction of the airways. The lungs are enclosed by the pleura, 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 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: C

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.

> A. 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 and is shorter than the left lung, due to the position of the liver underneath it. The left lung consist of two lobes and is longer and narrower than the right lung. The left lung has a concave region on the mediastinal surface called the cardiac notch that allows space for the heart.

Q. Why are the pleurae not damaged during normal breathing?

> A. There is a cavity, called the pleural cavity, between the parietal and visceral layers of the pleura. Mesothelial cells produce and secrete pleural fluid into the pleural cavity that acts as a lubricant. Therefore, as you breathe, the pleural fluid prevents the two layers of the pleura from rubbing against each other and causing damage due to friction.

## 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

**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

**lung**
organ of the respiratory system that performs gas exchange

**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 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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# CHAPTER OVERVIEW

## 21: The Digestive System


21.1: Introduction

21.2: Overview of the Digestive System

21.3: The Mouth, Pharynx, and Esophagus

21.4: The Stomach

21.5: The Small and Large Intestines

21.6: Accessory Organs in Digestion- The Liver, Pancreas, and Gallbladder


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# 21.1: Introduction

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: Overview of the Digestive System

**Learning Objectives**

- Identify the organs of the alimentary canal from proximal to distal, and briefly state their function
- Identify the accessory digestive organs and briefly state their 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
- Explain how the peritoneum anchors the digestive organs

The function of the digestive system is to break down the foods you eat, 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**).

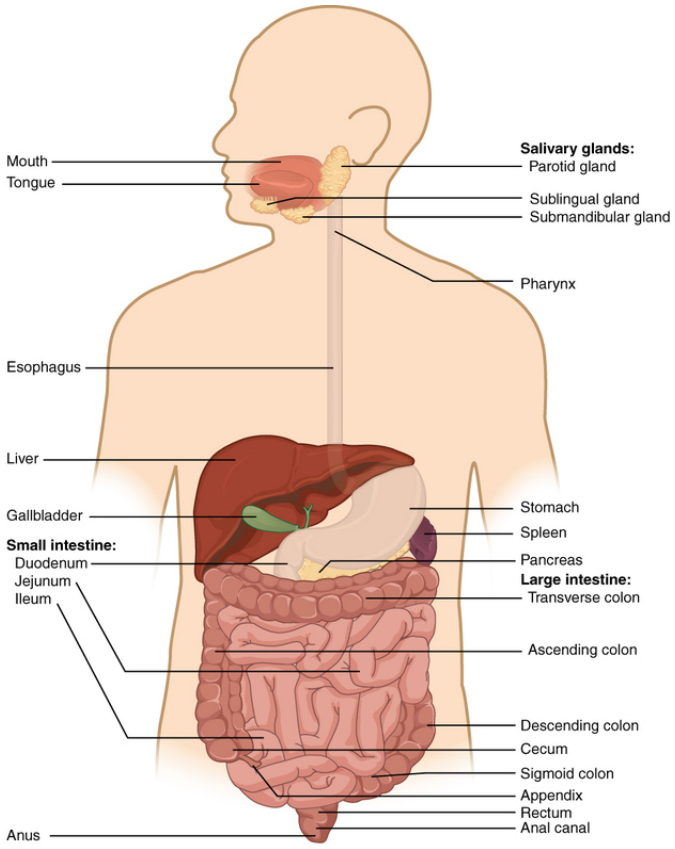



***Figure* 21.2.1*: Components of the Digestive System.*** *All digestive organs play integral roles in the life-sustaining process of digestion.*

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 SystemContribution 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 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. 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 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. 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 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 **21.2.2**). 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 their vital contributions, 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 their specific functions. 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**).

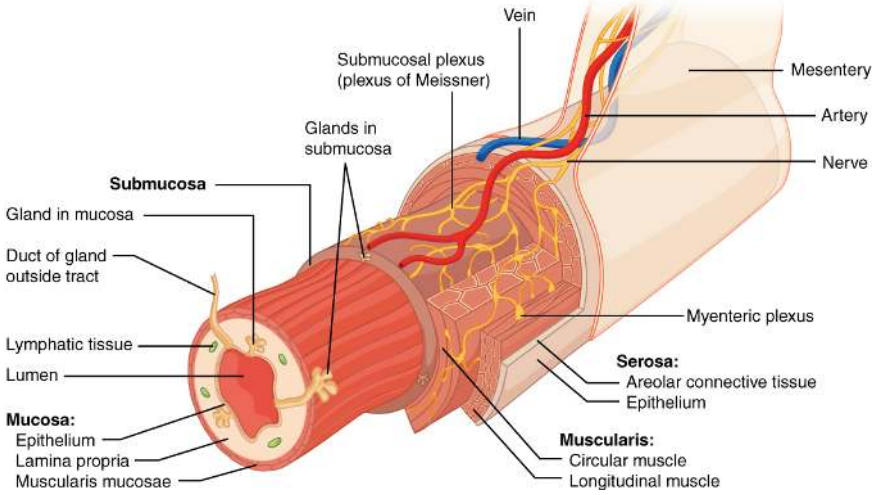



***Figure* 21.2.2*: Layers of the Alimentary Canal.*** *The wall of the alimentary canal has four basic tissue layers: the mucosa, submucosa, muscularis, and serosa.*

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 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 connective tissue, it connects the overlying mucosa to the underlying 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 muscalaris (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 and an outer longitudinal layer. 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 tenia coli, which make it look like a series of pouches rather than a simple tube.

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, and you would be unable to avoid biting yourself as you chew, an action enabled by the motor branches of cranial nerves.

Intrinsic 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, which includes both sympathetic and parasympathetic nerves. 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) 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 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.

## The 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 surrounded by 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**). The peritoneal cavity is the space bounded by the visceral and parietal peritoneal surfaces. A few milliliters of watery fluid act as a lubricant to minimize friction between the serosal surfaces of the peritoneum.

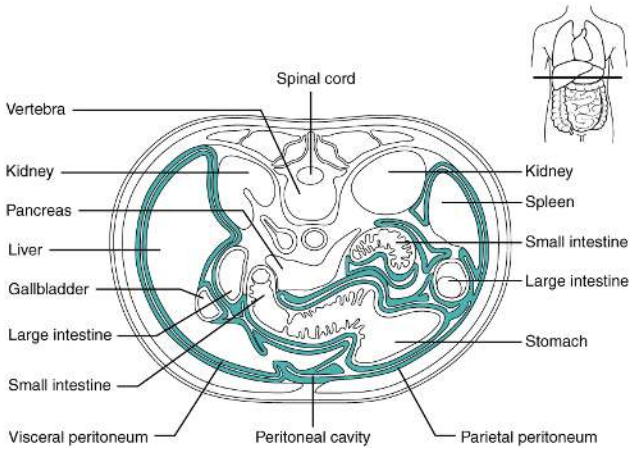



***Figure 21.2.3: The Peritoneum.*** *A cross-section of the abdomen shows the relationship between abdominal organs and the peritoneum (darker lines).*

### 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 still ranges from 30 to 40 percent.

The visceral peritoneum includes multiple large folds that envelope various abdominal organs, holding them to the dorsal surface of the body wall. Within these folds are blood vessels, lymphatic vessels, and nerves that innervate the organs with which they are in contact, supplying their adjacent organs. The five major peritoneal folds are described in Table **21.2.2**. 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.

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 | 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 |

## Chapter 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.

## Interactive Link Questions

By clicking on this link, you can watch a short video of what happens to the food you eat as it passes from your mouth to your intestine. Along the way, note how the food changes consistency and form. How does this change in consistency facilitate your gaining nutrients from food?

Answer: Answers may vary.

## Review Questions

Q. Which of these organs is not considered an accessory digestive structure?

A. mouth

B. salivary glands

C. pancreas

D. liver

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: A

Q. Which of the following membranes covers the stomach?

A. falciform ligament

B. mesocolon

C. parietal peritoneum

D. visceral peritoneum

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?

> 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?

> 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

## Contributors

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# 21.3: The Mouth, Pharynx, and Esophagus

**Learning Objectives**

- 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.

## The 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 **21.3.1**.

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 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 gums 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 digestion 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 **21.3.1**).

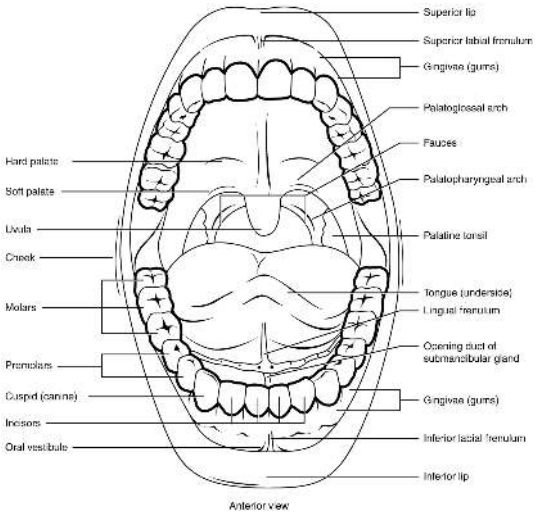



Figure **21.3.1**: Mouth. The mouth includes the lips, tongue, palate, gums, and teeth.

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 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, the **palatoglossal arch** lies next to the base of the tongue; behind 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.

## The 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, extensions of lamina propria of the mucosa, which are covered in stratified squamous epithelium (Figure 21.3.2). 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 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.

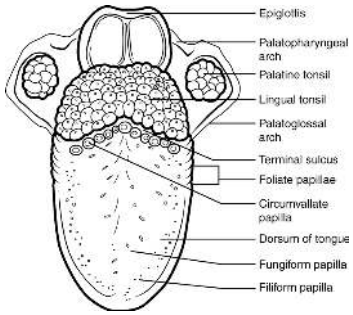



Figure 21.3.2: Tongue. This superior view of the tongue shows the locations and types of lingual papillae.

## The 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. Secretion increases 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.

### The 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:

- The **submandibular glands**, which are in the floor of the mouth, secrete saliva into the mouth through the submandibular ducts.
- The **sublingual glands**, which lie below the tongue, use the 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 (Figure **21.3.3**).

### Saliva

**Saliva** is essentially (95.5 percent) water. The remaining 4.5 percent is a complex mixture of ions, glycoproteins, enzymes, growth factors, and waste products. Perhaps the most important ingredient in salvia 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, 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.

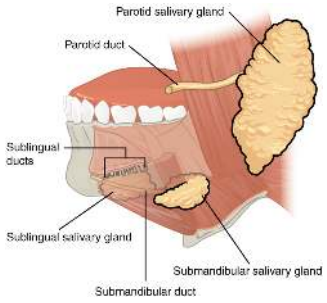



Figure **21.3.3**: Salivary glands. The major salivary glands are located outside the oral mucosa and deliver saliva into the mouth through ducts.

HOMEOSTATIC IMBALANCES

**The Parotid Glands: Mumps**

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 by 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.

## The 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**. Moving from the center of the mouth toward the side, these are as follows (Figure **21.3.4**):

- 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.

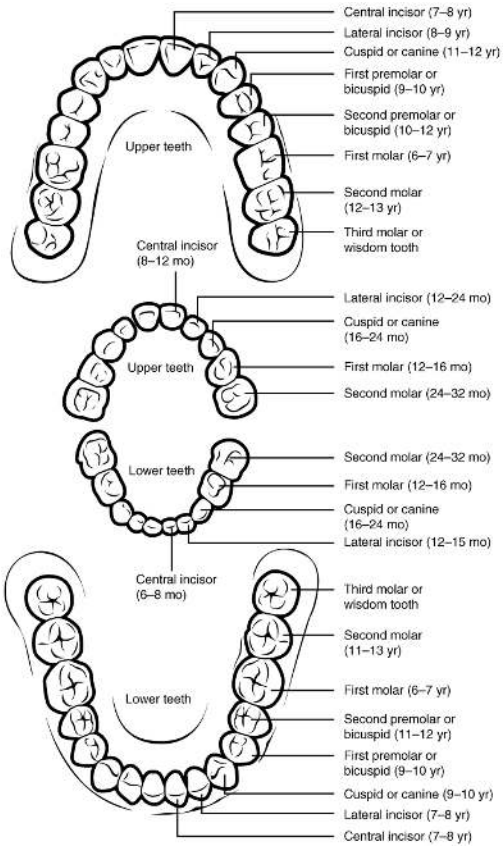



Figure **21.3.4**: Permanent and Deciduous Teeth. This figure of two human dentitions shows the arrangement of teeth in the maxilla and mandible, and the relationship between the deciduous and permanent teeth.

## 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 a 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 and mandible. Both parts contain an inner **pulp cavity**, containing loose connective tissue through which run 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 **21.3.5**).

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. The digestive functions of the mouth are summarized in Table **21.3.1**.

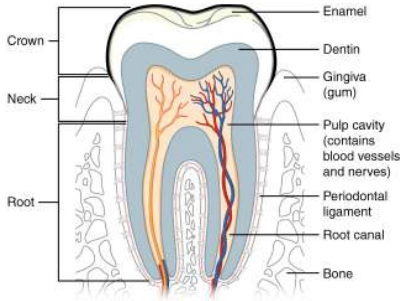



Figure **21.3.5**: The Structure of the Tooth. This longitudinal section through a molar in its alveolar socket shows the relationships between enamel, dentin, and pulp.

## The 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. It has three subdivisions. The most superior, the nasopharynx, is involved only in breathing and speech. 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 **21.3.6**). 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.

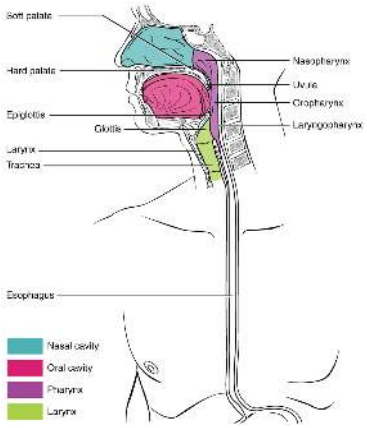



Figure **21.3.6**: Pharynx. The pharynx runs from the nostrils to the esophagus and the larynx.

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.

## The 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. As you can see in Figure **21.3.7**, 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.

### 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. 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, 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).

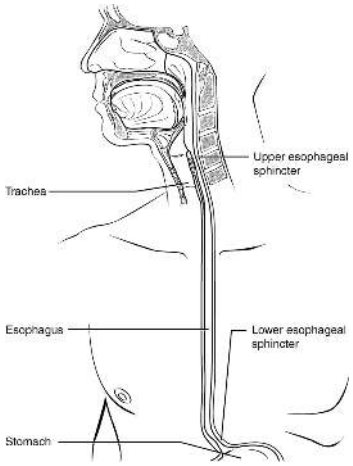



Figure 21.3.7: Esophagus. The upper esophageal sphincter controls the movement of food from the pharynx to the esophagus. The lower esophageal sphincter controls the movement of food from the esophagus to the stomach.

### 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 loose connective tissue of the adventitia is not covered by a fold of visceral peritoneum. The digestive functions of the esophagus are identified in Table 21.3.2.

## Chapter Review

In the mouth, the tongue and the teeth begin mechanical digestion, and saliva begins chemical digestion. 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.

## Interactive Link Questions

Watch this animation to see how swallowing is a complex process that involves the nervous system to coordinate the actions of upper respiratory and digestive activities. During which stage of swallowing is there a risk of food entering respiratory pathways and how is this risk blocked?

Answer: Answers may vary.

## Review Questions

Q. Which of these ingredients in saliva is responsible for activating salivary amylase?

A. mucus

B. phosphate ions

C. chloride ions

D. urea

Answer: C

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: B

Q. Which structure is located where the esophagus penetrates the diaphragm?

A. esophageal hiatus

B. cardiac orifice

C. upper esophageal sphincter

D. lower esophageal sphincter

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: 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.

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?

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?

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.

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. Describe the three processes involved in the esophageal phase of deglutition.

A. Peristalsis moves the bolus down the esophagus and toward the stomach. Esophageal glands secrete mucus that lubricates the bolus and reduces friction. When the bolus nears the stomach, the lower esophageal sphincter relaxes, allowing the bolus to pass into the stomach.

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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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# 21.4: The Stomach

**Learning Objectives**

- 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, this is not true. 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 **21.4.1**). 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 a large fold called a **ruga**.

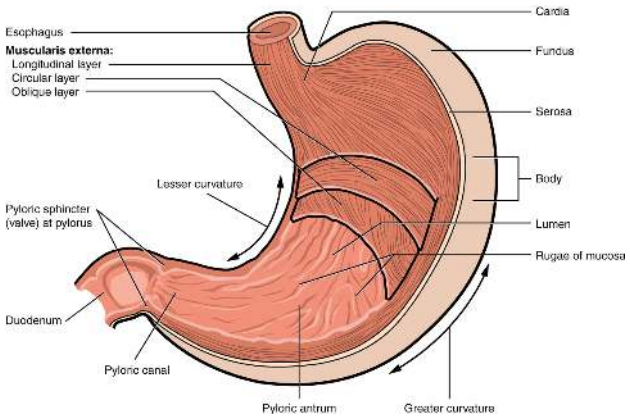



Figure **21.4.1**: Stomach. The stomach has four major regions: the cardia, fundus, body, and pylorus. The addition of an inner oblique smooth muscle layer gives the muscularis the ability to vigorously churn and mix food.

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 to the posterior abdominal wall.

## 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 **21.4.2**). As a result, in addition to moving food through the canal, the stomach can vigorously churn food, mechanically breaking it down into smaller particles.

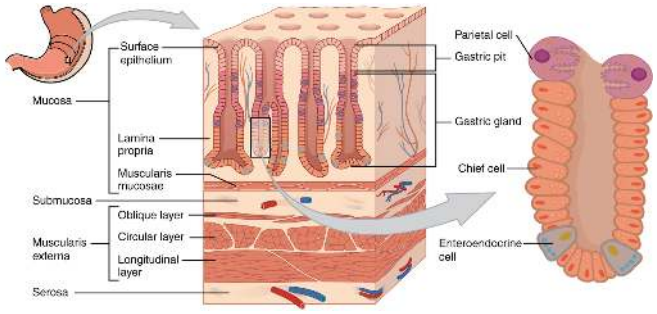



Figure **21.4.2**: Histology of the Stomach. The stomach wall is adapted for the functions of the stomach. In the epithelium, gastric pits lead to gastric glands that secrete gastric juice. The gastric glands (one gland is shown enlarged on the right) contain different types of cells that secrete a variety of enzymes, including hydrochloride acid, which activates the protein-digesting enzyme pepsin.

The stomach mucosa's epithelial lining consists only of surface mucus 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 each **gastric gland**, which secretes a complex digestive fluid referred to as gastric juice.

Although the walls of the gastric pits are made up primarily of mucus 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.

*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**.

Table **21.4.1** describes the digestive functions of important hormones secreted by the stomach.

*Watch this animation that depicts the structure of the stomach and how this structure functions in the initiation of protein digestion. This view of the stomach shows the characteristic rugae. What is the function of these rugae?*

Table 21.4.1: 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 |
| 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 |

## Chapter Review

The stomach participates in all digestive activities except ingestion and defecation. It vigorously churns food. It secretes gastric juices that break down food and absorbs certain drugs, including aspirin and some alcohol. The stomach begins the digestion of protein and continues the digestion of

carbohydrates and fats. It stores food as an acidic liquid called chyme, and releases it gradually into the small intestine through the pyloric sphincter.

## Interactive Link Questions

Watch this animation that depicts the structure of the stomach and how this structure functions in the initiation of protein digestion. This view of the stomach shows the characteristic rugae. What is the function of these rugae?

Answer: Answers may vary.

## Review Questions

Q. Which of these cells secrete hormones?

A. parietal cells

B. mucous neck cells

C. enteroendocrine cells

D. chief cells

Answer: C

Q. Parietal cells secrete _____.

A. gastrin

B. hydrochloric acid

C. pepsin

D. pepsinogen

Answer: B

## Critical Thinking Questions

Q. Describe unique anatomical features that enable the stomach to perform digestive functions.

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

## Contributors and Attributions

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# 21.5: The Small and Large Intestines

**Learning Objectives**

- 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.

## The 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 **21.5.1**).

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.

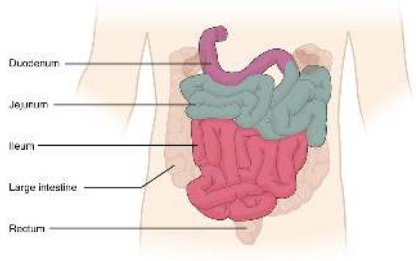



Figure **21.5.1**: Small Intestine. The three regions of the small intestine are the duodenum, jejunum, and ileum.

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-fold, include circular folds, villi, and microvilli (Figure 21.5.2). These adaptations are most abundant in the proximal two-thirds of the small intestine, where the majority of absorption occurs.

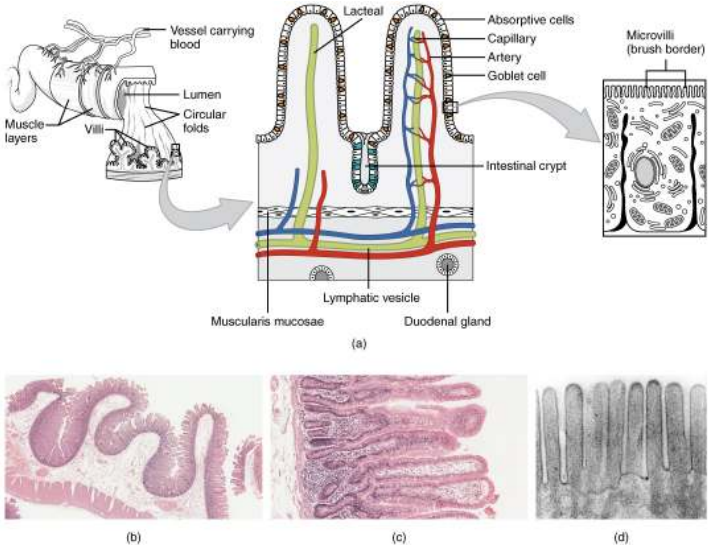



Figure 21.5.2: Histology of the Small Intestine. (a) The absorptive surface of the small intestine is vastly enlarged by the presence of circular folds, villi, and microvilli. (b) Micrograph of the circular folds. (c) Micrograph of the villi. (d) Electron micrograph of the microvilli. From left to right, 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)

## Circular folds

Also called a plica circulare, a **circular fold** is a deep ridge in the mucosa and submucosa. Beginning near the proximal part of the duodenum and ending near the middle of the ileum, these folds facilitate absorption. 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 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 $\mu$m) 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. 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 MALT

The lamina propria of the small intestine mucosa is studded with quite a bit of 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.

DISORDERS OF THE Small Intestine: 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.

## The 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 is more than twice the diameter of the small intestine, about 3 inches.

### Subdivisions

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 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. 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**. 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 **21.5.4**). 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.

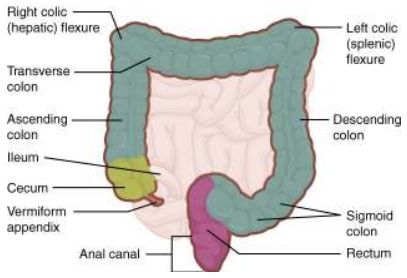



Figure **21.5.4**: Large Intestine. The large intestine includes the cecum, colon, and rectum.

HOMEOSTATIC IMBALANCES

**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 **21.5.5**). 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 enterocytes (absorptive cells) and goblet cells. In addition, the wall of the large intestine 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.

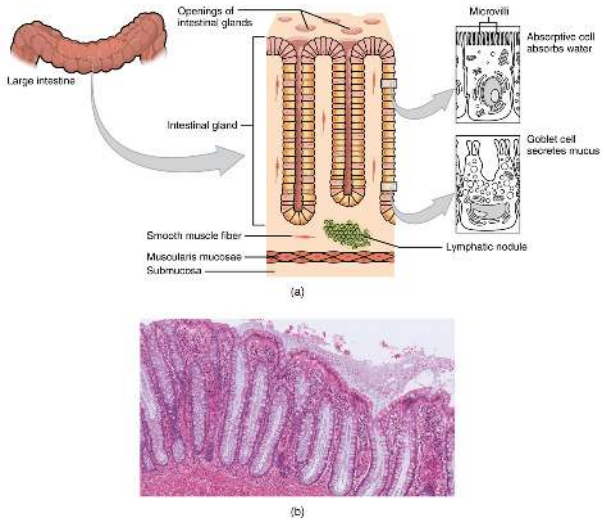



Figure 21.5.5: Histology of the large Intestine. (a) The histologies of the large intestine and small intestine (not shown) are adapted for the digestive functions of each organ. (b) This micrograph shows the colon's simple columnar epithelium and goblet cells. LM x 464. (credit b: Micrograph provided by the Regents of University of Michigan Medical School © 2012)

## Anatomy

Three features are unique to the large intestine: teniae coli, haustra, and epiploic appendages (Figure 21.5.6). 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.

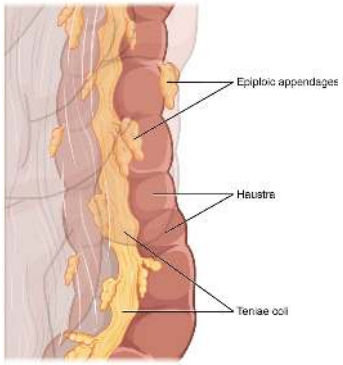



Figure 21.5.6: Teniae Coli, Haustra, and Epiploic Appendages.

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.

## Chapter 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.

## Interactive Link Questions

Watch this animation that depicts the structure of the small intestine, and, in particular, the villi. Epithelial cells continue the digestion and absorption of nutrients and transport these nutrients to the lymphatic and circulatory systems. In the small intestine, the products of food digestion are absorbed by different structures in the villi. Which structure absorbs and transports fats?

Answer: Answers may vary.

By watching this animation, you will see that for the various food groups—proteins, fats, and carbohydrates—digestion begins in different parts of the digestion system, though all end in the same place. Of the three major food classes (carbohydrates, fats, and proteins), which is digested in the mouth, the stomach, and the small intestine?

Answer: Answers may vary.

## Review Questions

Q. In which part of the alimentary canal does most digestion occur?

A. stomach

B. proximal small intestine

C. distal small intestine

D. ascending colon

> Answer: B

Q. Which of these is most associated with villi?

A. haustra

B. lacteals

C. bacterial flora

D. intestinal glands

> Answer: B

Q. What is the role of the small intestine's MALT?

A. secreting mucus

B. buffering acidic chyme

C. activating pepsin

D. preventing bacteria from entering the bloodstream

> 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. Explain how nutrients absorbed in the small intestine pass into the general circulation.

> A. 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. Why is it important that chyme from the stomach is delivered to the small intestine slowly and in small amounts?

> A. If large quantities of chyme were forced into the small intestine, it would result in osmotic water loss from the blood into the intestinal lumen that could cause potentially life-threatening low blood volume and erosion of the duodenum.

Q. Describe three of the differences between the walls of the large and small intestines.

> 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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# 21.6: Accessory Organs in Digestion- The Liver, Pancreas, and Gallbladder

**Learning Objectives**

- 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 **21.6.1**). 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.

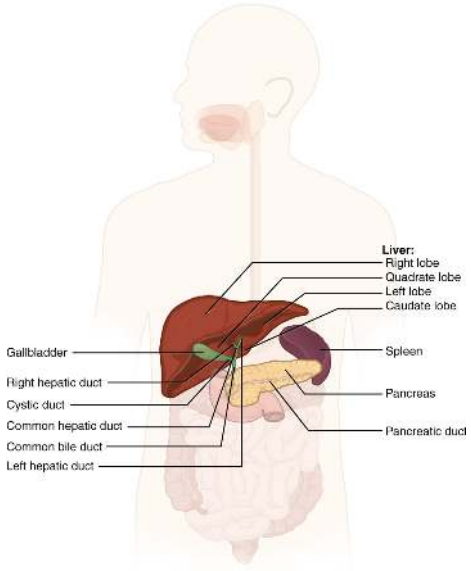



Figure **21.6.1**: Accessory Organs. The liver, pancreas, and gallbladder are considered accessory digestive organs, but their roles in the digestive system are vital.

## The 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 **21.6.2**, 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.

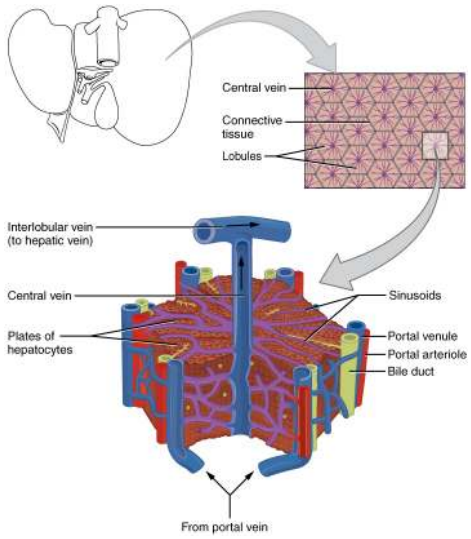



Figure 21.6.2: Microscopic Anatomy of the Liver. The liver receives oxygenated blood from the hepatic artery and nutrient-rich deoxygenated blood from the hepatic portal vein.

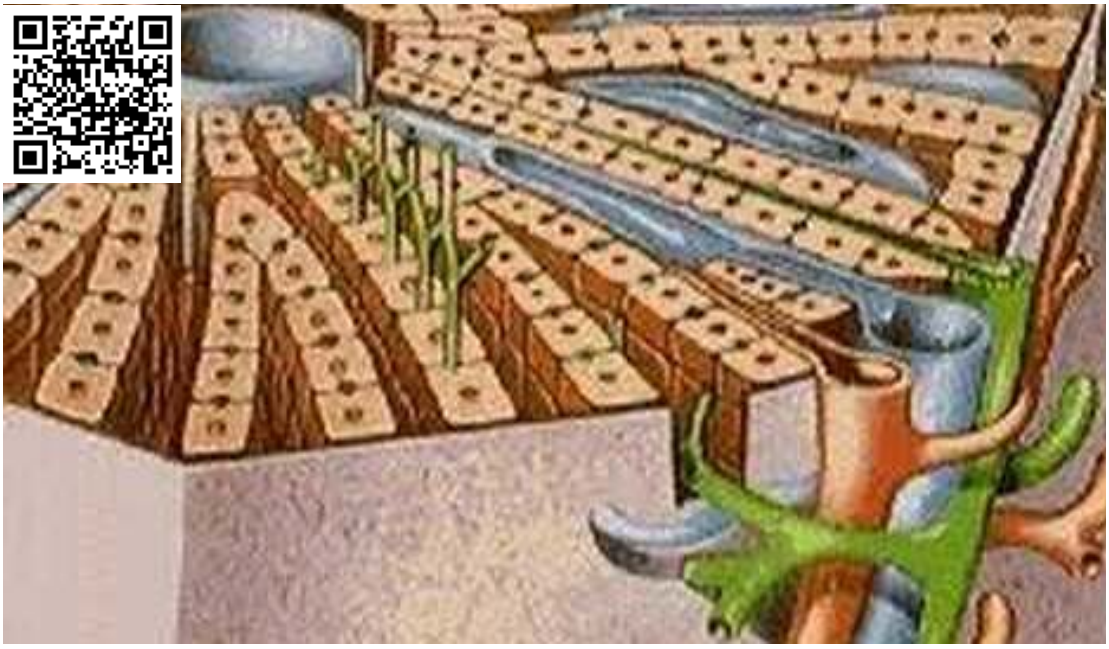
## Histology

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 portal vein in each **hepatic lobule**.

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 here, 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**. 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. The **portal triad** is a distinctive arrangement around the perimeter of hepatic lobules, consisting of three basic structures: a bile duct, a hepatic artery branch, and a hepatic portal vein branch.

*Watch this video to see the structure of the liver and how this structure supports the functions of the liver, including the processing of nutrients, toxins, and wastes. At rest, about 1500 mL of blood per minute flow through the liver. What percentage of this blood flow comes from the hepatic portal system?*



## The 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 is a curious mix of exocrine (secreting digestive enzymes) and endocrine (releasing hormones into the blood) functions (Figure **21.6.3**).

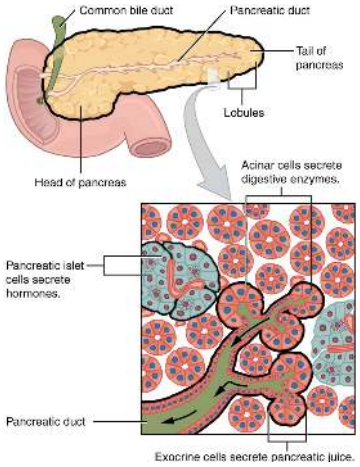



Figure **21.6.3**: Exocrine and Endocrine Pancreas. The pancreas has a head, a body, and a tail. It delivers pancreatic juice to the duodenum through the pancreatic duct.

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), 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.

## The Gallbladder

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. 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 **21.6.4**). 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.

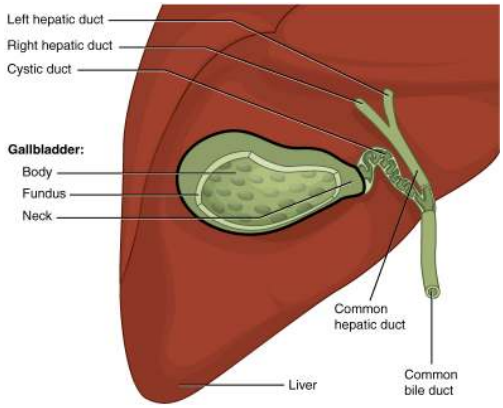



Figure **21.6.4**: Gallbladder. The gallbladder stores and concentrates bile, and releases it into the two-way cystic duct when it is needed by the small intestine.

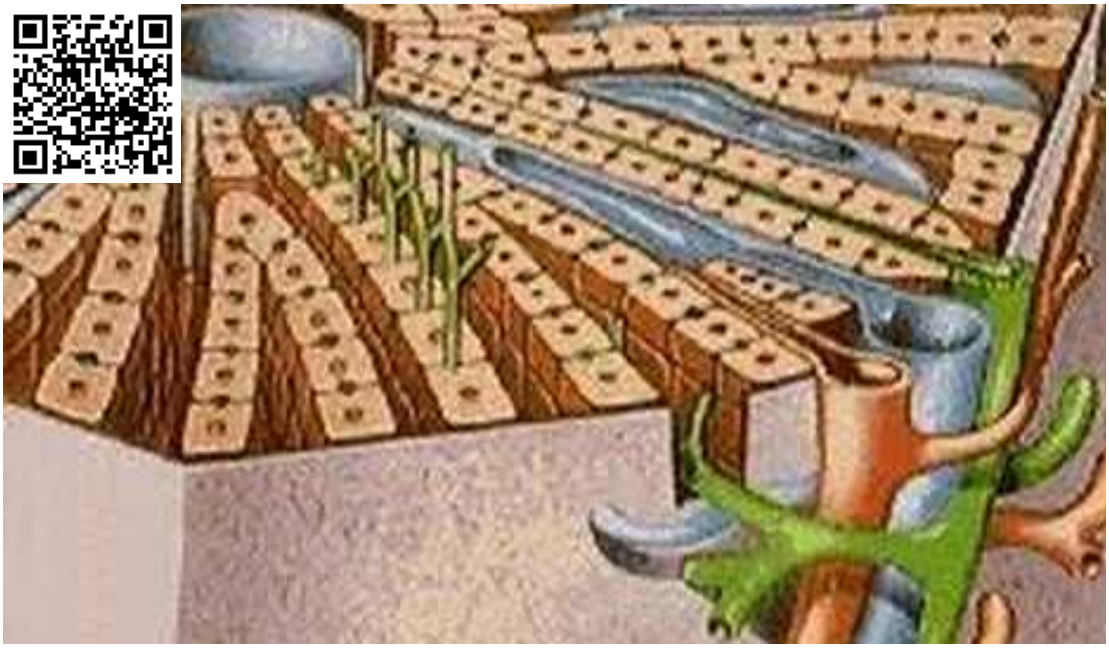
## Chapter Review

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.

## Interactive Link Questions

Watch this video to see the structure of the liver and how this structure supports the functions of the liver, including the processing of nutrients, toxins, and wastes. At rest, about 1500 mL of blood per minute flow through the liver. What percentage of this blood flow comes from the hepatic portal system?



Answer: Answers may vary.

## Review Questions

### Critical Thinking Questions

Q. Why does the pancreas secrete some enzymes in their inactive forms, and where are these enzymes activated?

> A. The pancreas secretes protein-digesting enzymes in their inactive forms. If secreted in their active forms, they would self-digest the pancreas. These enzymes are activated in the duodenum.

Q. Describe the location of hepatocytes in the liver and how this arrangement enhances their function.

> 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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# CHAPTER OVERVIEW

## 22: The Urinary System


22.1: Prelude to the Urinary System

22.2: Gross Anatomy of Urine Transport

22.3: Gross Anatomy of the Kidney

22.4: Microscopic Anatomy of the Kidney


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# 22.1: Prelude to the Urinary System

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# 22.2: Gross Anatomy of Urine Transport

**Learning Objectives**

- 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
- Describe voluntary and involuntary neural control of micturition

Rather than start with urine formation, this section will start with urine excretion. 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 due to the wide range of pH and osmolarity of the urine, prevents infection by foreign organisms, and for the male, provides reproductive functions.

## 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 22.2.1).

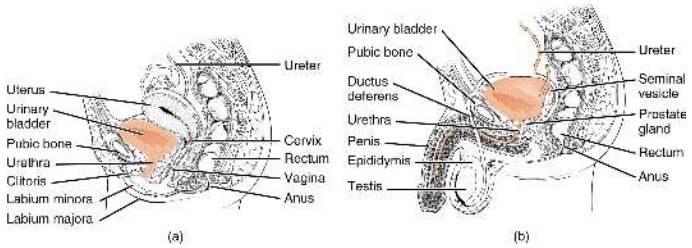



Figure 22.2.1: Female and Male Urethras.The urethra transports urine from the bladder to the outside of the body. This image shows (a) a female urethra and (b) a male urethra.

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 22.2.1.a). 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 22.2.1.b). 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.

## Bladder

The urinary bladder collects urine from both ureters (Figure **22.2.2**). 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.

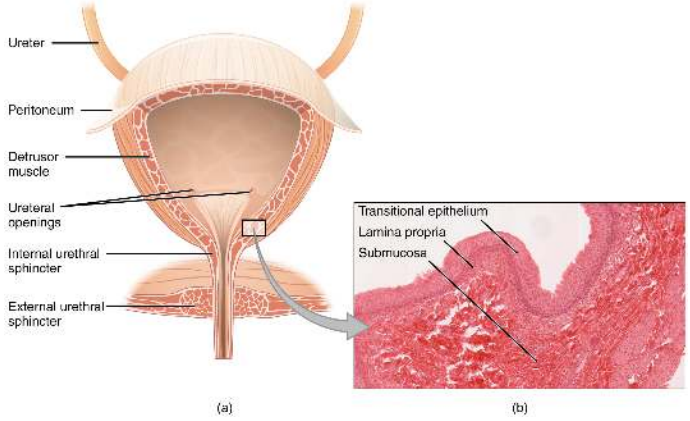



Figure **22.2.2**: Bladder. (a) Anterior cross section of the bladder. (b) The detrusor muscle of the bladder (source: monkey tissue) LM × 448. (Micrograph provided by the Regents of the University of Michigan Medical School © 2012)

View the University of Michigan WebScope at 141.214.65.171/Histology/Urin....svs/view.apml to explore the tissue sample in greater detail.

The bladder is a highly distensible organ 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 **22.2.2**). 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.

## 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. The inner mucosa is lined with transitional epithelium (Figure **22.2.4**) 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.

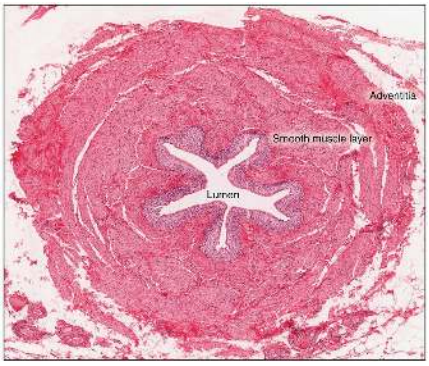



Figure **22.2.4**: Ureter. Peristaltic contractions help to move urine through the lumen with contributions from fluid pressure and gravity. LM × 128. (Micrograph provided by the Regents of the University of Michigan Medical School © 2012)

## Chapter Review

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. The bladder is largely retroperitoneal and can hold up to 500–600 mL urine. 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. 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.

## Review Questions

Q. Peristaltic contractions occur in the _____.

A. urethra

B. bladder

C. ureters

D. urethra, bladder, and ureters

Answer: C

Q. Which part of the urinary system is *not* completely retroperitoneal?

A. kidneys

B. ureters

C. bladder

D. nephrons

Answer: C

## Critical Thinking Questions

Q. Why are females more likely to contract bladder infections than males?

> A. The longer urethra of males means bacteria must travel farther to the bladder to cause an infection.

Q. Describe how forceful urination is accomplished.

> A. Forceful urination is accomplished by contraction of abdominal muscles.

## 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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# 22.3: Gross Anatomy of the Kidney

**Learning Objectives**

- 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
- Compare and contrast the cortical and juxtamedullary nephrons
- Name structures found in the cortex and medulla
- Describe the physiological characteristics of the cortex and medulla

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.

## 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 **22.3.1**). 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.

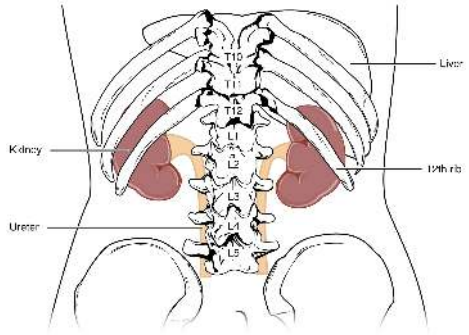



Figure **22.3.1**: Kidneys. The kidneys are slightly protected by the ribs and are surrounded by fat for protection (not shown).

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.

## Internal Anatomy

A frontal section through the kidney reveals an outer region called the **renal cortex** and an inner region called the **medulla** (Figure **22.3.2**). 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 to the **calyces** of the kidney 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.

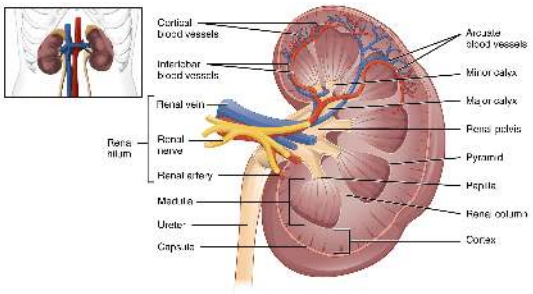



Figure **22.3.2**: Left Kidney.

## 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 calyxes 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.

### Nephrons and Vessels

The renal artery first divides into segmental arteries, followed by further branching to form interlobar arteries that pass through the renal columns to reach the cortex (Figure **22.3.3**). The interlobar arteries, in turn, branch into arcuate arteries, cortical radiate arteries, and then into afferent arterioles. The afferent arterioles service about 1.3 million nephrons in each kidney.

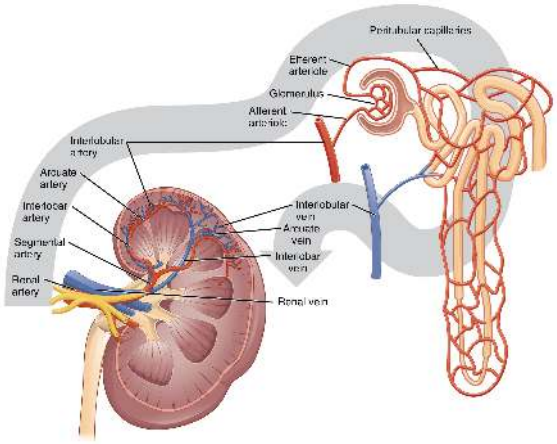



Figure **22.3.3**: Blood Flow in the Kidney.

**Nephrons** are the “functional units” of the kidney; they cleanse the blood and balance the constituents of the circulation. The afferent arterioles form a tuft of high-pressure capillaries about 200 µm in diameter, 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**. The glomerulus and Bowman’s capsule together form the **renal corpuscle**. As mentioned earlier, 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** (Figure **22.3.4**). These will next form a capillary network around the more distal portions of the nephron tubule, the **peritubular capillaries** and **vasa recta**, before returning to the venous system. 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.)

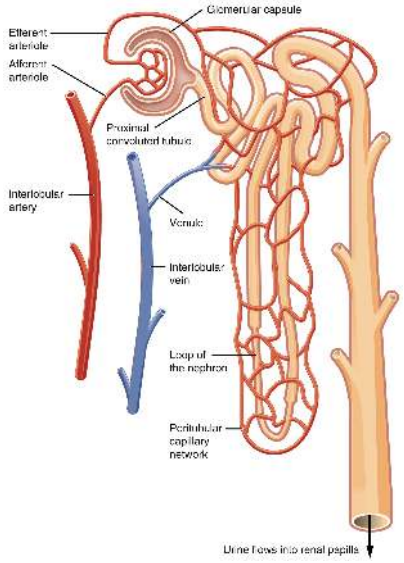



Figure 22.3.4: Blood Flow in the Nephron. The two capillary beds are clearly shown in this figure. The efferent arteriole is the connecting vessel between the glomerulus and the peritubular capillaries and vasa recta.

Visit this link to view an interactive tutorial of the flow of blood through the kidney.

### Cortex

In a dissected kidney, it is easy to identify the cortex; it appears lighter in color compared to the rest of the kidney. 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**.

## Chapter 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: D

Q. The primary structure found within the medulla is the _____.

A. loop of Henle

B. minor calyces

C. portal system

D. ureter

> 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: A

## Critical Thinking Questions

Q. What anatomical structures provide protection to the kidney?

> 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?

> A. The renal portal system has an artery between the first and second capillary bed. The others have a vein.

Q. Name the structures found in the renal hilum.

> A. The structures found in the renal hilum are arteries, veins, ureters, lymphatics, and nerves.

## 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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# 22.4: Microscopic Anatomy of the Kidney

**Learning Objectives**

- Distinguish the histological differences between the renal cortex and medulla
- Describe the structure of the filtration membrane
- Identify the major structures and subdivisions of the renal corpuscles, renal tubules, and renal capillaries
- Discuss the function of the peritubular capillaries and vasa recta
- 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 **22.4.1**). 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 **22.4.2**). These three features 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.

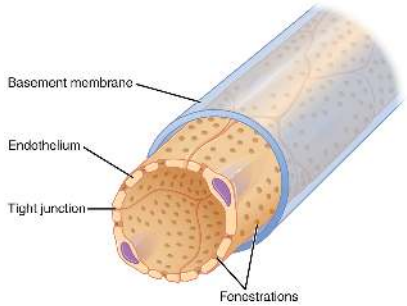



Figure **22.4.2**: Fenestrated Capillary. Fenestrations allow many substances to diffuse from the blood based primarily on size.

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)** (Figure 22.4.3). 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. In response to the concentration of $Na^+$ in the fluid flowing past them, these cells release paracrine signals. They also have a single, nonmotile cilium that responds to the rate of fluid movement in the tubule. The paracrine signals released in response to changes in flow rate and $Na^+$ concentration are adenosine triphosphate (ATP) and adenosine.

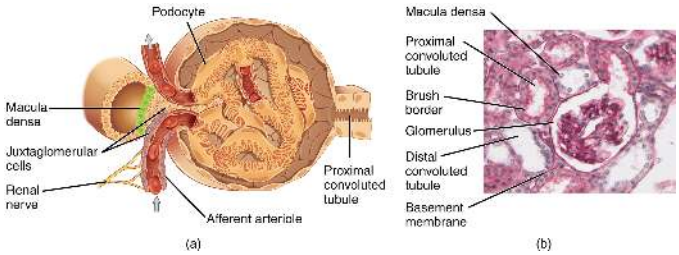



Figure 22.4.3: Juxtaglomerular Apparatus and Glomerulus. (a) The JGA allows specialized cells to monitor the composition of the fluid in the DCT and adjust the glomerular filtration rate. (b) This micrograph shows the glomerulus and surrounding structures. LM × 1540. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

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. If the osmolarity of the filtrate is too high (hyperosmotic), the juxtaglomerular cells will contract, decreasing the glomerular filtration rate (GFR) so less plasma is filtered, leading to less urine formation and greater retention of fluid. This will ultimately decrease blood osmolarity toward the physiologic norm. If the osmolarity of the filtrate is too low, the juxtaglomerular cells will relax, increasing the GFR and enhancing the loss of water to the urine, causing blood osmolarity to rise. In other words, when osmolarity goes up, filtration and urine formation decrease and water is retained. When osmolarity goes down, filtration and urine formation increase and water is lost by way of the urine. The net result of these opposing actions is to keep the rate of filtration relatively constant. A second function of the macula densa cells is to regulate renin release from the juxtaglomerular cells of the afferent arteriole (Figure 22.4.4). Active renin is a protein comprised of 304 amino acids that cleaves several amino acids from **angiotensinogen** to produce **angiotensin I**. Angiotensin I is not biologically active until converted to angiotensin II by **angiotensin-converting enzyme (ACE)** from the lungs. **Angiotensin II** is a systemic vasoconstrictor that helps to regulate blood pressure by increasing it. Angiotensin II also stimulates the release of the steroid hormone aldosterone from the adrenal cortex. Aldosterone stimulates $Na^+$ reabsorption by the kidney, which also results in water retention and increased blood pressure.

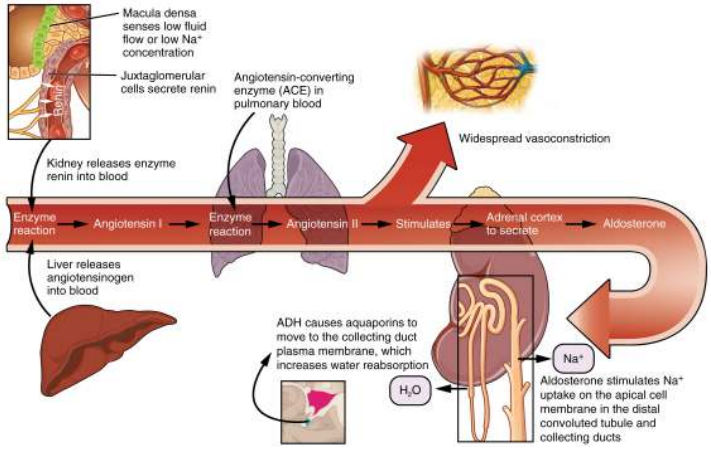



Figure **22.4.4**: Conversion of Angiotensin I to Angiotensin II. The enzyme renin converts the pro-enzyme angiotensin I; the lung-derived enzyme ACE converts angiotensin I into active angiotensin II.

## 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. As you will see later, 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. 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 **22.4.5**).

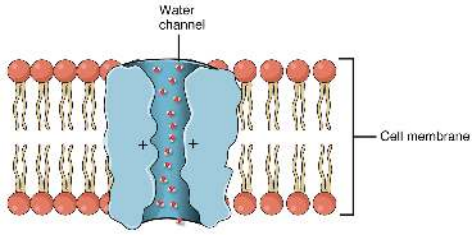



Figure **22.4.5**: Aquaporin Water Channel. Positive charges inside the channel prevent the leakage of electrolytes across the cell membrane, while allowing water to move due to osmosis.

## Chapter Review

The functional unit of the kidney, the nephron, consists of the renal corpuscle, PCT, loop of Henle, and DCT. Cortical nephrons have short loops of Henle, whereas juxtamedullary nephrons have long loops of Henle extending into the medulla. About 15 percent of nephrons are juxtamedullary. 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: B

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: C

Q. The functional unit of the kidney is called _____.

A. the renal hilus

B. the renal corpuscle

C. the nephron

D. Bowman's capsule

Answer: C

## Critical Thinking Questions

Q. Which structures make up the renal corpuscle?

> A. The structures that make up the renal corpuscle are the glomerulus, Bowman's capsule, and PCT.

Q. What are the major structures comprising the filtration membrane?

> 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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# CHAPTER OVERVIEW

## 23: The Reproductive System

**Chapter 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

23.1: Prelude to the Reproductive System
23.2: Anatomy and Physiology of the Male Reproductive System
23.3: Anatomy and Physiology of the Female Reproductive System
23.4: Development of the Male and Female Reproductive Systems

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# 23.1: Prelude to the Reproductive System

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.

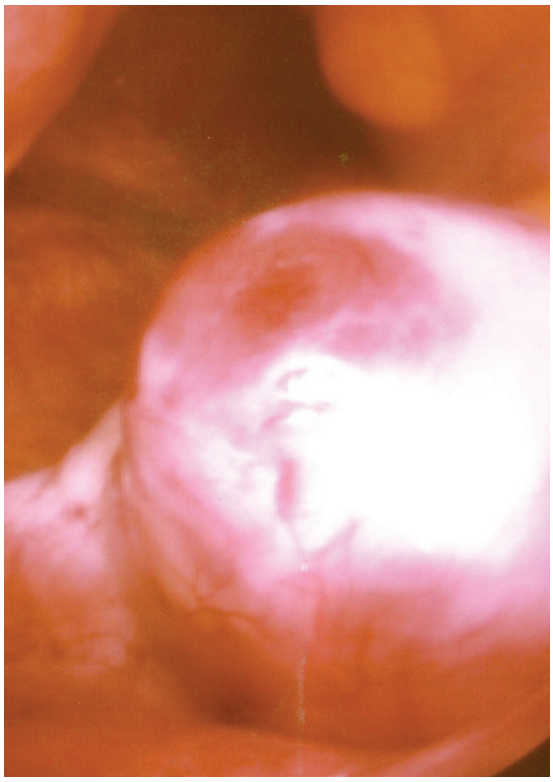


Figure **23.1.1**: Ovulation. Following a surge of luteinizing hormone (LH), an oocyte (immature egg cell) will be released into the uterine tube, where it will then be available to be fertilized by a male's sperm. Ovulation marks the end of the follicular phase of the ovarian cycle and the start of the luteal phase.

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# 23.2: Anatomy and Physiology of the Male Reproductive System

**Learning Objectives**

- 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 (Figure **23.2.1**) is to produce sperm and transfer them to the female reproductive tract. 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.

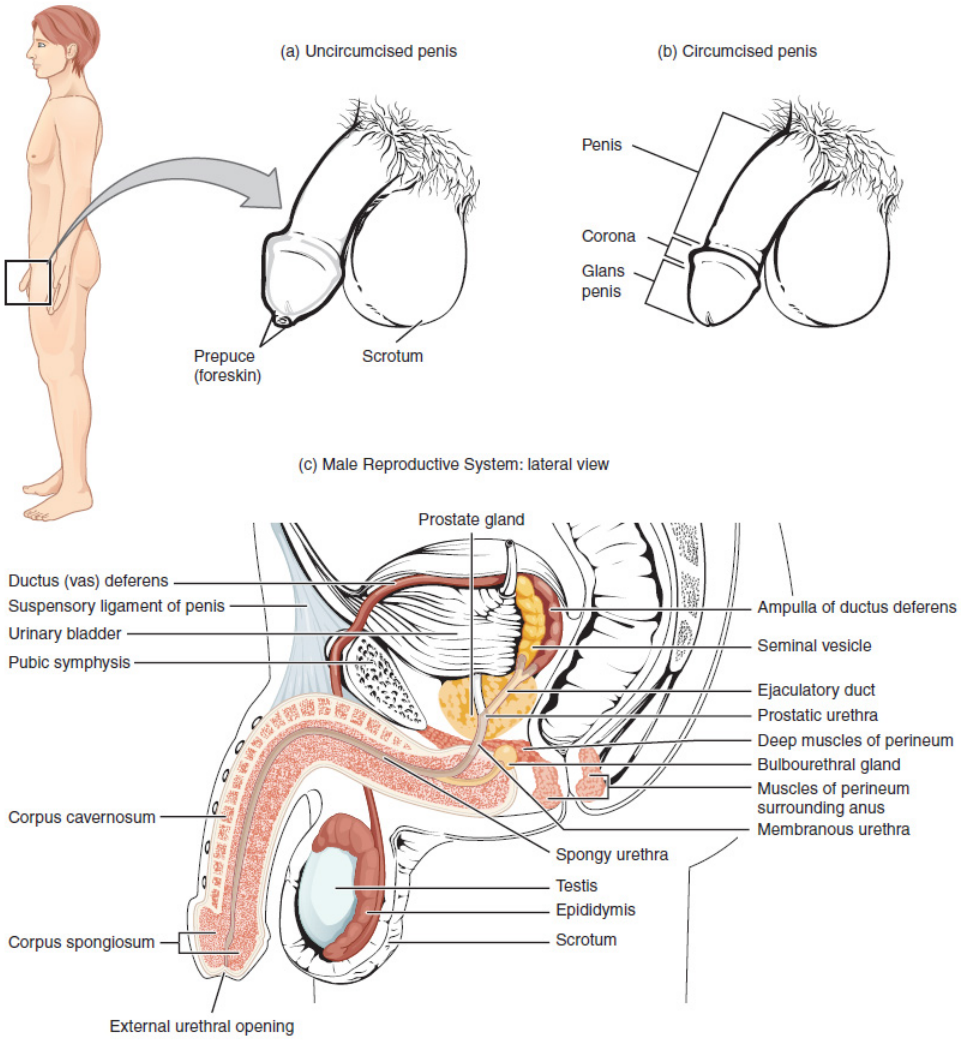



Figure **23.2.1**: Male Reproductive System. The structures of the male reproductive system include the testes, the epididymides, the penis, and the ducts and glands that produce and carry semen. Sperm exit the scrotum through the ductus deferens, which is bundled in the spermatic cord. The seminal vesicles and prostate gland add fluids to the sperm to create semen.

## 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 raphae.

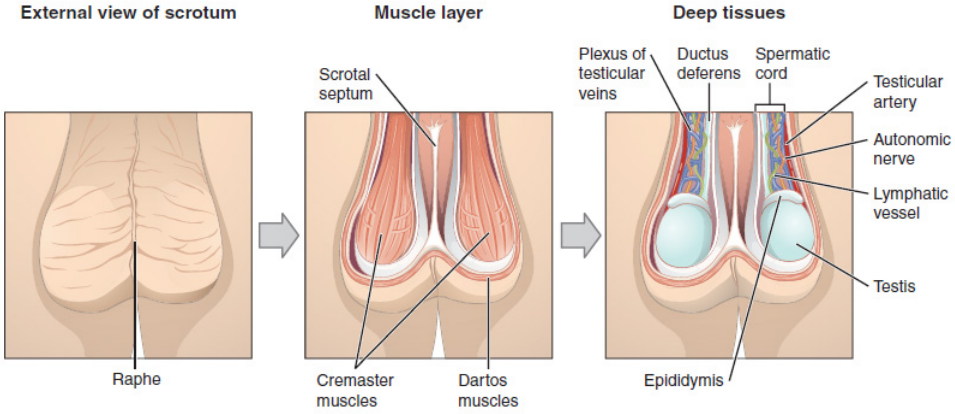



Figure **23.2.2**: The Scrotum and Testes. This anterior view shows the structures of the scrotum and testes.

## 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 (Figure **23.2.3**). 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. 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.

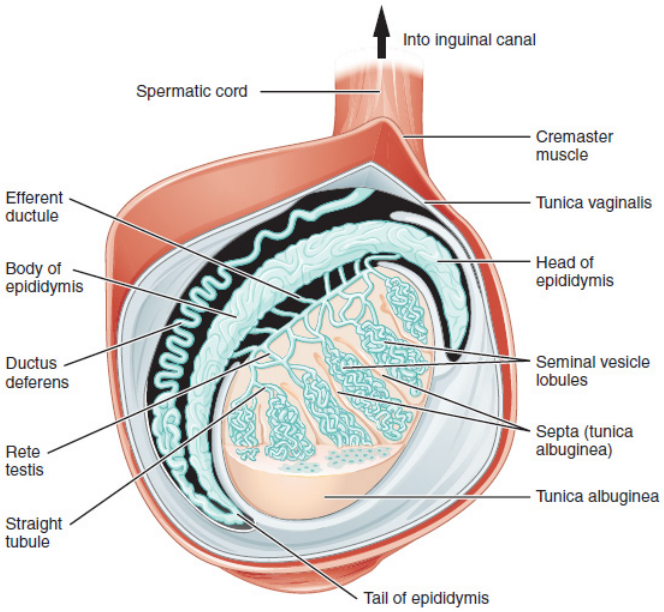



Figure **23.2.3**: Anatomy of the Testis. This sagittal view shows the seminiferous tubules, the site of sperm production. Formed sperm are transferred to the epididymis, where they mature. They leave the epididymis during an ejaculation via the ductus deferens.

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.

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**. Sertoli cells are a type of supporting cell called a sustentacular cell, 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. 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 (see 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 (Figure **23.2.4**). Because these cells are diploid (2*n*), they each have a complete copy of the father's genetic material, or 46 chromosomes. However, 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.

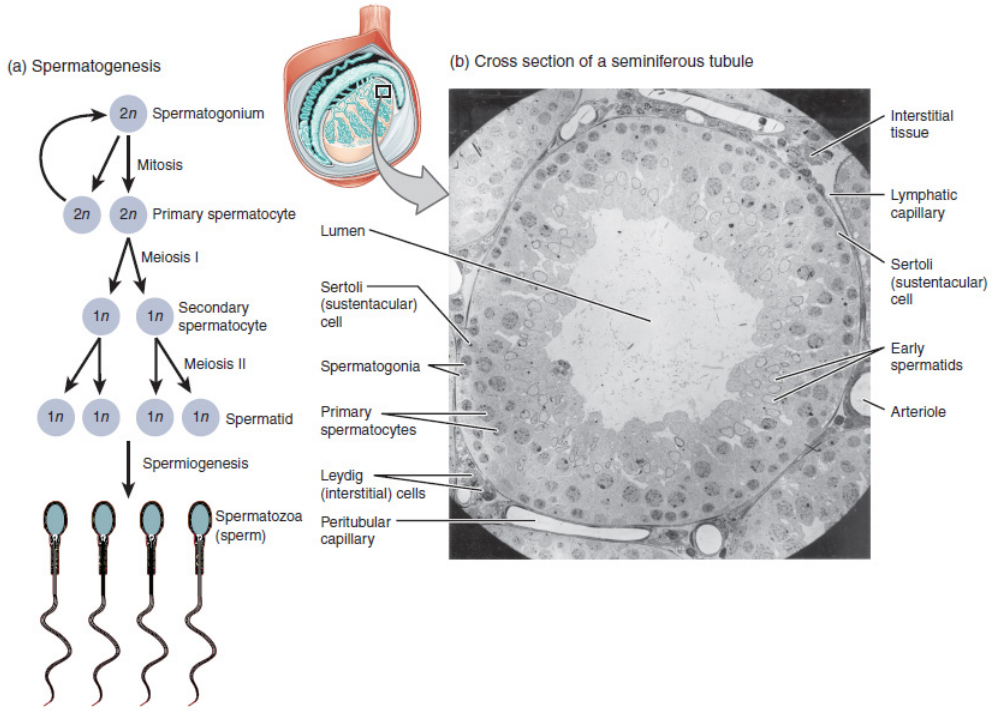



Figure **23.2.4**: Spermatogenesis. (a) Mitosis of a spermatogonial stem cell involves a single cell division that results in two identical, diploid daughter cells (spermatogonia to primary spermatocyte). Meiosis has two rounds of cell division: primary spermatocyte to secondary spermatocyte, and then 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)

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. Sperm have a distinctive head, mid-piece, and tail region (Figure **23.2.5**). The head of the sperm contains the extremely compact haploid nucleus with very little cytoplasm. These qualities contribute to the overall small size of the sperm (the head is only 5 $\mu$m 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.

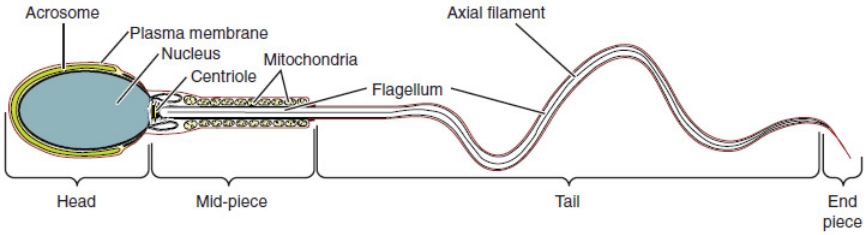



Figure **23.2.5**: Structure of Sperm. Sperm cells are divided into a head, containing DNA; a mid-piece, containing mitochondria; and a tail, providing motility. The acrosome is oval and somewhat flattened.

## 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. As they are moved along the length of the epididymis, the sperm further mature and acquire the ability to move under their own power. Once inside the female reproductive tract, they will use this ability to move independently toward the unfertilized egg. 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.

**Vasectomy**

*Watch this video to learn about a vasectomy. As described in this video, a vasectomy is 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?*

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.

### 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 23.2.1). 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.

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 23.2.1, 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.

**Note**

*Watch this video to explore the structures of the male reproductive system and the path of sperm, which starts in the testes and ends as the sperm leave the penis through the urethra. Where are sperm deposited after they leave the ejaculatory duct,*

## The 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.

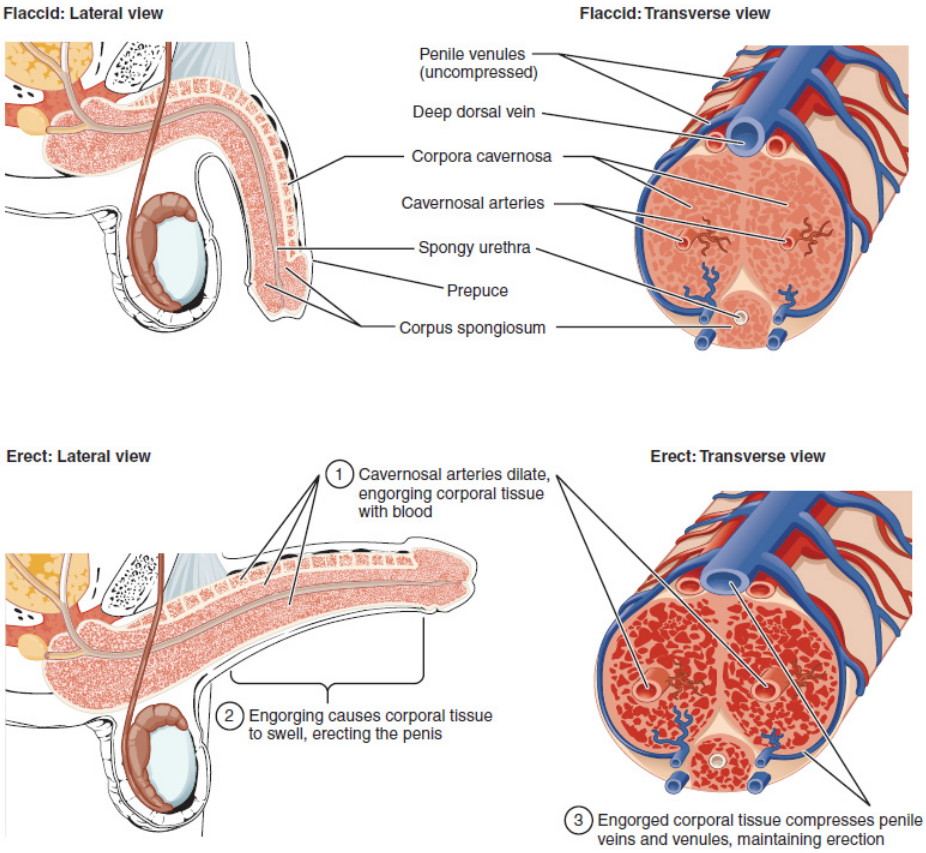



Figure **23.2.6**: Cross-Sectional Anatomy of the Penis. Three columns of erectile tissue make up most of the volume of the penis.

The shaft of the penis surrounds the urethra (Figure **23.2.6**). 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 **23.2.1**). 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.

#### 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.

## Chapter 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 the 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 with a negative feedback loop.

## Review Questions

Q. What are male gametes called?

A. ova

B. sperm

C. testes

D. testosterone

Answer: B

Q. Leydig cells _____.

A. secrete testosterone

B. activate the sperm flagellum

C. support spermatogenesis

D. secrete seminal fluid

Answer: A

Q. Which hypothalamic hormone contributes to the regulation of the male reproductive system?

A. luteinizing hormone

B. gonadotropin-releasing hormone

C. follicle-stimulating hormone

D. androgens

Answer: B

Q. What is the function of the epididymis?

A. sperm maturation and storage

B. produces the bulk of seminal fluid

C. provides nitric oxide needed for erections

D. spermatogenesis

Answer: A

Q. Spermatogenesis takes place in the _____.

A. prostate gland

B. glans penis

C. seminiferous tubules

D. ejaculatory duct

Answer: C

## Critical Thinking Questions

Q. Briefly explain why mature gametes carry only one set of chromosomes.

A. 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 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?

A. Unlike somatic cells, sperm are haploid. 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.

Q. What do each of the three male accessory glands contribute to the semen?

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.

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.

Q. While anabolic steroids (synthetic testosterone) bulk up muscles, they can also affect testosterone production in the testis. Using what you know about negative feedback, describe what would happen to testosterone production in the testis if a male takes large amounts of synthetic testosterone.

A. Testosterone production by the body would be reduced if a male were taking anabolic steroids. This is because the hypothalamus responds to rising testosterone levels by reducing its secretion of GnRH, which would in turn reduce the anterior pituitary's release of LH, finally reducing the manufacture of testosterone in the testes.

## 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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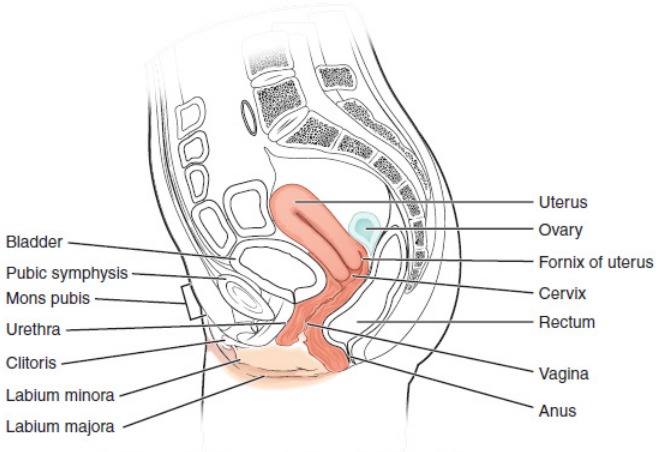
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# 23.3: Anatomy and Physiology of the Female Reproductive System

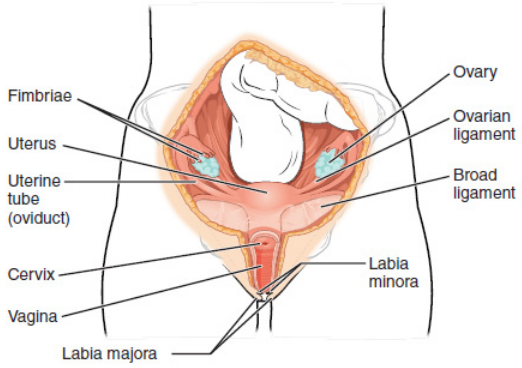
**Learning Objectives**

- Describe the structure and function of the organs of the female reproductive system
- List the steps of oogenesis
- Describe the hormonal 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 (Figure **23.3.1**). 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.




(a) Human female reproductive system: lateral view




(b) Human female reproductive system: anterior view

Figure **23.3.1**: Female Reproductive System. The major organs of the female reproductive system are located inside the pelvic cavity.

## 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).

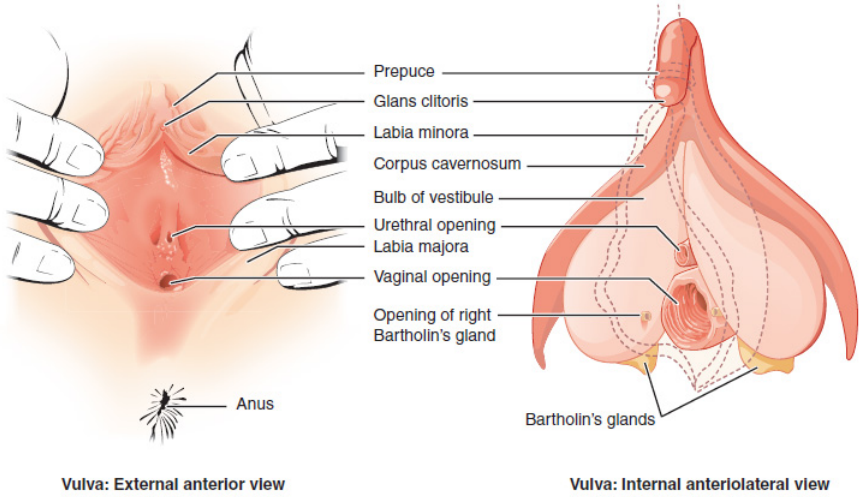



Figure **23.3.2**: The Vulva. The external female genitalia are referred to collectively as the vulva.

## Vagina

The **vagina**, shown at the bottom of Figure **23.3.1** and Figure **23.3.1**, 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 (see Figure **23.3.1**). Paired ovals, they are each about 2 to 3 cm in length, about the size of an almond. 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.

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. You will learn more about the overall anatomy of the female reproductive system at the end of this section.

## The 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

Gametogenesis in females is called **oogenesis**. The process begins with the ovarian stem cells, or **oogonia** (Figure **23.3.3**). 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 **23.3.3**, 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.

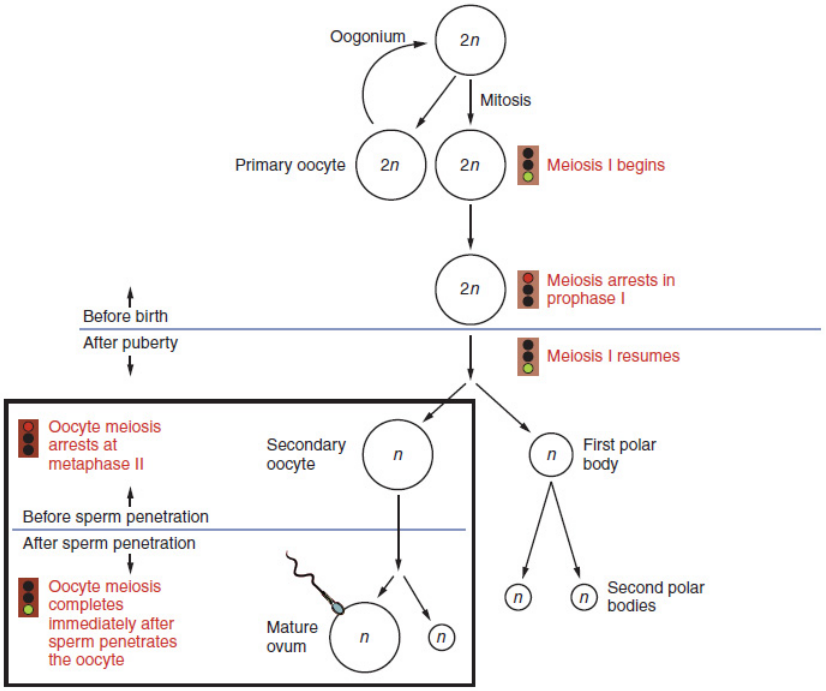



Figure **23.3.3**: Oogenesis. The unequal cell division of oogenesis produces one to three polar bodies that later degrade, as well as a single haploid ovum, which is produced only if there is penetration of the secondary oocyte by a sperm cell.

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. 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.

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 woman who lived in Africa about 200,000 years ago. Scientists have given this woman the biblical name Eve, although she is not, of course, the first Homo sapiens female. More precisely, she is 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. 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 (Figure **23.3.4**). 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 **23.3.4**)—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.

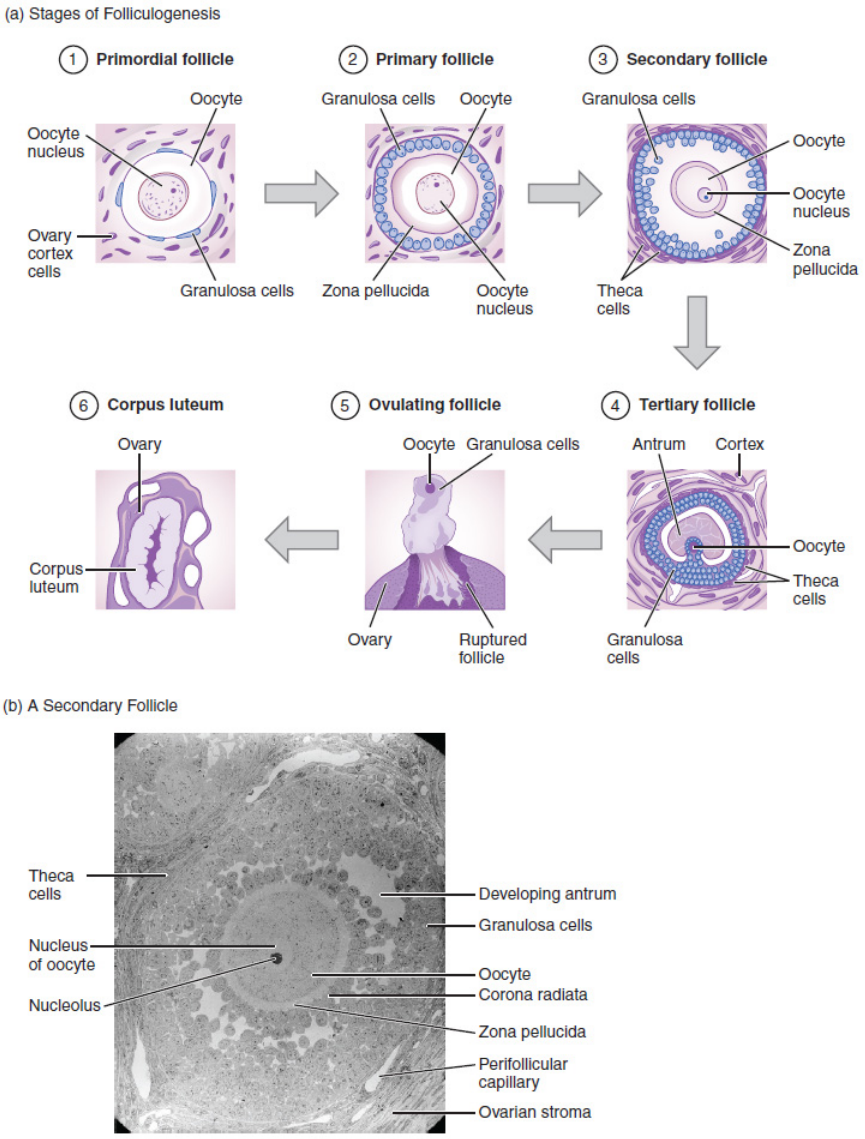



Figure **23.3.4**: Folliculogenesis. (a) The maturation of a follicle is shown in a clockwise direction proceeding from the primordial follicles. FSH stimulates the growth of a tertiary follicle, and LH stimulates the production of estrogen by granulosa and theca cells. Once the follicle is mature, it 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)

## The 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 **23.3.6**). Each of the two uterine tubes is close to, but not directly connected to, the ovary and 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 meet the egg while it is still moving through the ampulla.

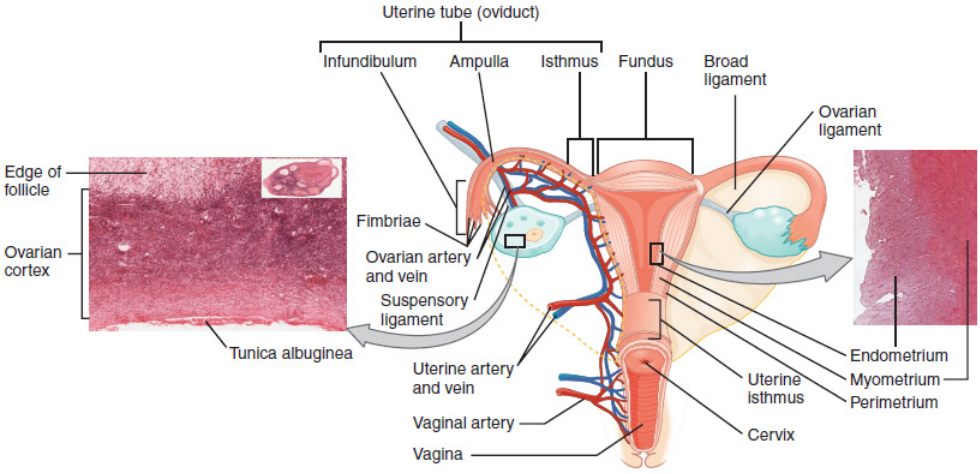



***Figure* 23.3.6*: Ovaries, Uterine Tubes, and Uterus.*** *This anterior view shows the relationship of the ovaries, uterine tubes (oviducts), and uterus. Sperm enter through the vagina, and fertilization of an ovulated oocyte usually occurs in the distal uterine tube. From left to right, LM × 400, LM × 20. (Micrographs provided by the Regents of University of Michigan Medical School © 2012)*

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.

> *Watch this series of videos to look at the movement of the oocyte through the ovary. The cilia in the uterine tube promote movement of the oocyte. What would likely occur if the cilia were paralyzed at the time of ovulation?*

## The Uterus and Cervix

The **uterus** is the muscular organ that nourishes and supports the growing embryo (see Figure **23.3.6**). 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. 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.

### 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.

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 (Figure **23.3.8**). 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.

When the high-risk types of HPV enter a cell, two viral proteins are used to neutralize proteins that the host cells use as checkpoints in the cell cycle. The best studied of these proteins is p53. In a normal cell, p53 detects DNA damage in the cell's genome and either halts the progression of the cell cycle—allowing time for DNA repair to occur—or initiates apoptosis. Both of these processes prevent the accumulation of mutations in a cell's genome. High-risk HPV can neutralize p53, keeping the cell in a state in which fast growth is possible and impairing apoptosis, allowing mutations to accumulate in the cellular DNA.

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.

## The 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** (Figure **23.3.9**), whose coloration may deepen during pregnancy. The areola is typically circular and can vary in size from 25 to 100 mm in diameter. 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 **23.3.9**). 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.

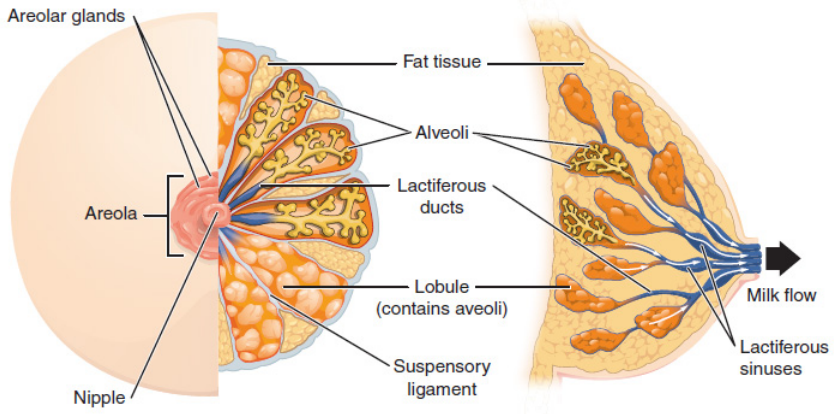



Figure **23.3.9**: Anatomy of the Breast. During lactation, milk moves from the alveoli through the lactiferous ducts to the nipple.

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.

## Chapter 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: 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: A

Q. From what structure does the corpus luteum originate?

A. uterine corpus

B. dominant follicle

C. fallopian tube

D. corpus albicans

> Answer: B

Q. Where does fertilization of the egg by the sperm typically occur?

A. vagina

B. uterus

C. uterine tube

D. ovary

Answer: C

Q. Why do estrogen levels fall after menopause?

A. The ovaries degrade.

B. There are no follicles left to produce estrogen.

C. The pituitary secretes a menopause-specific hormone.

D. The cells of the endometrium degenerate.

Answer: B

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: 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.

A. The sperm must swim upward in the vagina, through the cervix, and then through the body of the uterus to one or the other of the two uterine tubes. Fertilization generally occurs in the uterine tube.

Q. Identify some differences between meiosis in men and women.

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 are destined to die.

Q. Explain the hormonal regulation of the phases of the menstrual cycle.

A. As a result of the degradation of the corpus luteum, a decline in progesterone concentrations triggers the shedding of the endometrial lining, marking the menses phase of the menstrual cycle. Low progesterone levels also reduce the negative feedback that had been occurring at the hypothalamus and pituitary, and result in the release of GnRH and, subsequently, FSH and LH. FSH stimulates tertiary follicles to grow and granulosa and theca cells begin to produce increased amounts of estrogen. High estrogen concentrations stimulate the endometrial lining to rebuild, marking the proliferative phase of the menstrual cycle. The high estrogen concentrations will eventually lead to a decrease in FSH because of negative feedback, resulting in atresia of all but one of the developing tertiary follicles. The switch to positive feedback that occurs with elevated estrogen production from the dominant follicle stimulates the LH surge that will trigger ovulation. The luteinization of the granulosa cells of the collapsed follicle forms the progesterone-producing corpus luteum. Progesterone from the corpus luteum causes the endometrium to prepare for implantation, in part by secreting nutrient-rich fluid. This marks the secretory phase of the menstrual cycle. Finally, in a non-fertile cycle, the corpus luteum will degrade and menses will occur.

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.

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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# 23.4: Development of the Male and Female Reproductive Systems

**Learning Objectives**

- 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 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.

## 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 (*S*ex-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. For more information and a figure of differentiation of the gonads, seek additional content on fetal development.

## 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 **23.4.1**, 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.

The first changes begin around the age of eight or nine when the production of LH becomes detectable. The release of LH occurs primarily at night during sleep and precedes the physical changes of puberty by several years. In pre-pubertal children, the sensitivity of the negative feedback system in the hypothalamus and pituitary is very high. This means that very low concentrations of androgens or estrogens will negatively feed back onto the hypothalamus and pituitary, keeping the production of GnRH, LH, and FSH low.

As an individual approaches puberty, two changes in sensitivity occur. The first is a decrease of sensitivity in the hypothalamus and pituitary to negative feedback, meaning that it takes increasingly larger concentrations of sex steroid hormones to stop the production of LH and FSH. The second change in sensitivity is an increase in sensitivity of the gonads to the FSH and LH signals, meaning the gonads of adults are more responsive to gonadotropins than are the gonads of children. As a result of these two changes, the levels of LH and FSH slowly increase and lead to the enlargement and maturation of the gonads, which in turn leads to secretion of higher levels of sex hormones and the initiation of spermatogenesis and folliculogenesis.

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.

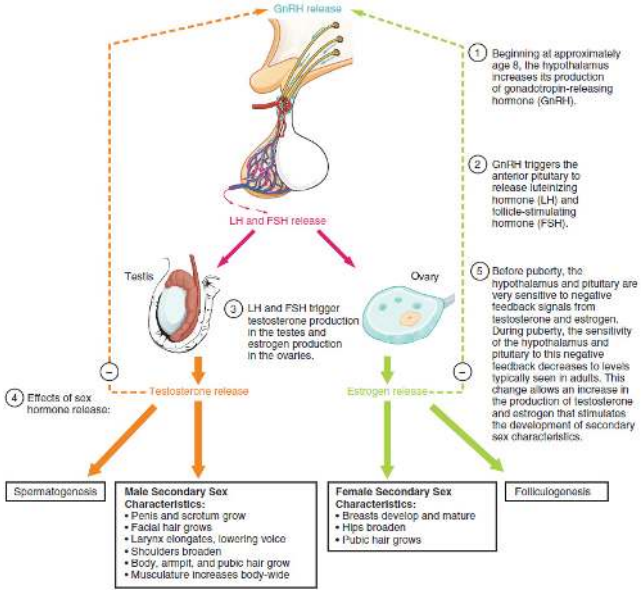



Figure **23.4.1**: Hormones of Puberty. During puberty, the release of LH and FSH from the anterior pituitary stimulates the gonads to produce sex hormones in both male and female adolescents.

## 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.

## Chapter 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 initiation of the changes that occur in puberty is the result of a decrease in sensitivity to negative feedback in the hypothalamus and pituitary gland, and an increase in sensitivity of the gonads to FSH and LH stimulation. These changes lead to increases in either estrogen or testosterone, in female and male adolescents, respectively. 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.

## Interactive Link Questions

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 animation 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: The testes are located in the abdomen.

## 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: 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: 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: D

## Critical Thinking Questions

Q. Identify the changes in sensitivity that occur in the hypothalamus, pituitary, and gonads as a boy or girl approaches puberty. Explain how these changes lead to the increases of sex steroid hormone secretions that drive many pubertal changes.

> A. As an individual approaches puberty, two changes in sensitivity occur. The first is a decrease of sensitivity in the hypothalamus and pituitary to negative feedback, meaning that it takes increasingly larger concentrations of sex steroid hormones to stop the production of LH and FSH. The second change in sensitivity is an increase in the sensitivity of the gonads to the FSH and LH signals, meaning that the gonads of adults are more responsive to gonadotropins than are the gonads of children. As a result of these two changes, the levels of LH and FSH slowly increase and lead to the enlargement and maturation of the gonads, which in turn leads to secretion of higher levels of sex hormones and the initiation of spermatogenesis and folliculogenesis.

Q. Explain how the internal female and male reproductive structures develop from two different duct systems.

> 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.

> 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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# Index


## A

abdominal aorta
18.3: Circulatory Pathways
abdominopelvic cavity
1.4: Anatomical Terminology
abducens nerve
12.4: The Peripheral Nervous System
abduct
10.2: Interactions of Skeletal Muscles, Their Fascicle Arrangement, and Their Lever Systems
abduction
8.6: Types of Body Movements
abductor
10.3: Naming Skeletal Muscle
abductor digiti minimi
10.6: Muscles of the Pectoral Girdle and Upper Limbs
abductor pollicis brevis
10.6: Muscles of the Pectoral Girdle and Upper Limbs
abductor pollicis longus
10.6: Muscles of the Pectoral Girdle and Upper Limbs
accessory digestive organ
21.2: Overview of the Digestive System
accessory duct
21.6: Accessory Organs in Digestion- The Liver, Pancreas, and Gallbladder
acetabular labrum
8.7: Anatomy of Selected Synovial Joints
acetylcholine (ACh)
9.3: Skeletal Muscle
14.2: Divisions of the Autonomic Nervous System
acinus
21.6: Accessory Organs in Digestion- The Liver, Pancreas, and Gallbladder
acne
4.4: Diseases, Disorders, and Injuries of the Integumentary System
acromegaly
15.3: The Pituitary Gland and Hypothalamus
acromial end of the clavicle
7.2: The Pectoral Girdle
acromial process
7.2: The Pectoral Girdle
acromioclavicular joint
7.2: The Pectoral Girdle
acromion
7.2: The Pectoral Girdle
actin
9.3: Skeletal Muscle
action potential
9.3: Skeletal Muscle
active transport
2.2: The Cell Membrane
adaptive immune response
19.2: Anatomy of the Lymphatic and Immune Systems
adduction
8.6: Types of Body Movements
adductor
10.3: Naming Skeletal Muscle
adductor brevis
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
adductor longus
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
adductor magnus
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
adductor pollicis
10.6: Muscles of the Pectoral Girdle and Upper Limbs
adductor tubercle
7.5: Bones of the Lower Limb
adipocytes
3.4: Connective Tissue Supports and Protects
adipose tissue
3.4: Connective Tissue Supports and Protects
adrenal artery
18.3: Circulatory Pathways
adrenal cortex
15.6: The Adrenal Glands
adrenal glands
15.6: The Adrenal Glands
adrenal medulla
14.2: Divisions of the Autonomic Nervous System
15.6: The Adrenal Glands
adrenal vein
18.3: Circulatory Pathways
adrenergic
14.2: Divisions of the Autonomic Nervous System
adrenocorticotropic hormone (ACTH)
15.3: The Pituitary Gland and Hypothalamus
aerobic respiration
9.4: Muscle Fiber Contraction and Relaxation
afferent branch
14.3: Autonomic Reflexes and Homeostasis
afferent lymphatic vessels
19.2: Anatomy of the Lymphatic and Immune Systems
agonist
10.2: Interactions of Skeletal Muscles, Their Fascicle Arrangement, and Their Lever Systems
agranular leukocytes
16.5: Leukocytes and Platelets
ala
20.2: Organs and Structures of the Respiratory System
alar cartilage
20.2: Organs and Structures of the Respiratory System
alar plate
12.2: The Central Nervous System
alarm reaction
15.6: The Adrenal Glands
albinism
4.2: Layers of the Skin
albumin
16.2: An Overview of Blood
aldosterone
15.6: The Adrenal Glands
alimentary canal
21.2: Overview of the Digestive System
alkaloid
13.2: Sensory Perception
alpha cell
15.8: The Endocrine Pancreas
alveolar duct
20.2: Organs and Structures of the Respiratory System
alveolar macrophage
20.2: Organs and Structures of the Respiratory System
alveolar pore
20.2: Organs and Structures of the Respiratory System
alveolar process of the mandible
6.3: The Skull
alveolar process of the maxilla
6.3: The Skull
alveolar sac
20.2: Organs and Structures of the Respiratory System
alveoli
23.3: Anatomy and Physiology of the Female Reproductive System
alveolus
20.2: Organs and Structures of the Respiratory System
amacrine cell
13.2: Sensory Perception
amphiarthrosis
8.2: Classification of Joints
amphipathic
2.2: The Cell Membrane
ampulla
13.2: Sensory Perception
23.3: Anatomy and Physiology of the Female Reproductive System
amygdala
12.2: The Central Nervous System
anagen
4.3: Accessory Structures of the Skin
anal canal
21.5: The Small and Large Intestines
anal column
21.5: The Small and Large Intestines
anal sinus
21.5: The Small and Large Intestines
anal triangle
10.5: Axial Muscles of the Abdominal Wall and Thorax
anaphase
2.5: Cell Growth and Division
anastomosis
17.2: Heart Anatomy
anatomical neck
7.3: Bones of the Upper Limb
anatomical position
1.4: Anatomical Terminology
anatomical sphincter
22.2: Gross Anatomy of Urine Transport
anatomy
1.2: Overview of Anatomy and Physiology
anchoring junction
3.3: Epithelial Tissue

anconeus
10.6: Muscles of the Pectoral Girdle and Upper Limbs
anemia
16.4: Erythrocytes
angiotensin I
22.4: Microscopic Anatomy of the Kidney
angiotensin II
22.4: Microscopic Anatomy of the Kidney
angiotensinogen
22.4: Microscopic Anatomy of the Kidney
angle of the mandible
6.3: The Skull
angle of the rib
6.5: The Thoracic Cage
ankle joint
7.5: Bones of the Lower Limb
annular ligament
8.7: Anatomy of Selected Synovial Joints
anosmia
13.2: Sensory Perception
antagonist
10.2: Interactions of Skeletal Muscles, Their Fascicle Arrangement, and Their Lever Systems
anterior
1.4: Anatomical Terminology
anterior (ventral) sacral foramen
6.4: The Vertebral Column
anterior arch
6.4: The Vertebral Column
anterior border of the tibia
7.5: Bones of the Lower Limb
anterior cardiac veins
17.2: Heart Anatomy
Anterior Cavity
1.4: Anatomical Terminology
anterior cerebral artery
18.3: Circulatory Pathways
anterior column
12.2: The Central Nervous System
anterior communicating artery
18.3: Circulatory Pathways
anterior compartment of the arm
10.6: Muscles of the Pectoral Girdle and Upper Limbs
anterior compartment of the forearm
10.6: Muscles of the Pectoral Girdle and Upper Limbs
anterior compartment of the leg
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
anterior compartment of the thigh
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
anterior cranial fossa
6.3: The Skull
anterior cruciate ligament
8.7: Anatomy of Selected Synovial Joints
anterior horn
12.2: The Central Nervous System
anterior interventricular artery
17.2: Heart Anatomy
anterior interventricular sulcus
17.2: Heart Anatomy
anterior longitudinal ligament
6.4: The Vertebral Column
anterior median fissure
12.2: The Central Nervous System
anterior scalene
10.4: Axial Muscles of the Head, Neck, and Back
anterior spinal artery
12.3: Circulation and the Central Nervous System
anterior talofibular ligament
8.7: Anatomy of Selected Synovial Joints
anterior tibial artery
18.3: Circulatory Pathways
anterior tibial vein
18.3: Circulatory Pathways
antibodies
16.2: An Overview of Blood
antibody
19.2: Anatomy of the Lymphatic and Immune Systems
antidiuretic hormone (ADH)
15.3: The Pituitary Gland and Hypothalamus
antigen
19.2: Anatomy of the Lymphatic and Immune Systems
antrum
23.3: Anatomy and Physiology of the Female Reproductive System
anulus fibrosus
6.4: The Vertebral Column
aorta
18.3: Circulatory Pathways
aortic arch
18.3: Circulatory Pathways
aortic hiatus
18.3: Circulatory Pathways
aortic valve
17.2: Heart Anatomy
apex
20.2: Organs and Structures of the Respiratory System
apical
3.3: Epithelial Tissue
apocrine secretion
3.3: Epithelial Tissue
apocrine sweat gland
4.3: Accessory Structures of the Skin
aponeurosis
9.3: Skeletal Muscle
appendicular
10.4: Axial Muscles of the Head, Neck, and Back
appendicular skeleton
6.2: Divisions of the Skeletal System
appendix
21.5: The Small and Large Intestines
aquaporin
22.4: Microscopic Anatomy of the Kidney
aqueous humor
13.2: Sensory Perception
arachnoid granulation
12.3: Circulation and the Central Nervous System
arachnoid mater
12.3: Circulation and the Central Nervous System
arachnoid trabeculae
12.3: Circulation and the Central Nervous System
areola
23.3: Anatomy and Physiology of the Female Reproductive System
areolar tissue
3.4: Connective Tissue Supports and Protects
arm
7.3: Bones of the Upper Limb
arrector pili
4.3: Accessory Structures of the Skin
arterial circle
18.3: Circulatory Pathways
arteriole
18.2: Structure of Blood Vessels
arteriovenous anastomosis
18.2: Structure of Blood Vessels
artery
18.2: Structure of Blood Vessels
articular capsule
8.5: Synovial Joints
articular cartilage
5.4: Bone Structure
8.5: Synovial Joints
articular disc
8.5: Synovial Joints
articular tubercle
6.3: The Skull
articulation
5.4: Bone Structure
8.2: Classification of Joints
artificial pacemaker
17.3: Cardiac Muscle
ascending aorta
18.3: Circulatory Pathways
ascending colon
21.5: The Small and Large Intestines
ascending tract
12.2: The Central Nervous System
astrocyte
3.6: Nervous Tissue
11.3: Nervous Tissue
atlantoaxial joint
8.7: Anatomy of Selected Synovial Joints
atlas
6.4: The Vertebral Column
ATPase
9.4: Muscle Fiber Contraction and Relaxation
atrial natriuretic peptide (ANP)
15.9: Organs with Secondary Endocrine Functions
atrioventricular (AV) node
17.3: Cardiac Muscle
atrioventricular bundle
17.3: Cardiac Muscle
atrioventricular bundle branches
17.3: Cardiac Muscle
atrioventricular septum
17.2: Heart Anatomy
atrioventricular valves
17.2: Heart Anatomy
atrium
17.2: Heart Anatomy
audition
13.2: Sensory Perception

auricle
13.2: Sensory Perception
17.2: Heart Anatomy
autocrine
15.2: An Overview of the Endocrine System
Autolysis
2.3: The Cytoplasm and Cellular Organelles
autonomic nervous system (ANS)
11.2: Basic Structures of the Nervous System
autonomic tone
14.3: Autonomic Reflexes and Homeostasis
autophagy
2.3: The Cytoplasm and Cellular Organelles
autorhythmicity
9.6: Cardiac Muscle Tissue
17.3: Cardiac Muscle
axial
10.4: Axial Muscles of the Head, Neck, and Back
axial skeleton
6.2: Divisions of the Skeletal System
axillary artery
18.3: Circulatory Pathways
axillary nerve
12.4: The Peripheral Nervous System
axillary vein
18.3: Circulatory Pathways
axis
6.4: The Vertebral Column
axon
11.2: Basic Structures of the Nervous System
axon hillock
11.3: Nervous Tissue
axon segment
11.3: Nervous Tissue
axon terminal
11.3: Nervous Tissue
axoplasm
11.3: Nervous Tissue
azygos vein
18.3: Circulatory Pathways

## B

B cells
19.2: Anatomy of the Lymphatic and Immune Systems
B lymphocytes
16.5: Leukocytes and Platelets
Bachmann’s bundle
17.3: Cardiac Muscle
bacterial flora
21.5: The Small and Large Intestines
baroreceptor
14.3: Autonomic Reflexes and Homeostasis
barrier defenses
19.2: Anatomy of the Lymphatic and Immune Systems
Bartholin’s glands
23.3: Anatomy and Physiology of the Female Reproductive System
basal cell
4.2: Layers of the Skin
basal cell carcinoma
4.4: Diseases, Disorders, and Injuries of the Integumentary System
basal forebrain
12.2: The Central Nervous System
basal lamina
3.3: Epithelial Tissue
basal nuclei
12.2: The Central Nervous System
basal plate
12.2: The Central Nervous System
base of the metatarsal bone
7.5: Bones of the Lower Limb
basement membrane
3.3: Epithelial Tissue
basilar artery
12.3: Circulation and the Central Nervous System
18.3: Circulatory Pathways
basilar membrane
13.2: Sensory Perception
basilic vein
18.3: Circulatory Pathways
basophils
16.5: Leukocytes and Platelets
bedsore
4.4: Diseases, Disorders, and Injuries of the Integumentary System
belly
10.2: Interactions of Skeletal Muscles, Their Fascicle Arrangement, and Their Lever Systems
beta cell
15.8: The Endocrine Pancreas
bi
10.3: Naming Skeletal Muscle
biaxial joint
8.2: Classification of Joints
biceps brachii
10.6: Muscles of the Pectoral Girdle and Upper Limbs
biceps femoris
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
bicipital groove
7.3: Bones of the Upper Limb
bicuspid valve
17.2: Heart Anatomy
bile
21.6: Accessory Organs in Digestion- The Liver, Pancreas, and Gallbladder
bilirubin
16.4: Erythrocytes
21.6: Accessory Organs in Digestion- The Liver, Pancreas, and Gallbladder
biliverdin
16.4: Erythrocytes
bipennate
10.2: Interactions of Skeletal Muscles, Their Fascicle Arrangement, and Their Lever Systems
bipolar
11.3: Nervous Tissue
bipolar cell
13.2: Sensory Perception
blood
16.2: An Overview of Blood
blood–testis barrier
23.2: Anatomy and Physiology of the Male Reproductive System
body
21.4: The Stomach
body of the rib
6.5: The Thoracic Cage
body of uterus
23.3: Anatomy and Physiology of the Female Reproductive System
bolus
21.3: The Mouth, Pharynx, and Esophagus
bone
5.2: The Functions of the Skeletal System
bone marrow
19.2: Anatomy of the Lymphatic and Immune Systems
bone marrow biopsy
16.3: Production of the Formed Elements
bone marrow transplant
16.3: Production of the Formed Elements
brachial artery
18.3: Circulatory Pathways
brachial plexus
12.4: The Peripheral Nervous System
brachial vein
18.3: Circulatory Pathways
brachialis
10.6: Muscles of the Pectoral Girdle and Upper Limbs
brachiocephalic artery
18.3: Circulatory Pathways
brachiocephalic vein
18.3: Circulatory Pathways
brachioradialis
10.6: Muscles of the Pectoral Girdle and Upper Limbs
brain
11.2: Basic Structures of the Nervous System
brain case
6.3: The Skull
brevis
10.3: Naming Skeletal Muscle
bridge
20.2: Organs and Structures of the Respiratory System
broad ligament
23.3: Anatomy and Physiology of the Female Reproductive System
Broca's area
12.2: The Central Nervous System
Brodmann’s areas
12.2: The Central Nervous System
bronchial artery
18.3: Circulatory Pathways
bronchial tree
20.2: Organs and Structures of the Respiratory System
bronchial vein
18.3: Circulatory Pathways
bronchiole
20.2: Organs and Structures of the Respiratory System
bronchoconstriction
20.3: The Lungs
bronchodilation
20.3: The Lungs

bronchus
20.2: Organs and Structures of the Respiratory System
brush border
21.5: The Small and Large Intestines
22.4: Microscopic Anatomy of the Kidney
buccinator
10.4: Axial Muscles of the Head, Neck, and Back
buffy coat
16.2: An Overview of Blood
bulbourethral glands
23.2: Anatomy and Physiology of the Male Reproductive System
bundle of His
17.3: Cardiac Muscle
bursa
8.5: Synovial Joints

## C

calcaneal tendon
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
calcaneofibular ligament
8.7: Anatomy of Selected Synovial Joints
calcaneus
7.5: Bones of the Lower Limb
calcitonin
15.4: The Thyroid Gland
callus
4.4: Diseases, Disorders, and Injuries of the Integumentary System
calmodulin
9.7: Smooth Muscle
calvaria
6.3: The Skull
canaliculi
5.4: Bone Structure
capacitance
18.2: Structure of Blood Vessels
capacitance vessels
18.2: Structure of Blood Vessels
capillary
18.2: Structure of Blood Vessels
capillary bed
18.2: Structure of Blood Vessels
capitate
7.3: Bones of the Upper Limb
capitulum
7.3: Bones of the Upper Limb
capsaicin
13.2: Sensory Perception
carbaminohemoglobin
16.4: Erythrocytes
cardia
21.4: The Stomach
cardiac muscle
3.5: Muscle Tissue
9.2: Overview of Muscle Tissues
cardiac notch
17.2: Heart Anatomy
20.3: The Lungs
cardiac skeleton
17.2: Heart Anatomy
cardiomyocyte
17.2: Heart Anatomy
carotid canal
6.3: The Skull
12.3: Circulation and the Central Nervous System
carpal bone
7.3: Bones of the Upper Limb
carpal tunnel
7.3: Bones of the Upper Limb
carpometacarpal joint
7.3: Bones of the Upper Limb
cartilage
5.2: The Functions of the Skeletal System
cartilaginous joint
8.2: Classification of Joints
catagen
4.3: Accessory Structures of the Skin
cauda equina
12.2: The Central Nervous System
Caudal
1.4: Anatomical Terminology
caval opening
10.5: Axial Muscles of the Abdominal Wall and Thorax
cavernous sinus
18.3: Circulatory Pathways
Cecum
21.5: The Small and Large Intestines
celiac ganglion
14.2: Divisions of the Autonomic Nervous System
celiac trunk
18.3: Circulatory Pathways
cell
1.3: Structural Organization of the Human Body
cell cycle
2.5: Cell Growth and Division
cell junction
3.3: Epithelial Tissue
cell membrane
2.2: The Cell Membrane
cementum
21.3: The Mouth, Pharynx, and Esophagus
central canal
5.4: Bone Structure
12.3: Circulation and the Central Nervous System
central nervous system (CNS)
11.2: Basic Structures of the Nervous System
central neuron
14.2: Divisions of the Autonomic Nervous System
central sulcus
12.2: The Central Nervous System
central vein
21.6: Accessory Organs in Digestion- The Liver, Pancreas, and Gallbladder
centriole
2.3: The Cytoplasm and Cellular Organelles
centromere
2.5: Cell Growth and Division
centrosome
2.5: Cell Growth and Division
cephalic phase
21.4: The Stomach
cephalic vein
18.3: Circulatory Pathways
cerebellum
12.2: The Central Nervous System
cerebral aqueduct
12.3: Circulation and the Central Nervous System
cerebral cortex
12.2: The Central Nervous System
cerebral hemisphere
12.2: The Central Nervous System
cerebrospinal fluid (CSF)
11.3: Nervous Tissue
cerebrovascular accident (CVA)
18.3: Circulatory Pathways
cerebrum
12.2: The Central Nervous System
cervical curve
6.4: The Vertebral Column
cervical plexus
12.4: The Peripheral Nervous System
cervical vertebrae
6.4: The Vertebral Column
cervix
23.3: Anatomy and Physiology of the Female Reproductive System
channel protein
2.2: The Cell Membrane
checkpoint
2.5: Cell Growth and Division
chemoreceptor
13.2: Sensory Perception
chief cell
21.4: The Stomach
cholinergic
14.2: Divisions of the Autonomic Nervous System
chondrocytes
3.4: Connective Tissue Supports and Protects
chordae tendineae
17.2: Heart Anatomy
choroid
13.2: Sensory Perception
choroid plexus
11.3: Nervous Tissue
12.3: Circulation and the Central Nervous System
chromaffin
15.6: The Adrenal Glands
chromaffin cells
14.2: Divisions of the Autonomic Nervous System
chromatin
2.4: The Nucleus
chromosome
2.4: The Nucleus
chyle
19.2: Anatomy of the Lymphatic and Immune Systems
cilia
2.3: The Cytoplasm and Cellular Organelles
ciliary body
13.2: Sensory Perception
ciliary ganglion
14.2: Divisions of the Autonomic Nervous System
circle of Willis
12.3: Circulation and the Central Nervous System
18.3: Circulatory Pathways
circular
10.2: Interactions of Skeletal Muscles, Their Fascicle Arrangement, and Their Lever Systems

circular fold
21.5: The Small and Large Intestines
circumduction
8.6: Types of Body Movements
circumflex artery
17.2: Heart Anatomy
cisterna chyli
19.2: Anatomy of the Lymphatic and Immune Systems
claudate
12.2: The Central Nervous System
clavicle
7.2: The Pectoral Girdle
clavicular notch
6.5: The Thoracic Cage
cleavage furrow
2.5: Cell Growth and Division
clitoris
23.3: Anatomy and Physiology of the Female Reproductive System
closed reduction
5.6: Fractures - Bone Repair
coccyx
6.2: Divisions of the Skeletal System
cochlea
13.2: Sensory Perception
cochlear duct
13.2: Sensory Perception
collagen fiber
3.4: Connective Tissue Supports and Protects
collateral ganglia
14.2: Divisions of the Autonomic Nervous System
colloid
15.4: The Thyroid Gland
colon
21.5: The Small and Large Intestines
common bile duct
21.6: Accessory Organs in Digestion- The Liver, Pancreas, and Gallbladder
common carotid artery
12.3: Circulation and the Central Nervous System
18.3: Circulatory Pathways
common hepatic artery
18.3: Circulatory Pathways
common iliac artery
18.3: Circulatory Pathways
common iliac vein
18.3: Circulatory Pathways
compact bone
5.4: Bone Structure
compressor urethrae
10.5: Axial Muscles of the Abdominal Wall and Thorax
Computed Tomography (CT)
1.5: Medical Imaging
concentration gradient
2.2: The Cell Membrane
conducting zone
20.2: Organs and Structures of the Respiratory System
condylar process of the mandible
6.3: The Skull
condyloid joint
8.5: Synovial Joints
cone photoreceptor
13.2: Sensory Perception
connective tissue
3.2: Types of Tissues
connective tissue membrane
3.2: Types of Tissues
connective tissue proper
3.4: Connective Tissue Supports and Protects
continuous capillary
18.2: Structure of Blood Vessels
contractility
9.2: Overview of Muscle Tissues
contralateral
13.2: Sensory Perception
convergent
10.2: Interactions of Skeletal Muscles, Their Fascicle Arrangement, and Their Lever Systems
coracobrachialis
10.6: Muscles of the Pectoral Girdle and Upper Limbs
coracoclavicular ligament
7.2: The Pectoral Girdle
coracohumeral ligament
8.7: Anatomy of Selected Synovial Joints
coracoid process
7.2: The Pectoral Girdle
corn
4.4: Diseases, Disorders, and Injuries of the Integumentary System
cornea
13.2: Sensory Perception
coronary arteries
17.2: Heart Anatomy
coronary sinus
17.2: Heart Anatomy
coronary sulcus
17.2: Heart Anatomy
coronary veins
17.2: Heart Anatomy
coronoid fossa
7.3: Bones of the Upper Limb
coronoid process of the ulna
7.3: Bones of the Upper Limb
corpus albicans
23.3: Anatomy and Physiology of the Female Reproductive System
corpus callosum
12.2: The Central Nervous System
corpus cavernosum
23.2: Anatomy and Physiology of the Male Reproductive System
corpus luteum
23.3: Anatomy and Physiology of the Female Reproductive System
corpus spongiosum
23.2: Anatomy and Physiology of the Male Reproductive System
corrugator supercilii
10.4: Axial Muscles of the Head, Neck, and Back
cortex
4.3: Accessory Structures of the Skin
cortisol
15.6: The Adrenal Glands
costal cartilage
6.5: The Thoracic Cage
costal facet
6.4: The Vertebral Column
costal groove
6.5: The Thoracic Cage
costoclavicular ligament
7.2: The Pectoral Girdle
Cranial
1.4: Anatomical Terminology
cranial cavity
1.4: Anatomical Terminology
6.3: The Skull
cranial nerve
12.4: The Peripheral Nervous System
cranial nerve ganglion
12.4: The Peripheral Nervous System
craniosacral system
14.2: Divisions of the Autonomic Nervous System
cranium
6.3: The Skull
creatine phosphate
9.4: Muscle Fiber Contraction and Relaxation
cribriform plate
6.3: The Skull
cricoid cartilage
20.2: Organs and Structures of the Respiratory System
crista galli
6.3: The Skull
crown
21.3: The Mouth, Pharynx, and Esophagus
cuboid
7.5: Bones of the Lower Limb
cupula
13.2: Sensory Perception
cuspid
21.3: The Mouth, Pharynx, and Esophagus
cutaneous membrane
3.2: Types of Tissues
cuticle
4.3: Accessory Structures of the Skin
cyclin
2.5: Cell Growth and Division
cystic artery
18.3: Circulatory Pathways
cystic duct
21.6: Accessory Organs in Digestion- The Liver, Pancreas, and Gallbladder
cytokines
16.3: Production of the Formed Elements
cytokinesis
2.5: Cell Growth and Division
cytoplasm
2.3: The Cytoplasm and Cellular Organelles
cytoskeleton
2.3: The Cytoplasm and Cellular Organelles
cytosol
2.3: The Cytoplasm and Cellular Organelles

## D

deciduous tooth
21.3: The Mouth, Pharynx, and Esophagus
Deep
1.4: Anatomical Terminology

deep anterior compartment
10.6: Muscles of the Pectoral Girdle and Upper Limbs
deep femoral artery
18.3: Circulatory Pathways
deep femoral vein
18.3: Circulatory Pathways
deep posterior compartment of the forearm
10.6: Muscles of the Pectoral Girdle and Upper Limbs
deep transverse perineal
10.5: Axial Muscles of the Abdominal Wall and Thorax
defensins
16.5: Leukocytes and Platelets
deglutition
10.4: Axial Muscles of the Head, Neck, and Back
21.3: The Mouth, Pharynx, and Esophagus
delta cell
15.8: The Endocrine Pancreas
deltoid
10.6: Muscles of the Pectoral Girdle and Upper Limbs
deltoid ligament
8.7: Anatomy of Selected Synovial Joints
deltoid tuberosity
7.3: Bones of the Upper Limb
dendrite
11.2: Basic Structures of the Nervous System
dens
6.4: The Vertebral Column
21.3: The Mouth, Pharynx, and Esophagus
dense body
9.7: Smooth Muscle
dense connective tissue
3.4: Connective Tissue Supports and Protects
dentin
21.3: The Mouth, Pharynx, and Esophagus
dentition
21.3: The Mouth, Pharynx, and Esophagus
deoxyhemoglobin
16.4: Erythrocytes
depolarize
9.3: Skeletal Muscle
depression
8.6: Types of Body Movements
dermal papilla
4.2: Layers of the Skin
dermis
4.2: Layers of the Skin
descending aorta
18.3: Circulatory Pathways
descending colon
21.5: The Small and Large Intestines
descending tract
12.2: The Central Nervous System
desmosome
4.2: Layers of the Skin
9.6: Cardiac Muscle Tissue
detrusor muscle
22.2: Gross Anatomy of Urine Transport
diabetes mellitus
15.8: The Endocrine Pancreas
diapedesis
16.5: Leukocytes and Platelets
diaphragm
10.5: Axial Muscles of the Abdominal Wall and Thorax
diaphysis
5.4: Bone Structure
diarthrosis
8.2: Classification of Joints
diffusion
2.2: The Cell Membrane
digastric
10.4: Axial Muscles of the Head, Neck, and Back
digital arteries
18.3: Circulatory Pathways
digital veins
18.3: Circulatory Pathways
diploë
5.4: Bone Structure
diploid
2.5: Cell Growth and Division
direct pathway
12.2: The Central Nervous System
disinhibition
12.2: The Central Nervous System
Distal
1.4: Anatomical Terminology
distal radioulnar joint
7.3: Bones of the Upper Limb
distal tibiofibular joint
7.5: Bones of the Lower Limb
DNA Polymerase
2.4: The Nucleus
DNA replication
2.4: The Nucleus
Dorsal
1.4: Anatomical Terminology
dorsal (posterior) nerve root
12.2: The Central Nervous System
dorsal (posterior) root ganglion
12.4: The Peripheral Nervous System
dorsal arch
18.3: Circulatory Pathways
dorsal cavity
1.4: Anatomical Terminology
dorsal group
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
dorsal interossei
10.6: Muscles of the Pectoral Girdle and Upper Limbs
dorsal nucleus of the vagus nerve
14.2: Divisions of the Autonomic Nervous System
dorsal venous arch
18.3: Circulatory Pathways
dorsalis pedis artery
18.3: Circulatory Pathways
dorsiflexion
8.6: Types of Body Movements
dorsum nasi
20.2: Organs and Structures of the Respiratory System
ductus deferens
23.2: Anatomy and Physiology of the Male Reproductive System
duodenal gland
21.5: The Small and Large Intestines
duodenum
21.5: The Small and Large Intestines
dura mater
12.3: Circulation and the Central Nervous System
dural sinus
12.3: Circulation and the Central Nervous System

## E

ear ossicles
6.2: Divisions of the Skeletal System
eccrine sweat gland
4.3: Accessory Structures of the Skin
ectoderm
3.2: Types of Tissues
eczema
4.4: Diseases, Disorders, and Injuries of the Integumentary System
Eddinger–Westphal nucleus
14.2: Divisions of the Autonomic Nervous System
edoderm
3.2: Types of Tissues
efferent branch
14.3: Autonomic Reflexes and Homeostasis
efferent lymphatic vessels
19.2: Anatomy of the Lymphatic and Immune Systems
ejaculatory duct
23.2: Anatomy and Physiology of the Male Reproductive System
elastic artery
18.2: Structure of Blood Vessels
elastic cartilage
3.4: Connective Tissue Supports and Protects
elastic fiber
3.4: Connective Tissue Supports and Protects
elasticity
9.2: Overview of Muscle Tissues
elastin fibers
4.2: Layers of the Skin
elbow joint
7.3: Bones of the Upper Limb
8.7: Anatomy of Selected Synovial Joints
Electrical Gradient
2.2: The Cell Membrane
electrocardiogram (ECG)
17.3: Cardiac Muscle
eleiden
4.2: Layers of the Skin
elevation
8.6: Types of Body Movements
emigration
16.5: Leukocytes and Platelets
enamel
21.3: The Mouth, Pharynx, and Esophagus
encapsulated ending
13.2: Sensory Perception
endocardium
17.2: Heart Anatomy

endochondral ossification
5.5: Bone Formation and Development
endocrine gland
3.3: Epithelial Tissue
15.2: An Overview of the Endocrine System
endocrine system
15: The Endocrine System
15.2: An Overview of the Endocrine System
Endocrine Systems
15.1: Prelude to the Endocrine System
endocytosis
2.2: The Cell Membrane
endogenous
14.2: Divisions of the Autonomic Nervous System
endometrium
23.3: Anatomy and Physiology of the Female Reproductive System
endomysium
9.3: Skeletal Muscle
endoneurium
12.4: The Peripheral Nervous System
Endoplasmic Reticulum (ER)
2.3: The Cytoplasm and Cellular Organelles
endosteum
5.4: Bone Structure
endothelium
3.3: Epithelial Tissue
17.2: Heart Anatomy
enteric nervous system
12.4: The Peripheral Nervous System
enteric nervous system (ENS)
11.2: Basic Structures of the Nervous System
enteric plexus
12.4: The Peripheral Nervous System
enteroendocrine cell
21.4: The Stomach
enterohepatic circulation
21.6: Accessory Organs in Digestion- The Liver, Pancreas, and Gallbladder
enteropeptidase
21.6: Accessory Organs in Digestion- The Liver, Pancreas, and Gallbladder
eosinophils
16.5: Leukocytes and Platelets
ependymal cell
11.3: Nervous Tissue
epicardial coronary arteries
17.2: Heart Anatomy
epicardium
17.2: Heart Anatomy
epicranial aponeurosis
10.4: Axial Muscles of the Head, Neck, and Back
epidermis
4.2: Layers of the Skin
epididymis
23.2: Anatomy and Physiology of the Male Reproductive System
epiglottis
20.2: Organs and Structures of the Respiratory System
epimysium
9.3: Skeletal Muscle
epinephrine
14.2: Divisions of the Autonomic Nervous System
15.6: The Adrenal Glands
epineurium
12.4: The Peripheral Nervous System
epiphyseal line
5.5: Bone Formation and Development
epiphyseal plate
5.4: Bone Structure
epiphysis
5.4: Bone Structure
epiploic appendage
21.5: The Small and Large Intestines
epithalamus
12.2: The Central Nervous System
epithelial membrane
3.2: Types of Tissues
epithelial tissue
3.2: Types of Tissues
eponychium
4.3: Accessory Structures of the Skin
equilibrium
13.2: Sensory Perception
erector spinae group
10.4: Axial Muscles of the Head, Neck, and Back
erythrocyte
16.4: Erythrocytes
erythropoietin (EPO)
15.9: Organs with Secondary Endocrine Functions
16.3: Production of the Formed Elements
esophageal artery
18.3: Circulatory Pathways
esophageal plexus
12.4: The Peripheral Nervous System
esophageal vein
18.3: Circulatory Pathways
esophagus
21.3: The Mouth, Pharynx, and Esophagus
ethmoid air cell
6.3: The Skull
eversion
8.6: Types of Body Movements
excitability
9.2: Overview of Muscle Tissues
exocrine gland
3.3: Epithelial Tissue
exocrine system
15.2: An Overview of the Endocrine System
exocytosis
2.2: The Cell Membrane
exogenous
14.2: Divisions of the Autonomic Nervous System
extensibility
9.2: Overview of Muscle Tissues
extension
8.6: Types of Body Movements
extensor
10.3: Naming Skeletal Muscle
extensor carpi radialis brevis
10.6: Muscles of the Pectoral Girdle and Upper Limbs
extensor carpi ulnaris
10.6: Muscles of the Pectoral Girdle and Upper Limbs
extensor digiti minimi
10.6: Muscles of the Pectoral Girdle and Upper Limbs
extensor digitorum
10.6: Muscles of the Pectoral Girdle and Upper Limbs
extensor digitorum brevis
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
extensor digitorum longus
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
extensor hallucis longus
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
extensor indicis
10.6: Muscles of the Pectoral Girdle and Upper Limbs
extensor pollicis brevis
10.6: Muscles of the Pectoral Girdle and Upper Limbs
extensor pollicis longus
10.6: Muscles of the Pectoral Girdle and Upper Limbs
extensor radialis longus
10.6: Muscles of the Pectoral Girdle and Upper Limbs
extensor retinaculum
10.6: Muscles of the Pectoral Girdle and Upper Limbs
external acoustic meatus
6.3: The Skull
external anal sphincter
21.5: The Small and Large Intestines
external callus
5.6: Fractures - Bone Repair
external carotid artery
18.3: Circulatory Pathways
external ear
13.2: Sensory Perception
external elastic membrane
18.2: Structure of Blood Vessels
external iliac artery
18.3: Circulatory Pathways
external iliac vein
18.3: Circulatory Pathways
external intercostal
10.5: Axial Muscles of the Abdominal Wall and Thorax
external jugular vein
18.3: Circulatory Pathways
external nose
20.2: Organs and Structures of the Respiratory System
external oblique
10.5: Axial Muscles of the Abdominal Wall and Thorax
external occipital protuberance
6.3: The Skull
external root sheath
4.3: Accessory Structures of the Skin
external urinary sphincter
22.2: Gross Anatomy of Urine Transport
exteroceptor
13.2: Sensory Perception
extracellular fluid (ECF)
2.2: The Cell Membrane
extraocular muscle
13.2: Sensory Perception

extraocular muscles
12.4: The Peripheral Nervous System
extrinsic eye muscles
10.4: Axial Muscles of the Head, Neck, and Back
extrinsic ligament
8.5: Synovial Joints
extrinsic muscles of the hand
10.6: Muscles of the Pectoral Girdle and Upper Limbs

## F

facet
6.4: The Vertebral Column
facial bones
6.3: The Skull
facial nerve
12.4: The Peripheral Nervous System
facilitated diffusion
2.2: The Cell Membrane
false ribs
6.5: The Thoracic Cage
fascicle
9.3: Skeletal Muscle
10.2: Interactions of Skeletal Muscles, Their Fascicle Arrangement, and Their Lever Systems
12.4: The Peripheral Nervous System
fast glycolytic (FG)
9.5: Types of Muscle Fibers
fast oxidative (FO)
9.5: Types of Muscle Fibers
fauces
20.2: Organs and Structures of the Respiratory System
21.3: The Mouth, Pharynx, and Esophagus
feces
21.5: The Small and Large Intestines
femoral artery
18.3: Circulatory Pathways
femoral circumflex vein
18.3: Circulatory Pathways
femoral nerve
12.4: The Peripheral Nervous System
femoral triangle
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
femoral vein
18.3: Circulatory Pathways
femoropatellar joint
8.7: Anatomy of Selected Synovial Joints
femur
7.5: Bones of the Lower Limb
fenestrated capillary
18.2: Structure of Blood Vessels
fenestrations
22.4: Microscopic Anatomy of the Kidney
ferritin
16.4: Erythrocytes
fibrinogen
16.2: An Overview of Blood
fibroblast
3.4: Connective Tissue Supports and Protects
fibrocartilage
3.4: Connective Tissue Supports and Protects
fibrocyte
3.4: Connective Tissue Supports and Protects
fibroelastic membrane
20.2: Organs and Structures of the Respiratory System
fibrous joint
8.2: Classification of Joints
fibrous tunic
13.2: Sensory Perception
fibula
7.5: Bones of the Lower Limb
fibular collateral ligament
8.7: Anatomy of Selected Synovial Joints
fibular nerve
12.4: The Peripheral Nervous System
fibular notch
7.5: Bones of the Lower Limb
fibular vein
18.3: Circulatory Pathways
fibularis brevis
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
fibularis longus
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
fibularis tertius
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
filtration slits
22.4: Microscopic Anatomy of the Kidney
fimbriae
23.3: Anatomy and Physiology of the Female Reproductive System
flagellum
2.3: The Cytoplasm and Cellular Organelles
flat bone
5.3: Bone Classification
flatus
21.5: The Small and Large Intestines
flexion
8.6: Types of Body Movements
10.2: Interactions of Skeletal Muscles, Their Fascicle Arrangement, and Their Lever Systems
flexor
10.3: Naming Skeletal Muscle
flexor carpi radialis
10.6: Muscles of the Pectoral Girdle and Upper Limbs
flexor carpi ulnaris
10.6: Muscles of the Pectoral Girdle and Upper Limbs
flexor digiti minimi brevis
10.6: Muscles of the Pectoral Girdle and Upper Limbs
flexor digitorum longus
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
flexor digitorum profundus
10.6: Muscles of the Pectoral Girdle and Upper Limbs
flexor digitorum superficialis
10.6: Muscles of the Pectoral Girdle and Upper Limbs
flexor hallucis longus
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
flexor pollicis brevis
10.6: Muscles of the Pectoral Girdle and Upper Limbs
flexor pollicis longus
10.6: Muscles of the Pectoral Girdle and Upper Limbs
flexor retinaculum
7.3: Bones of the Upper Limb
10.6: Muscles of the Pectoral Girdle and Upper Limbs
floating ribs
6.5: The Thoracic Cage
fluid connective tissue
3.4: Connective Tissue Supports and Protects
follicle
23.3: Anatomy and Physiology of the Female Reproductive System
folliculogenesis
23.3: Anatomy and Physiology of the Female Reproductive System
fontanelle
6.6: Embryonic Development of the Axial Skeleton
fontanelles
8.3: Fibrous Joints
foot
7.5: Bones of the Lower Limb
foramen magnum
6.3: The Skull
12.3: Circulation and the Central Nervous System
foramen ovale
17.2: Heart Anatomy
foramen ovale of the middle cranial fossa
6.3: The Skull
foramen rotundum
6.3: The Skull
foramen spinosum
6.3: The Skull
forearm
7.3: Bones of the Upper Limb
formed elements
16.2: An Overview of Blood
forming urine
22.4: Microscopic Anatomy of the Kidney
fossa
7.2: The Pectoral Girdle
fossa ovalis
17.2: Heart Anatomy
fourth ventricle
12.3: Circulation and the Central Nervous System
fovea
13.2: Sensory Perception
fovea capitis
7.5: Bones of the Lower Limb
fracture
5.6: Fractures - Bone Repair
fracture hematoma
5.6: Fractures - Bone Repair
free nerve ending
13.2: Sensory Perception
frontal bone
6.3: The Skull
frontal eye field
12.2: The Central Nervous System
frontal lobe
12.2: The Central Nervous System

Frontal Plane
1.4: Anatomical Terminology
frontal sinus
6.3: The Skull
frontalis
10.4: Axial Muscles of the Head, Neck, and Back
fundus
21.4: The Stomach
23.3: Anatomy and Physiology of the Female Reproductive System
fusiform
10.2: Interactions of Skeletal Muscles, Their Fascicle Arrangement, and Their Lever Systems

## G

G cell
21.4: The Stomach
G protein–coupled receptor
14.2: Divisions of the Autonomic Nervous System
G0 phase
2.5: Cell Growth and Division
G1 phase
2.5: Cell Growth and Division
G2 phase
2.5: Cell Growth and Division
gamete
23.2: Anatomy and Physiology of the Male Reproductive System
ganglion
11.2: Basic Structures of the Nervous System
ganglionic neuron
14.2: Divisions of the Autonomic Nervous System
gap junction
3.3: Epithelial Tissue
gastric emptying
21.4: The Stomach
gastric gland
21.4: The Stomach
gastric phase
21.4: The Stomach
gastric pit
21.4: The Stomach
gastric plexuses
12.4: The Peripheral Nervous System
gastrin
21.4: The Stomach
gastrocnemius
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
gastrocolic reflex
21.5: The Small and Large Intestines
gastroileal reflex
21.5: The Small and Large Intestines
general adaptation syndrome (GAS)
15.6: The Adrenal Glands
general sense
13.2: Sensory Perception
genicular artery
18.3: Circulatory Pathways
genioglossus
10.4: Axial Muscles of the Head, Neck, and Back
geniohyoid
10.4: Axial Muscles of the Head, Neck, and Back
genome
2.4: The Nucleus
germinal centers
19.2: Anatomy of the Lymphatic and Immune Systems
gigantism
15.3: The Pituitary Gland and Hypothalamus
gingiva
21.3: The Mouth, Pharynx, and Esophagus
glabella
6.3: The Skull
glans penis
23.2: Anatomy and Physiology of the Male Reproductive System
glassy membrane
4.3: Accessory Structures of the Skin
glenohumeral joint
7.2: The Pectoral Girdle
8.7: Anatomy of Selected Synovial Joints
glenohumeral ligament
8.7: Anatomy of Selected Synovial Joints
glenoid cavity
7.2: The Pectoral Girdle
glenoid labrum
8.7: Anatomy of Selected Synovial Joints
glial cell
11.2: Basic Structures of the Nervous System
globin
16.4: Erythrocytes
globulins
16.2: An Overview of Blood
globus pallidus
12.2: The Central Nervous System
glossopharyngeal nerve
12.4: The Peripheral Nervous System
glottis
20.2: Organs and Structures of the Respiratory System
glucagon
15.8: The Endocrine Pancreas
glucocorticoids
15.6: The Adrenal Glands
gluteal group
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
gluteal tuberosity
7.5: Bones of the Lower Limb
gluteus maximus
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
gluteus medius
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
gluteus minimus
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
Glycocalyx
2.2: The Cell Membrane
glycolysis
9.4: Muscle Fiber Contraction and Relaxation
goblet cell
3.3: Epithelial Tissue
goiter
15.4: The Thyroid Gland
Golgi apparatus
2.3: The Cytoplasm and Cellular Organelles
gomphosis
8.3: Fibrous Joints
gonadal artery
18.3: Circulatory Pathways
gonadal vein
18.3: Circulatory Pathways
gonadotropins
15.3: The Pituitary Gland and Hypothalamus
gonads
23.2: Anatomy and Physiology of the Male Reproductive System
gracilis
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
granular leukocytes
16.5: Leukocytes and Platelets
granulosa cells
23.3: Anatomy and Physiology of the Female Reproductive System
gray matter
11.2: Basic Structures of the Nervous System
gray rami communicantes
14.2: Divisions of the Autonomic Nervous System
great cardiac vein
17.2: Heart Anatomy
great cerebral vein
18.3: Circulatory Pathways
great saphenous vein
18.3: Circulatory Pathways
greater splanchnic nerve
14.2: Divisions of the Autonomic Nervous System
greater trochanter
7.5: Bones of the Lower Limb
greater tubercle
7.3: Bones of the Upper Limb
greater wings of sphenoid bone
6.3: The Skull
ground substance
3.4: Connective Tissue Supports and Protects
growth hormone (GH)
15.3: The Pituitary Gland and Hypothalamus
gustation
13.2: Sensory Perception
gustatory receptor cells
13.2: Sensory Perception
gyrus
12.2: The Central Nervous System

## H

hair
4.3: Accessory Structures of the Skin
hair bulb
4.3: Accessory Structures of the Skin
hair cells
13.2: Sensory Perception
hair follicle
4.3: Accessory Structures of the Skin
hair matrix
4.3: Accessory Structures of the Skin
hair papilla
4.3: Accessory Structures of the Skin

hair root
4.3: Accessory Structures of the Skin
hair shaft
4.3: Accessory Structures of the Skin
hallux
7.5: Bones of the Lower Limb
hamate
7.3: Bones of the Upper Limb
hamstring group
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
hand
7.3: Bones of the Upper Limb
hard palate
6.3: The Skull
haustral contraction
21.5: The Small and Large Intestines
haustrum
21.5: The Small and Large Intestines
head of the femur
7.5: Bones of the Lower Limb
head of the fibula
7.5: Bones of the Lower Limb
head of the humerus
7.3: Bones of the Upper Limb
head of the metatarsal bone
7.5: Bones of the Lower Limb
head of the radius
7.3: Bones of the Upper Limb
head of the rib
6.5: The Thoracic Cage
Head of the ulna
7.3: Bones of the Upper Limb
heart block
17.3: Cardiac Muscle
helicase
2.4: The Nucleus
hematocrit
16.2: An Overview of Blood
hematopoiesis
5.2: The Functions of the Skeletal System
16.3: Production of the Formed Elements
heme
16.4: Erythrocytes
hemiazygos vein
18.3: Circulatory Pathways
hemocytoblast
16.3: Production of the Formed Elements
hemoglobin
16.4: Erythrocytes
hemopoiesis
16.3: Production of the Formed Elements
hemopoietic growth factors
16.3: Production of the Formed Elements
hemopoietic stem cell
16.3: Production of the Formed Elements
hemosiderin
16.4: Erythrocytes
hepatic artery
21.6: Accessory Organs in Digestion- The Liver, Pancreas, and Gallbladder
hepatic artery proper
18.3: Circulatory Pathways
hepatic lobule
21.6: Accessory Organs in Digestion- The Liver, Pancreas, and Gallbladder
hepatic portal system
18.3: Circulatory Pathways
hepatic portal vein
21.6: Accessory Organs in Digestion- The Liver, Pancreas, and Gallbladder
hepatic sinusoid
21.6: Accessory Organs in Digestion- The Liver, Pancreas, and Gallbladder
hepatic vein
18.3: Circulatory Pathways
21.6: Accessory Organs in Digestion- The Liver, Pancreas, and Gallbladder
hepatocytes
21.6: Accessory Organs in Digestion- The Liver, Pancreas, and Gallbladder
hepatopancreatic ampulla
21.5: The Small and Large Intestines
hepatopancreatic sphincter
21.5: The Small and Large Intestines
high endothelial venules
19.2: Anatomy of the Lymphatic and Immune Systems
hilum
20.3: The Lungs
hinge joint
8.5: Synovial Joints
hip joint
7.5: Bones of the Lower Limb
hippocampus
12.2: The Central Nervous System
histology
3.2: Types of Tissues
histone
2.4: The Nucleus
hole
5.4: Bone Structure
holocrine secretion
3.3: Epithelial Tissue
homeostasis
1.2: Overview of Anatomy and Physiology
homologous
2.5: Cell Growth and Division
hook of the hamate bone
7.3: Bones of the Upper Limb
horizontal plate
6.3: The Skull
hormone
15.2: An Overview of the Endocrine System
humeroradial joint
8.7: Anatomy of Selected Synovial Joints
humeroulnar joint
8.7: Anatomy of Selected Synovial Joints
humerus
7.3: Bones of the Upper Limb
hyaline cartilage
3.4: Connective Tissue Supports and Protects
hydrochloric acid (HCl)
21.4: The Stomach
hydrophilic
2.2: The Cell Membrane
hydrophobic
2.2: The Cell Membrane
hymen
23.3: Anatomy and Physiology of the Female Reproductive System
hyoglossus
10.4: Axial Muscles of the Head, Neck, and Back
hyoid bone
6.2: Divisions of the Skeletal System
hyperextension
8.6: Types of Body Movements
hyperflexion
8.6: Types of Body Movements
hyperglycemia
15.8: The Endocrine Pancreas
hyperparathyroidism
15.5: The Parathyroid Glands
hyperplasia
9.7: Smooth Muscle
hypertonic
2.2: The Cell Membrane
hypertrophic cardiomyopathy
17.2: Heart Anatomy
hypodermis
4.2: Layers of the Skin
hypoglossal canal
6.3: The Skull
hypoglossal nerve
12.4: The Peripheral Nervous System
hyponychium
4.3: Accessory Structures of the Skin
hypoparathyroidism
15.5: The Parathyroid Glands
hypophyseal (pituitary) fossa
6.3: The Skull
hypophyseal portal system
15.3: The Pituitary Gland and Hypothalamus
hypothalamus
12.2: The Central Nervous System
15.3: The Pituitary Gland and Hypothalamus
hypothenar
10.6: Muscles of the Pectoral Girdle and Upper Limbs
hypothenar eminence
10.6: Muscles of the Pectoral Girdle and Upper Limbs
hypothyroidism
15.4: The Thyroid Gland
hypotonic
2.2: The Cell Membrane
hypoxemia
16.4: Erythrocytes

## I

ileocecal sphincter
21.5: The Small and Large Intestines
Ileum
21.5: The Small and Large Intestines
iliacus
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
iliococcygeus
10.5: Axial Muscles of the Abdominal Wall and Thorax
iliocostalis cervicis
10.4: Axial Muscles of the Head, Neck, and Back

iliocostalis group
10.4: Axial Muscles of the Head, Neck, and Back
iliocostalis lumborum
10.4: Axial Muscles of the Head, Neck, and Back
iliocostalis thoracis
10.4: Axial Muscles of the Head, Neck, and Back
iliofemoral ligament
8.7: Anatomy of Selected Synovial Joints
iliopsoas group
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
iliotibial tract
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
immune system
19.2: Anatomy of the Lymphatic and Immune Systems
immunoglobulins
16.2: An Overview of Blood
incisor
21.3: The Mouth, Pharynx, and Esophagus
incontinence
22.2: Gross Anatomy of Urine Transport
incus
13.2: Sensory Perception
indirect pathway
12.2: The Central Nervous System
inferior
1.4: Anatomical Terminology
inferior angle of the scapula
7.2: The Pectoral Girdle
inferior articular process
6.4: The Vertebral Column
inferior colliculus
12.2: The Central Nervous System
inferior extensor retinaculum
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
inferior gemellus
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
inferior mesenteric artery
18.3: Circulatory Pathways
inferior mesenteric ganglion
14.2: Divisions of the Autonomic Nervous System
inferior nasal concha
6.3: The Skull
inferior oblique
13.2: Sensory Perception
inferior olive
12.2: The Central Nervous System
inferior phrenic artery
18.3: Circulatory Pathways
inferior rectus
13.2: Sensory Perception
inferior rotation
8.6: Types of Body Movements
inferior vena cava
17.2: Heart Anatomy
18.3: Circulatory Pathways
infraglenoid fossa
7.2: The Pectoral Girdle
infraglenoid tubercle
7.2: The Pectoral Girdle
infrahyoid muscles
10.4: Axial Muscles of the Head, Neck, and Back
infraorbital foramen
6.3: The Skull
infraspinatus
10.6: Muscles of the Pectoral Girdle and Upper Limbs
infraspinous fossa
7.2: The Pectoral Girdle
infratemporal fossa
6.3: The Skull
infundibulum
15.3: The Pituitary Gland and Hypothalamus
23.3: Anatomy and Physiology of the Female Reproductive System
inguinal canal
23.2: Anatomy and Physiology of the Male Reproductive System
initial segment
11.3: Nervous Tissue
innate immune response
19.2: Anatomy of the Lymphatic and Immune Systems
inner ear
13.2: Sensory Perception
inner segment
13.2: Sensory Perception
inner synaptic layer
13.2: Sensory Perception
innermost intercostal
10.5: Axial Muscles of the Abdominal Wall and Thorax
insertion
10.2: Interactions of Skeletal Muscles, Their Fascicle Arrangement, and Their Lever Systems
insulin
15.8: The Endocrine Pancreas
integral protein
2.2: The Cell Membrane
integration
11.2: Basic Structures of the Nervous System
integumentary system
4: The Integumentary System
4.2: Layers of the Skin
interatrial band
17.3: Cardiac Muscle
interatrial septum
17.2: Heart Anatomy
intercalated disc
9.6: Cardiac Muscle Tissue
17.3: Cardiac Muscle
intercondylar eminence
7.5: Bones of the Lower Limb
intercondylar fossa
7.5: Bones of the Lower Limb
intercostal artery
18.3: Circulatory Pathways
intercostal muscles
10.5: Axial Muscles of the Abdominal Wall and Thorax
intercostal nerve
12.4: The Peripheral Nervous System
intercostal vein
18.3: Circulatory Pathways
interleukins
16.3: Production of the Formed Elements
intermediate
10.6: Muscles of the Pectoral Girdle and Upper Limbs
intermediate cuneiform
7.5: Bones of the Lower Limb
intermediate filament
2.3: The Cytoplasm and Cellular Organelles
internal anal sphincter
21.5: The Small and Large Intestines
internal callus
5.6: Fractures - Bone Repair
internal carotid artery
12.3: Circulation and the Central Nervous System
18.3: Circulatory Pathways
internal elastic membrane
18.2: Structure of Blood Vessels
internal iliac artery
18.3: Circulatory Pathways
internal iliac vein
18.3: Circulatory Pathways
internal intercostal
10.5: Axial Muscles of the Abdominal Wall and Thorax
internal jugular vein
18.3: Circulatory Pathways
internal oblique
10.5: Axial Muscles of the Abdominal Wall and Thorax
internal root sheath
4.3: Accessory Structures of the Skin
internal thoracic artery
18.3: Circulatory Pathways
internal thoracic vein
18.3: Circulatory Pathways
internal urinary sphincter
22.2: Gross Anatomy of Urine Transport
internodal pathways
17.3: Cardiac Muscle
interoceptor
13.2: Sensory Perception
interosseous border of the fibula
7.5: Bones of the Lower Limb
interosseous border of the radius
7.3: Bones of the Upper Limb
interosseous border of the tibia
7.5: Bones of the Lower Limb
interosseous border of the ulna
7.3: Bones of the Upper Limb
interosseous membrane
8.3: Fibrous Joints
interosseous membrane of the forearm
7.3: Bones of the Upper Limb
interosseous membrane of the leg
7.5: Bones of the Lower Limb
interphalangeal joint
7.3: Bones of the Upper Limb
interphase
2.5: Cell Growth and Division
interstitial fluid (IF)
2.2: The Cell Membrane
intertrochanteric crest
7.5: Bones of the Lower Limb

intertrochanteric line
7.5: Bones of the Lower Limb
intertubercular groove (sulcus)
7.3: Bones of the Upper Limb
interventricular foramina
12.3: Circulation and the Central Nervous System
interventricular septum
17.2: Heart Anatomy
intervertebral disc
6.4: The Vertebral Column
intervertebral foramen
6.4: The Vertebral Column
intestinal gland
21.5: The Small and Large Intestines
intestinal juice
21.5: The Small and Large Intestines
intestinal phase
21.4: The Stomach
intracapsular ligament
8.5: Synovial Joints
intracellular fluid (ICF)
2.2: The Cell Membrane
intramembranous ossification
5.5: Bone Formation and Development
intramural ganglia
14.2: Divisions of the Autonomic Nervous System
intrinsic factor
21.4: The Stomach
intrinsic ligament
8.5: Synovial Joints
intrinsic muscles of the hand
10.6: Muscles of the Pectoral Girdle and Upper Limbs
inversion
8.6: Types of Body Movements
ipsilateral
13.2: Sensory Perception
iris
13.2: Sensory Perception
irregular bone
5.3: Bone Classification
ischiococcygeus
10.5: Axial Muscles of the Abdominal Wall and Thorax
ischiofemoral ligament
8.7: Anatomy of Selected Synovial Joints
Islets of Langerhans
15.8: The Endocrine Pancreas
isotonic
2.2: The Cell Membrane
isthmus
23.3: Anatomy and Physiology of the Female Reproductive System

J

jejunum
21.5: The Small and Large Intestines
joint
8.2: Classification of Joints
joint cavity
8.2: Classification of Joints
jugular (suprasternal) notch
6.5: The Thoracic Cage
jugular foramen
6.3: The Skull
jugular veins
12.3: Circulation and the Central Nervous System
juxtaglomerular apparatus (JGA)
22.4: Microscopic Anatomy of the Kidney
juxtaglomerular cell
22.4: Microscopic Anatomy of the Kidney

K

keratin
4.2: Layers of the Skin
keratinocyte
4.2: Layers of the Skin
keratohyalin
4.2: Layers of the Skin
kinesthesia
12.2: The Central Nervous System
13.2: Sensory Perception
kinetochore
2.5: Cell Growth and Division
knee joint
7.5: Bones of the Lower Limb
kyphosis
6.4: The Vertebral Column

L

labia majora
23.3: Anatomy and Physiology of the Female Reproductive System
labia minora
23.3: Anatomy and Physiology of the Female Reproductive System
labial frenulum
21.3: The Mouth, Pharynx, and Esophagus
labium
21.3: The Mouth, Pharynx, and Esophagus
lacrimal bone
6.3: The Skull
lacrimal duct
13.2: Sensory Perception
lacrimal fossa
6.3: The Skull
lacrimal gland
13.2: Sensory Perception
lacteal
21.5: The Small and Large Intestines
lactic acid
9.4: Muscle Fiber Contraction and Relaxation
lactiferous ducts
23.3: Anatomy and Physiology of the Female Reproductive System
lactiferous sinus
23.3: Anatomy and Physiology of the Female Reproductive System
lacunae
3.4: Connective Tissue Supports and Protects
lambdoid suture
6.3: The Skull
lamina
6.4: The Vertebral Column
lamina propria
3.2: Types of Tissues
Langerhans cell
4.2: Layers of the Skin
large intestine
21.5: The Small and Large Intestines
laryngeal prominence
20.2: Organs and Structures of the Respiratory System
laryngopharynx
20.2: Organs and Structures of the Respiratory System
21.3: The Mouth, Pharynx, and Esophagus
larynx
20.2: Organs and Structures of the Respiratory System
lateral
1.4: Anatomical Terminology
lateral (external) rotation
8.6: Types of Body Movements
lateral apertures
12.3: Circulation and the Central Nervous System
lateral border of the scapula
7.2: The Pectoral Girdle
lateral circumflex artery
18.3: Circulatory Pathways
lateral column
12.2: The Central Nervous System
lateral compartment of the leg
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
lateral condyle of the femur
7.5: Bones of the Lower Limb
lateral condyle of the tibia
7.5: Bones of the Lower Limb
lateral cuneiform
7.5: Bones of the Lower Limb
lateral epicondyle of the femur
7.5: Bones of the Lower Limb
lateral epicondyle of the humerus
7.3: Bones of the Upper Limb
lateral excursion
8.6: Types of Body Movements
lateral flexion
8.6: Types of Body Movements
lateral horn
12.2: The Central Nervous System
lateral malleolus
7.5: Bones of the Lower Limb
lateral meniscus
8.7: Anatomy of Selected Synovial Joints
lateral plantar artery
18.3: Circulatory Pathways
lateral pterygoid
10.4: Axial Muscles of the Head, Neck, and Back
lateral pterygoid plate
6.3: The Skull
lateral rectus
13.2: Sensory Perception
lateral sacral crest
6.4: The Vertebral Column
lateral sulcus
12.2: The Central Nervous System
lateral supracondylar ridge
7.3: Bones of the Upper Limb

lateral tibiofemoral joint
8.7: Anatomy of Selected Synovial Joints
lateral ventricles
12.3: Circulation and the Central Nervous System
lateralis
10.3: Naming Skeletal Muscle
latissimus dorsi
10.6: Muscles of the Pectoral Girdle and Upper Limbs
left atrioventricular valve
17.2: Heart Anatomy
left colic flexure
21.5: The Small and Large Intestines
left gastric artery
18.3: Circulatory Pathways
leg
7.5: Bones of the Lower Limb
lens
13.2: Sensory Perception
leptin
15.9: Organs with Secondary Endocrine Functions
lesser splanchnic nerve
14.2: Divisions of the Autonomic Nervous System
lesser trochanter
7.5: Bones of the Lower Limb
lesser tubercle
7.3: Bones of the Upper Limb
lesser wings of the sphenoid bone
6.3: The Skull
leukemia
16.5: Leukocytes and Platelets
leukocyte
16.5: Leukocytes and Platelets
leukocytosis
16.5: Leukocytes and Platelets
leukopenia
16.5: Leukocytes and Platelets
levator ani
10.5: Axial Muscles of the Abdominal Wall and Thorax
levator palpebrae superioris
13.2: Sensory Perception
Leydig cells
23.2: Anatomy and Physiology of the Male Reproductive System
ligament
8.3: Fibrous Joints
ligament of the head of the femur
7.5: Bones of the Lower Limb
8.7: Anatomy of Selected Synovial Joints
ligamentum flavum
6.4: The Vertebral Column
ligand
2.2: The Cell Membrane
limbic cortex
12.2: The Central Nervous System
limbic system
12.2: The Central Nervous System
linea alba
10.5: Axial Muscles of the Abdominal Wall and Thorax
linea aspera
7.5: Bones of the Lower Limb
lingual frenulum
21.3: The Mouth, Pharynx, and Esophagus
lingual lipase
21.3: The Mouth, Pharynx, and Esophagus
lingual tonsil
20.2: Organs and Structures of the Respiratory System
lingula
6.3: The Skull
liver
21.6: Accessory Organs in Digestion- The Liver, Pancreas, and Gallbladder
long bone
5.3: Bone Classification
long reflex
14.3: Autonomic Reflexes and Homeostasis
longissimus capitis
10.4: Axial Muscles of the Head, Neck, and Back
longissimus group
10.4: Axial Muscles of the Head, Neck, and Back
longissimus thoracis
10.4: Axial Muscles of the Head, Neck, and Back
longitudinal fissure
12.2: The Central Nervous System
longus
10.3: Naming Skeletal Muscle
loose connective tissue
3.4: Connective Tissue Supports and Protects
lordosis
6.4: The Vertebral Column
lower esophageal sphincter
21.3: The Mouth, Pharynx, and Esophagus
lucunae
5.4: Bone Structure
lumbar arteries
18.3: Circulatory Pathways
lumbar curve
6.4: The Vertebral Column
lumbar plexus
12.4: The Peripheral Nervous System
lumbar puncture
12.3: Circulation and the Central Nervous System
lumbar veins
18.3: Circulatory Pathways
lumbar vertebrae
6.4: The Vertebral Column
lumbrical
10.6: Muscles of the Pectoral Girdle and Upper Limbs
Lumen
18.2: Structure of Blood Vessels
lunate
7.3: Bones of the Upper Limb
lung
20.3: The Lungs
lunula
4.3: Accessory Structures of the Skin
luteinizing hormone (LH)
15.3: The Pituitary Gland and Hypothalamus
lymph
19.2: Anatomy of the Lymphatic and Immune Systems
lymph node
19.2: Anatomy of the Lymphatic and Immune Systems
lymphatic capillaries
19.2: Anatomy of the Lymphatic and Immune Systems
lymphatic system
19.2: Anatomy of the Lymphatic and Immune Systems
lymphatic trunks
19.2: Anatomy of the Lymphatic and Immune Systems
lymphocytes
16.5: Leukocytes and Platelets
19.2: Anatomy of the Lymphatic and Immune Systems
lymphoid nodules
19.2: Anatomy of the Lymphatic and Immune Systems
lymphoid stem cells
16.3: Production of the Formed Elements
lymphoma
16.5: Leukocytes and Platelets
lysosome
2.3: The Cytoplasm and Cellular Organelles
Lysozyme
16.5: Leukocytes and Platelets

## M

Müllerian duct
23.4: Development of the Male and Female Reproductive Systems
macrophage
16.4: Erythrocytes
macula
13.2: Sensory Perception
macula densa
22.4: Microscopic Anatomy of the Kidney
Magnetic Resonance Imaging (MRI)
1.5: Medical Imaging
main pancreatic duct
21.5: The Small and Large Intestines
major duodenal papilla
21.5: The Small and Large Intestines
malleus
13.2: Sensory Perception
mammary glands
23.3: Anatomy and Physiology of the Female Reproductive System
mandible
6.3: The Skull
mandibular foramen
6.3: The Skull
mandibular fossa
6.3: The Skull
mandibular notch
6.3: The Skull
manubrium
6.5: The Thoracic Cage
marginal arteries
17.2: Heart Anatomy
mass movement
21.5: The Small and Large Intestines
masseter
10.4: Axial Muscles of the Head, Neck, and Back

mastication
10.4: Axial Muscles of the Head, Neck, and Back
mastoid process
6.3: The Skull
matrix
3.4: Connective Tissue Supports and Protects
maxillary bone
6.3: The Skull
maxillary sinus
6.3: The Skull
maxillary vein
18.3: Circulatory Pathways
maximus
10.3: Naming Skeletal Muscle
meatus
20.2: Organs and Structures of the Respiratory System
mechanoreceptor
13.2: Sensory Perception
medial
1.4: Anatomical Terminology
medial (internal) rotation
8.6: Types of Body Movements
medial border of the scapula
7.2: The Pectoral Girdle
medial compartment of the thigh
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
medial condyle of the femur
7.5: Bones of the Lower Limb
medial condyle of the tibia
7.5: Bones of the Lower Limb
medial cuneiform
7.5: Bones of the Lower Limb
medial epicondyle of the femur
7.5: Bones of the Lower Limb
medial epicondyle of the humerus
7.3: Bones of the Upper Limb
medial excursion
8.6: Types of Body Movements
medial malleolus
7.5: Bones of the Lower Limb
medial meniscus
8.7: Anatomy of Selected Synovial Joints
medial plantar artery
18.3: Circulatory Pathways
medial pterygoid
10.4: Axial Muscles of the Head, Neck, and Back
medial pterygoid plate
6.3: The Skull
medial rectus
13.2: Sensory Perception
medial tibiofemoral joint
8.7: Anatomy of Selected Synovial Joints
medialis
10.3: Naming Skeletal Muscle
median antebrachial vein
18.3: Circulatory Pathways
median cubital vein
18.3: Circulatory Pathways
median nerve
12.4: The Peripheral Nervous System
median sacral artery
18.3: Circulatory Pathways
mediastinal artery
18.3: Circulatory Pathways
medius
10.3: Naming Skeletal Muscle
medulla
4.3: Accessory Structures of the Skin
medullary cavity
5.4: Bone Structure
megakaryocyte
16.5: Leukocytes and Platelets
melanin
4.2: Layers of the Skin
melanocyte
4.2: Layers of the Skin
melanoma
4.4: Diseases, Disorders, and Injuries of the Integumentary System
melanosome
4.2: Layers of the Skin
melatonin
15.7: The Pineal Gland
memory cell
16.5: Leukocytes and Platelets
menarche
23.3: Anatomy and Physiology of the Female Reproductive System
meninges
12.3: Circulation and the Central Nervous System
meniscus
8.5: Synovial Joints
menses
23.3: Anatomy and Physiology of the Female Reproductive System
menses phase
23.3: Anatomy and Physiology of the Female Reproductive System
menstrual cycle
23.3: Anatomy and Physiology of the Female Reproductive System
mental foramen
6.3: The Skull
mental protuberance
6.3: The Skull
Merkel cell
4.2: Layers of the Skin
merocrine secretion
3.3: Epithelial Tissue
mesangial
22.4: Microscopic Anatomy of the Kidney
mesenchymal cell
3.4: Connective Tissue Supports and Protects
mesenchyme
3.4: Connective Tissue Supports and Protects
mesenteric plexus
14.2: Divisions of the Autonomic Nervous System
mesoappendix
21.5: The Small and Large Intestines
mesoderm
3.2: Types of Tissues
mesothelium
3.3: Epithelial Tissue
17.2: Heart Anatomy
metacarpal bone
7.3: Bones of the Upper Limb
metacarpophalangeal joint
7.3: Bones of the Upper Limb
metaphase
2.5: Cell Growth and Division
metaphase plate
2.5: Cell Growth and Division
metarteriole
18.2: Structure of Blood Vessels
metastasis
4.4: Diseases, Disorders, and Injuries of the Integumentary System
metatarsal bone
7.5: Bones of the Lower Limb
metatarsophalangeal joint
7.5: Bones of the Lower Limb
microcirculation
18.2: Structure of Blood Vessels
microfilament
2.3: The Cytoplasm and Cellular Organelles
microglia
11.3: Nervous Tissue
Microscopic Anatomy
1.2: Overview of Anatomy and Physiology
microtubule
2.3: The Cytoplasm and Cellular Organelles
microvillus
21.5: The Small and Large Intestines
micturition
22.2: Gross Anatomy of Urine Transport
midcarpal joint
7.3: Bones of the Upper Limb
middle cardiac vein
17.2: Heart Anatomy
middle cerebral artery
18.3: Circulatory Pathways
middle cranial fossa
6.3: The Skull
middle ear
13.2: Sensory Perception
middle nasal concha
6.3: The Skull
middle sacral vein
18.3: Circulatory Pathways
middle scalene
10.4: Axial Muscles of the Head, Neck, and Back
migrating motility complex
21.5: The Small and Large Intestines
mineralocorticoids
15.6: The Adrenal Glands
minimus
10.3: Naming Skeletal Muscle
mitochondrion
2.3: The Cytoplasm and Cellular Organelles
mitosis
2.5: Cell Growth and Division
mitotic phase
2.5: Cell Growth and Division
mitotic spindle
2.5: Cell Growth and Division
mitral valve
17.2: Heart Anatomy
mixing wave
21.4: The Stomach

modeling
5.5: Bone Formation and Development
moderator band
17.2: Heart Anatomy
molar
21.3: The Mouth, Pharynx, and Esophagus
monocytes
16.5: Leukocytes and Platelets
mons pubis
23.3: Anatomy and Physiology of the Female Reproductive System
motilin
21.5: The Small and Large Intestines
motility
21.2: Overview of the Digestive System
mucosa
21.2: Overview of the Digestive System
mucosal barrier
21.4: The Stomach
mucous connective tissue
3.4: Connective Tissue Supports and Protects
mucous gland
3.3: Epithelial Tissue
mucous membrane
3.2: Types of Tissues
mucous neck cell
21.4: The Stomach
multiaxial joint
8.2: Classification of Joints
multifidus
10.4: Axial Muscles of the Head, Neck, and Back
multipennate
10.2: Interactions of Skeletal Muscles, Their Fascicle Arrangement, and Their Lever Systems
multipolar
11.3: Nervous Tissue
muscarinic receptor
14.2: Divisions of the Autonomic Nervous System
muscle tissue
3.2: Types of Tissues
9: Muscle Tissue
muscular artery
18.2: Structure of Blood Vessels
muscularis
21.2: Overview of the Digestive System
mutation
2.3: The Cytoplasm and Cellular Organelles
myelin
3.6: Nervous Tissue
11.2: Basic Structures of the Nervous System
myelin sheath
11.3: Nervous Tissue
myeloid stem cells
16.3: Production of the Formed Elements
myenteric plexus
21.2: Overview of the Digestive System
mylohyoid
10.4: Axial Muscles of the Head, Neck, and Back
mylohyoid line
6.3: The Skull
myocardial conducting cells
17.3: Cardiac Muscle
myocardial contractile cells
17.3: Cardiac Muscle
myocardium
17.2: Heart Anatomy
myocyte
3.5: Muscle Tissue
myofibril
9.3: Skeletal Muscle
myometrium
23.3: Anatomy and Physiology of the Female Reproductive System
myosin
9.3: Skeletal Muscle

## N

naïve lymphocyte
19.2: Anatomy of the Lymphatic and Immune Systems
nail bed
4.3: Accessory Structures of the Skin
nail body
4.3: Accessory Structures of the Skin
nail cuticle
4.3: Accessory Structures of the Skin
nail fold
4.3: Accessory Structures of the Skin
nail root
4.3: Accessory Structures of the Skin
naris
20.2: Organs and Structures of the Respiratory System
nasal bone
20.2: Organs and Structures of the Respiratory System
nasal cavity
6.3: The Skull
nasal conchae
6.3: The Skull
nasal septum
6.3: The Skull
20.2: Organs and Structures of the Respiratory System
nasolacrimal canal
6.3: The Skull
nasopharynx
20.2: Organs and Structures of the Respiratory System
natural killer (NK) cells
16.5: Leukocytes and Platelets
natural killer cell (NK)
19.2: Anatomy of the Lymphatic and Immune Systems
navicular
7.5: Bones of the Lower Limb
neck of the femur
7.5: Bones of the Lower Limb
neck of the radius
7.3: Bones of the Upper Limb
neck of the rib
6.5: The Thoracic Cage
neonatal hypothyroidism
15.4: The Thyroid Gland
nerve
11.2: Basic Structures of the Nervous System
nerve plexus
12.4: The Peripheral Nervous System
nervi vasorum
18.2: Structure of Blood Vessels
nervous tissue
3.2: Types of Tissues
neural tunic
13.2: Sensory Perception
neuroglia
3.6: Nervous Tissue
neuromuscular junction (NMJ)
9.3: Skeletal Muscle
neuron
3.6: Nervous Tissue
11.2: Basic Structures of the Nervous System
neurotransmitter
9.3: Skeletal Muscle
neutrophils
16.5: Leukocytes and Platelets
nicotinic receptor
14.2: Divisions of the Autonomic Nervous System
nociceptor
13.2: Sensory Perception
node of Ranvier
11.3: Nervous Tissue
norepinephrine
14.2: Divisions of the Autonomic Nervous System
15.6: The Adrenal Glands
notochord
6.6: Embryonic Development of the Axial Skeleton
nuchal ligament
6.4: The Vertebral Column
nuclear envelope
2.4: The Nucleus
Nuclear Pore
2.4: The Nucleus
nucleolus
2.4: The Nucleus
nucleosome
2.4: The Nucleus
nucleus
2.3: The Cytoplasm and Cellular Organelles
11.2: Basic Structures of the Nervous System
nucleus ambiguus
14.2: Divisions of the Autonomic Nervous System
nucleus pulposus
6.4: The Vertebral Column
nutrient foramen
5.4: Bone Structure

## O

oblique
10.3: Naming Skeletal Muscle
obturator externus
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
obturator internus
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
occipital bone
6.3: The Skull
occipital condyle
6.3: The Skull
occipital lobe
12.2: The Central Nervous System

occipital sinus
18.3: Circulatory Pathways
occipital sinuses
12.3: Circulation and the Central Nervous System
occipitalis
10.4: Axial Muscles of the Head, Neck, and Back
occipitofrontalis
10.4: Axial Muscles of the Head, Neck, and Back
oculomotor nerve
12.4: The Peripheral Nervous System
odorant molecules
13.2: Sensory Perception
olecranon fossa
7.3: Bones of the Upper Limb
olecranon process
7.3: Bones of the Upper Limb
olfaction
12.2: The Central Nervous System
13.2: Sensory Perception
olfactory bulb
13.2: Sensory Perception
olfactory epithelium
13.2: Sensory Perception
olfactory sensory neuron
13.2: Sensory Perception
oligodendrocyte
3.6: Nervous Tissue
11.3: Nervous Tissue
omohyoid
10.4: Axial Muscles of the Head, Neck, and Back
ongissimus cervicis
10.4: Axial Muscles of the Head, Neck, and Back
oocyte
23.3: Anatomy and Physiology of the Female Reproductive System
oogenesis
23.3: Anatomy and Physiology of the Female Reproductive System
oogonia
23.3: Anatomy and Physiology of the Female Reproductive System
open reduction
5.6: Fractures - Bone Repair
ophthalmic artery
18.3: Circulatory Pathways
opponens digiti minimi
10.6: Muscles of the Pectoral Girdle and Upper Limbs
opponens pollicis
10.6: Muscles of the Pectoral Girdle and Upper Limbs
opposition
8.6: Types of Body Movements
opsin
13.2: Sensory Perception
optic disc
13.2: Sensory Perception
optic nerve
12.4: The Peripheral Nervous System
13.2: Sensory Perception
oral cavity
21.3: The Mouth, Pharynx, and Esophagus
oral vestibule
21.3: The Mouth, Pharynx, and Esophagus
Oranelle
2.3: The Cytoplasm and Cellular Organelles
orbicularis oculi
10.4: Axial Muscles of the Head, Neck, and Back
orbicularis oris
10.4: Axial Muscles of the Head, Neck, and Back
organ
1.3: Structural Organization of the Human Body
organ of corti
13.2: Sensory Perception
organ system
1.3: Structural Organization of the Human Body
organism
1.3: Structural Organization of the Human Body
origin
10.2: Interactions of Skeletal Muscles, Their Fascicle Arrangement, and Their Lever Systems
oropharynx
20.2: Organs and Structures of the Respiratory System
21.3: The Mouth, Pharynx, and Esophagus
orthopedist
5.2: The Functions of the Skeletal System
orthostatic reflex
12.3: Circulation and the Central Nervous System
osmoreceptor
13.2: Sensory Perception
15.3: The Pituitary Gland and Hypothalamus
osmosis
2.2: The Cell Membrane
osseous tissue
5.2: The Functions of the Skeletal System
ossicles
13.2: Sensory Perception
ossification
5.5: Bone Formation and Development
ossification center
5.5: Bone Formation and Development
osteoblast
5.4: Bone Structure
osteoclast
5.4: Bone Structure
osteocyte
5.4: Bone Structure
osteogenic cell
5.4: Bone Structure
osteoid
5.5: Bone Formation and Development
osteon
5.4: Bone Structure
otolith
13.2: Sensory Perception
otolithic membrane
13.2: Sensory Perception
outer segment
13.2: Sensory Perception
outer synaptic layer
13.2: Sensory Perception
oval window
13.2: Sensory Perception
ovarian artery
18.3: Circulatory Pathways
ovarian cycle
23.3: Anatomy and Physiology of the Female Reproductive System
ovarian vein
18.3: Circulatory Pathways
ovaries
23.3: Anatomy and Physiology of the Female Reproductive System
ovulation
23.3: Anatomy and Physiology of the Female Reproductive System
ovum
23.3: Anatomy and Physiology of the Female Reproductive System
oxygen debt
9.4: Muscle Fiber Contraction and Relaxation
oxyhemoglobin
16.4: Erythrocytes
oxytocin
15.3: The Pituitary Gland and Hypothalamus

## P

P wave
17.3: Cardiac Muscle
pacemaker
17.3: Cardiac Muscle
pacesetter cell
9.7: Smooth Muscle
packed cell volume (PCV)
16.2: An Overview of Blood
palatine bone
6.3: The Skull
palatine process
6.3: The Skull
palatine tonsil
20.2: Organs and Structures of the Respiratory System
palatoglossal arch
21.3: The Mouth, Pharynx, and Esophagus
palatoglossus
10.4: Axial Muscles of the Head, Neck, and Back
palatopharyngeal arch
21.3: The Mouth, Pharynx, and Esophagus
palmar arches
18.3: Circulatory Pathways
palmar interossei
10.6: Muscles of the Pectoral Girdle and Upper Limbs
palmar venous arches
18.3: Circulatory Pathways
palmaris longus
10.6: Muscles of the Pectoral Girdle and Upper Limbs
palpebral conjunctiva
13.2: Sensory Perception
pancreas
15.8: The Endocrine Pancreas
21.6: Accessory Organs in Digestion- The Liver, Pancreas, and Gallbladder
pancreatic islets
15.8: The Endocrine Pancreas
pancreatic juice
21.6: Accessory Organs in Digestion- The Liver, Pancreas, and Gallbladder

papilla
13.2: Sensory Perception
papillary layer
4.2: Layers of the Skin
papillary muscle
17.2: Heart Anatomy
paracrine
15.2: An Overview of the Endocrine System
parallel
10.2: Interactions of Skeletal Muscles, Their Fascicle Arrangement, and Their Lever Systems
paranasal sinus
20.2: Organs and Structures of the Respiratory System
paranasal sinuses
6.3: The Skull
parasympathetic division
14.2: Divisions of the Autonomic Nervous System
parathyroid glands
15.5: The Parathyroid Glands
paravertebral ganglia
12.4: The Peripheral Nervous System
14.2: Divisions of the Autonomic Nervous System
parenchyma
3.4: Connective Tissue Supports and Protects
parietal bone
6.3: The Skull
parietal branches
18.3: Circulatory Pathways
parietal cell
21.4: The Stomach
parietal lobe
12.2: The Central Nervous System
parietal pleura
20.3: The Lungs
parotid gland
21.3: The Mouth, Pharynx, and Esophagus
passive transport
2.2: The Cell Membrane
patella
7.5: Bones of the Lower Limb
patellar ligament
8.7: Anatomy of Selected Synovial Joints
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
patellar surface
7.5: Bones of the Lower Limb
pectinate line
21.5: The Small and Large Intestines
pectinate muscles
17.2: Heart Anatomy
pectineus
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
pectoral girdle
7.2: The Pectoral Girdle
10.6: Muscles of the Pectoral Girdle and Upper Limbs
pectoralis major
10.6: Muscles of the Pectoral Girdle and Upper Limbs
pectoralis minor
10.6: Muscles of the Pectoral Girdle and Upper Limbs
pedicels
22.4: Microscopic Anatomy of the Kidney
pedicle
6.4: The Vertebral Column
pelvic diaphragm
10.5: Axial Muscles of the Abdominal Wall and Thorax
pelvic girdle
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
penis
23.2: Anatomy and Physiology of the Male Reproductive System
pennate
10.2: Interactions of Skeletal Muscles, Their Fascicle Arrangement, and Their Lever Systems
pepsinogen
21.4: The Stomach
perforating canal
5.4: Bone Structure
perfusion
18.2: Structure of Blood Vessels
pericardial artery
18.3: Circulatory Pathways
pericardial cavity
17.2: Heart Anatomy
pericardial sac
17.2: Heart Anatomy
pericardium
1.4: Anatomical Terminology
17.2: Heart Anatomy
perichondrium
5.5: Bone Formation and Development
perimetrium
23.3: Anatomy and Physiology of the Female Reproductive System
perimysium
9.3: Skeletal Muscle
perineum
10.5: Axial Muscles of the Abdominal Wall and Thorax
perineurium
12.4: The Peripheral Nervous System
periodontal ligament
8.3: Fibrous Joints
periosteum
5.4: Bone Structure
peripheral nervous system (PNS)
11.2: Basic Structures of the Nervous System
peripheral protein
2.2: The Cell Membrane
peritoneum
1.4: Anatomical Terminology
permanent tooth
21.3: The Mouth, Pharynx, and Esophagus
peroxisome
2.3: The Cytoplasm and Cellular Organelles
perpendicular plate of the ethmoid bone
6.3: The Skull
petrosal sinus
18.3: Circulatory Pathways
petrous ridge
6.3: The Skull
phagocytosis
2.2: The Cell Membrane
phalanx bone of the foot
7.5: Bones of the Lower Limb
phalanx bone of the hand
7.3: Bones of the Upper Limb
pharyngeal tonsil
20.2: Organs and Structures of the Respiratory System
pharynx
20.2: Organs and Structures of the Respiratory System
21.3: The Mouth, Pharynx, and Esophagus
philtrum
20.2: Organs and Structures of the Respiratory System
photoisomerization
13.2: Sensory Perception
photon
13.2: Sensory Perception
photoreceptor
13.2: Sensory Perception
phrenic nerve
12.4: The Peripheral Nervous System
phrenic vein
18.3: Circulatory Pathways
physiological sphincter
22.2: Gross Anatomy of Urine Transport
physiology
1.2: Overview of Anatomy and Physiology
pia mater
12.3: Circulation and the Central Nervous System
pineal gland
15.7: The Pineal Gland
pinealocyte
15.7: The Pineal Gland
pinocytosis
2.2: The Cell Membrane
piriformis
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
pisiform
7.3: Bones of the Upper Limb
pituitary dwarfism
15.3: The Pituitary Gland and Hypothalamus
pituitary gland
15.3: The Pituitary Gland and Hypothalamus
pivot joint
8.5: Synovial Joints
Plane
1.4: Anatomical Terminology
plane joint
8.5: Synovial Joints
plantar aponeurosis
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
plantar arch
18.3: Circulatory Pathways
plantar flexion
8.6: Types of Body Movements
plantar group
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
plantar veins
18.3: Circulatory Pathways
plantar venous arch
18.3: Circulatory Pathways

plantaris
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
plasma
16.2: An Overview of Blood
plasma cell
19.2: Anatomy of the Lymphatic and Immune Systems
platelets
16.2: An Overview of Blood
pleura
1.4: Anatomical Terminology
pleural cavity
20.3: The Lungs
pleural fluid
20.3: The Lungs
plexus
12.4: The Peripheral Nervous System
pluripotent stem cell
16.3: Production of the Formed Elements
podocytes
22.4: Microscopic Anatomy of the Kidney
polar body
23.3: Anatomy and Physiology of the Female Reproductive System
pollex
7.3: Bones of the Upper Limb
polycythemia
16.4: Erythrocytes
polymorphonuclear
16.5: Leukocytes and Platelets
popliteal artery
18.3: Circulatory Pathways
popliteal fossa
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
popliteal vein
18.3: Circulatory Pathways
popliteus
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
porta hepatis
21.6: Accessory Organs in Digestion- The Liver, Pancreas, and Gallbladder
portal triad
21.6: Accessory Organs in Digestion- The Liver, Pancreas, and Gallbladder
positive chemotaxis
16.5: Leukocytes and Platelets
Positron Emission Tomography (PET)
1.5: Medical Imaging
postcentral gyrus
12.2: The Central Nervous System
posterior
1.4: Anatomical Terminology
posterior (dorsal) sacral foramen
6.4: The Vertebral Column
posterior arch
6.4: The Vertebral Column
posterior cardiac vein
17.2: Heart Anatomy
Posterior Cavity
1.4: Anatomical Terminology
posterior columns
12.2: The Central Nervous System
posterior communicating artery
18.3: Circulatory Pathways
posterior compartment of the leg
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
posterior compartment of the thigh
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
posterior cruciate ligament
8.7: Anatomy of Selected Synovial Joints
posterior horn
12.2: The Central Nervous System
posterior interventricular artery
17.2: Heart Anatomy
posterior interventricular sulcus
17.2: Heart Anatomy
posterior longitudinal ligament
6.4: The Vertebral Column
posterior median sulcus
12.2: The Central Nervous System
posterior scalene
10.4: Axial Muscles of the Head, Neck, and Back
posterior talofibular ligament
8.7: Anatomy of Selected Synovial Joints
posterior tibial artery
18.3: Circulatory Pathways
posterior tibial vein
18.3: Circulatory Pathways
posterolateral sulcus
12.2: The Central Nervous System
postganglionic fiber
14.2: Divisions of the Autonomic Nervous System
power stroke
9.4: Muscle Fiber Contraction and Relaxation
PP cell
15.8: The Endocrine Pancreas
precapillary sphincters
18.2: Structure of Blood Vessels
precentral gyrus
12.2: The Central Nervous System
prefrontal lobe
12.2: The Central Nervous System
preganglionic fiber
14.2: Divisions of the Autonomic Nervous System
premolar
21.3: The Mouth, Pharynx, and Esophagus
premotor area
12.2: The Central Nervous System
prepotential depolarization
17.3: Cardiac Muscle
prepuce
23.2: Anatomy and Physiology of the Male Reproductive System
prevertebral ganglia
12.4: The Peripheral Nervous System
14.2: Divisions of the Autonomic Nervous System
primary curve
6.4: The Vertebral Column
primary follicles
23.3: Anatomy and Physiology of the Female Reproductive System
primary lymphoid organ
19.2: Anatomy of the Lymphatic and Immune Systems
primary ossification center
5.5: Bone Formation and Development
prime mover
10.2: Interactions of Skeletal Muscles, Their Fascicle Arrangement, and Their Lever Systems
primordial follicles
23.3: Anatomy and Physiology of the Female Reproductive System
process
11.2: Basic Structures of the Nervous System
projection
5.4: Bone Structure
prolactin (PRL)
15.3: The Pituitary Gland and Hypothalamus
proliferative phase
23.3: Anatomy and Physiology of the Female Reproductive System
proliferative zone
5.5: Bone Formation and Development
pronated position
8.6: Types of Body Movements
pronation
8.6: Types of Body Movements
pronator quadratus
10.6: Muscles of the Pectoral Girdle and Upper Limbs
pronator teres
10.6: Muscles of the Pectoral Girdle and Upper Limbs
Prone
1.4: Anatomical Terminology
prophase
2.5: Cell Growth and Division
Proprioception
12.2: The Central Nervous System
13.2: Sensory Perception
proprioceptor
13.2: Sensory Perception
prostate gland
23.2: Anatomy and Physiology of the Male Reproductive System
protraction
8.6: Types of Body Movements
proximal
1.4: Anatomical Terminology
proximal radioulnar joint
7.3: Bones of the Upper Limb
8.5: Synovial Joints
proximal tibiofibular joint
7.5: Bones of the Lower Limb
pseudostratified columnar epithelium
3.3: Epithelial Tissue
psoas major
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
pterion
6.3: The Skull
puberty
23.4: Development of the Male and Female Reproductive Systems
pubococcygeus
10.5: Axial Muscles of the Abdominal Wall and Thorax
pubofemoral ligament
8.7: Anatomy of Selected Synovial Joints

pulmonary arteries
17.2: Heart Anatomy
pulmonary artery
18.3: Circulatory Pathways
20.3: The Lungs
pulmonary capillaries
17.2: Heart Anatomy
pulmonary circuit
17.2: Heart Anatomy
pulmonary plexus
20.3: The Lungs
pulmonary surfactant
20.2: Organs and Structures of the Respiratory System
pulmonary trunk
17.2: Heart Anatomy
18.3: Circulatory Pathways
pulmonary valve
17.2: Heart Anatomy
pulmonary veins
17.2: Heart Anatomy
18.3: Circulatory Pathways
pulp cavity
21.3: The Mouth, Pharynx, and Esophagus
pupil
13.2: Sensory Perception
Purkinje fibers
17.3: Cardiac Muscle
putamen
12.2: The Central Nervous System
pyloric antrum
21.4: The Stomach
pyloric canal
21.4: The Stomach
pyloric sphincter
21.4: The Stomach
pylorus
21.4: The Stomach
pyruvic acid
9.4: Muscle Fiber Contraction and Relaxation

## Q

QRS complex
17.3: Cardiac Muscle
quadratus femoris
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
quadratus lumborum
10.5: Axial Muscles of the Abdominal Wall and Thorax
quadriceps femoris group
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
quadriceps tendon
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs

## R

radial artery
18.3: Circulatory Pathways
radial collateral ligament
8.7: Anatomy of Selected Synovial Joints
radial fossa
7.3: Bones of the Upper Limb
radial nerve
12.4: The Peripheral Nervous System
radial notch of the ulna
7.3: Bones of the Upper Limb
radial tuberosity
7.3: Bones of the Upper Limb
radial vein
18.3: Circulatory Pathways
radiocarpal joint
7.3: Bones of the Upper Limb
radius
7.3: Bones of the Upper Limb
ramus of the mandible
6.3: The Skull
Reactive Oxygen Species (ROS)
2.3: The Cytoplasm and Cellular Organelles
receptor
2.2: The Cell Membrane
receptor cell
13.2: Sensory Perception
rectal valve
21.5: The Small and Large Intestines
rectum
21.5: The Small and Large Intestines
rectus
10.3: Naming Skeletal Muscle
rectus abdominis
10.5: Axial Muscles of the Abdominal Wall and Thorax
rectus femoris
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
rectus sheaths
10.5: Axial Muscles of the Abdominal Wall and Thorax
red blood cells (RBCs)
16.2: An Overview of Blood
red marrow
5.2: The Functions of the Skeletal System
referred pain
14.3: Autonomic Reflexes and Homeostasis
reflex arc
14.3: Autonomic Reflexes and Homeostasis
regional anatomy
1.2: Overview of Anatomy and Physiology
remodeling
5.5: Bone Formation and Development
renal artery
18.3: Circulatory Pathways
renal vein
18.3: Circulatory Pathways
renin
22.4: Microscopic Anatomy of the Kidney
reposition
8.6: Types of Body Movements
reserve zone
5.5: Bone Formation and Development
respiratory bronchiole
20.2: Organs and Structures of the Respiratory System
respiratory epithelium
20.2: Organs and Structures of the Respiratory System
respiratory membrane
20.2: Organs and Structures of the Respiratory System
respiratory system
20: The Respiratory System
20.1: Prelude to the Respiratory System
respiratory zone
20.2: Organs and Structures of the Respiratory System
response
11.2: Basic Structures of the Nervous System
rest and digest
14.2: Divisions of the Autonomic Nervous System
reticular fiber
3.4: Connective Tissue Supports and Protects
reticular formation
12.2: The Central Nervous System
reticular lamina
3.3: Epithelial Tissue
reticular layer
4.2: Layers of the Skin
reticular tissue
3.4: Connective Tissue Supports and Protects
reticulocyte
16.4: Erythrocytes
reticuloendothelial cell
21.6: Accessory Organs in Digestion- The Liver, Pancreas, and Gallbladder
retina
13.2: Sensory Perception
retinacula
10.6: Muscles of the Pectoral Girdle and Upper Limbs
Retinal
13.2: Sensory Perception
retinal ganglion cell (RGC)
13.2: Sensory Perception
retraction
8.6: Types of Body Movements
retroperitoneal
21.2: Overview of the Digestive System
22.2: Gross Anatomy of Urine Transport
rhodopsin
13.2: Sensory Perception
rhomboid major
10.6: Muscles of the Pectoral Girdle and Upper Limbs
rhomboid minor
10.6: Muscles of the Pectoral Girdle and Upper Limbs
ribosome
2.3: The Cytoplasm and Cellular Organelles
ribs
6.2: Divisions of the Skeletal System
right atrioventricular valve
17.2: Heart Anatomy
right colic flexure
21.5: The Small and Large Intestines
right gastric artery
18.3: Circulatory Pathways
right lymphatic duct
19.2: Anatomy of the Lymphatic and Immune Systems
rod photoreceptor
13.2: Sensory Perception

root
20.2: Organs and Structures of the Respiratory System
21.3: The Mouth, Pharynx, and Esophagus
rotation
8.6: Types of Body Movements
rotator cuff
8.7: Anatomy of Selected Synovial Joints
10.6: Muscles of the Pectoral Girdle and Upper Limbs
round window
13.2: Sensory Perception
ruga
21.4: The Stomach
rugae
23.3: Anatomy and Physiology of the Female Reproductive System

## S

S phase
2.5: Cell Growth and Division
saccharolytic fermentation
21.5: The Small and Large Intestines
saccule
13.2: Sensory Perception
sacral canal
6.4: The Vertebral Column
sacral foramina
6.4: The Vertebral Column
sacral hiatus
6.4: The Vertebral Column
sacral micturition center
22.2: Gross Anatomy of Urine Transport
sacral plexus
12.4: The Peripheral Nervous System
sacral promontory
6.4: The Vertebral Column
sacrococcygeal curve
6.4: The Vertebral Column
sacrum
6.2: Divisions of the Skeletal System
saddle joint
8.5: Synovial Joints
sagittal plane
1.4: Anatomical Terminology
sagittal suture
6.3: The Skull
saliva
21.3: The Mouth, Pharynx, and Esophagus
salivary amylase
21.3: The Mouth, Pharynx, and Esophagus
salivary gland
21.3: The Mouth, Pharynx, and Esophagus
salivation
21.3: The Mouth, Pharynx, and Esophagus
saphenous nerve
12.4: The Peripheral Nervous System
sarcolemma
9.3: Skeletal Muscle
sarcomere
9.3: Skeletal Muscle
sarcoplasm
9.3: Skeletal Muscle
sarcoplasmic reticulum (SR)
9.3: Skeletal Muscle
sartorius
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
satellite cell
11.3: Nervous Tissue
scala tympani
13.2: Sensory Perception
scala vestibuli
13.2: Sensory Perception
scalene muscles
10.4: Axial Muscles of the Head, Neck, and Back
scaphoid
7.3: Bones of the Upper Limb
scapula
7.2: The Pectoral Girdle
scar
4.4: Diseases, Disorders, and Injuries of the Integumentary System
Schwann cell
3.6: Nervous Tissue
11.3: Nervous Tissue
sciatic nerve
12.4: The Peripheral Nervous System
sciatica
12.4: The Peripheral Nervous System
sclera
13.2: Sensory Perception
sclerotome
6.6: Embryonic Development of the Axial Skeleton
scoliosis
6.4: The Vertebral Column
scrotum
23.2: Anatomy and Physiology of the Male Reproductive System
sebaceous gland
4.3: Accessory Structures of the Skin
sebum
4.3: Accessory Structures of the Skin
secondary curve
6.4: The Vertebral Column
Secondary Endocrine Functions
15.9: Organs with Secondary Endocrine Functions
secondary follicles
23.3: Anatomy and Physiology of the Female Reproductive System
secondary lymphoid organs
19.2: Anatomy of the Lymphatic and Immune Systems
secondary ossification center
5.5: Bone Formation and Development
secondary sex characteristics
23.4: Development of the Male and Female Reproductive Systems
secretory phase
23.3: Anatomy and Physiology of the Female Reproductive System
Section
1.4: Anatomical Terminology
segmental muscle group
10.4: Axial Muscles of the Head, Neck, and Back
selective permeability
2.2: The Cell Membrane
sella turcica
6.3: The Skull
semen
23.2: Anatomy and Physiology of the Male Reproductive System
semicircular canals
13.2: Sensory Perception
semilunar valves
17.2: Heart Anatomy
semimembranosus
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
seminal vesicle
23.2: Anatomy and Physiology of the Male Reproductive System
seminiferous tubules
23.2: Anatomy and Physiology of the Male Reproductive System
semispinalis capitis
10.4: Axial Muscles of the Head, Neck, and Back
semispinalis cervicis
10.4: Axial Muscles of the Head, Neck, and Back
semispinalis thoracis
10.4: Axial Muscles of the Head, Neck, and Back
semitendinosus
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
sensation
11.2: Basic Structures of the Nervous System
sensory modality
13.2: Sensory Perception
septal cartilage
6.3: The Skull
septum
17.2: Heart Anatomy
septum primum
17.2: Heart Anatomy
serosa
1.4: Anatomical Terminology
21.2: Overview of the Digestive System
serous gland
3.3: Epithelial Tissue
serous membrane
1.4: Anatomical Terminology
3.2: Types of Tissues
serratus anterior
10.6: Muscles of the Pectoral Girdle and Upper Limbs
Sertoli cells
23.2: Anatomy and Physiology of the Male Reproductive System
sesamoid bone
5.3: Bone Classification
shaft of the femur
7.5: Bones of the Lower Limb
shaft of the fibula
7.5: Bones of the Lower Limb
shaft of the humerus
7.3: Bones of the Upper Limb
shaft of the radius
7.3: Bones of the Upper Limb
shaft of the tibia
7.5: Bones of the Lower Limb
shaft of the ulna
7.3: Bones of the Upper Limb

short bone
5.3: Bone Classification
short reflex
14.3: Autonomic Reflexes and Homeostasis
sickle cell disease
16.4: Erythrocytes
sigmoid colon
21.5: The Small and Large Intestines
sigmoid sinuses
12.3: Circulation and the Central Nervous System
18.3: Circulatory Pathways
simple columnar epithelium
3.3: Epithelial Tissue
simple cuboidal epithelium
3.3: Epithelial Tissue
simple squamous epithelium
3.3: Epithelial Tissue
sinoatrial (SA) node
17.3: Cardiac Muscle
sinus rhythm
17.3: Cardiac Muscle
sinusoid capillary
18.2: Structure of Blood Vessels
sister chromatid
2.5: Cell Growth and Division
skeletal muscle
3.5: Muscle Tissue
9.2: Overview of Muscle Tissues
skeletal system
5.2: The Functions of the Skeletal System
skeleton
6.2: Divisions of the Skeletal System
skull
6.2: Divisions of the Skeletal System
slow oxidative (SO)
9.5: Types of Muscle Fibers
small cardiac vein
17.2: Heart Anatomy
small intestine
21.5: The Small and Large Intestines
small saphenous vein
18.3: Circulatory Pathways
smooth muscle
3.5: Muscle Tissue
9.2: Overview of Muscle Tissues
soft palate
21.3: The Mouth, Pharynx, and Esophagus
soleal line
7.5: Bones of the Lower Limb
soleus
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
soma
11.2: Basic Structures of the Nervous System
somatic cell
2.5: Cell Growth and Division
somatic nervous system (SNS)
11.2: Basic Structures of the Nervous System
somatic reflex
14.3: Autonomic Reflexes and Homeostasis
somatosensation
12.2: The Central Nervous System
13.2: Sensory Perception
somite
6.6: Embryonic Development of the Axial Skeleton
special sense
13.2: Sensory Perception
special senses
7.2: The Pectoral Girdle
sperm
23.2: Anatomy and Physiology of the Male Reproductive System
spermatic cord
23.2: Anatomy and Physiology of the Male Reproductive System
spermatid
23.2: Anatomy and Physiology of the Male Reproductive System
spermatocyte
23.2: Anatomy and Physiology of the Male Reproductive System
spermatogenesis
23.2: Anatomy and Physiology of the Male Reproductive System
spermatogonia
23.2: Anatomy and Physiology of the Male Reproductive System
spermiogenesis
23.2: Anatomy and Physiology of the Male Reproductive System
sphenoid bone
6.3: The Skull
sphenoid sinus
6.3: The Skull
sphincter urethrovaginalis
10.5: Axial Muscles of the Abdominal Wall and Thorax
spinal accessory nerve
12.4: The Peripheral Nervous System
spinal cavity
1.4: Anatomical Terminology
spinal cord
11.2: Basic Structures of the Nervous System
spinal nerve
12.4: The Peripheral Nervous System
spinalis capitis
10.4: Axial Muscles of the Head, Neck, and Back
spinalis cervicis
10.4: Axial Muscles of the Head, Neck, and Back
spinalis group
10.4: Axial Muscles of the Head, Neck, and Back
spinalis thoracis
10.4: Axial Muscles of the Head, Neck, and Back
spine of the scapula
7.2: The Pectoral Girdle
spinous process
6.4: The Vertebral Column
spiral ganglion
13.2: Sensory Perception
spleen
19.2: Anatomy of the Lymphatic and Immune Systems
splenic artery
18.3: Circulatory Pathways
splenius
10.4: Axial Muscles of the Head, Neck, and Back
splenius capitis
10.4: Axial Muscles of the Head, Neck, and Back
splenius cervicis
10.4: Axial Muscles of the Head, Neck, and Back
spongy bone
5.4: Bone Structure
spontaneous depolarizationv
17.3: Cardiac Muscle
squamous cell carcinoma
4.4: Diseases, Disorders, and Injuries of the Integumentary System
squamous suture
6.3: The Skull
stage of exhaustion
15.6: The Adrenal Glands
stage of resistance
15.6: The Adrenal Glands
stapes
13.2: Sensory Perception
stereocilia
13.2: Sensory Perception
sternal angle
6.5: The Thoracic Cage
sternal end of the clavicle
7.2: The Pectoral Girdle
sternoclavicular joint
7.2: The Pectoral Girdle
sternocleidomastoid
10.4: Axial Muscles of the Head, Neck, and Back
sternohyoid
10.4: Axial Muscles of the Head, Neck, and Back
sternothyroid
10.4: Axial Muscles of the Head, Neck, and Back
sternum
6.2: Divisions of the Skeletal System
stimulus
11.2: Basic Structures of the Nervous System
stomach
21.4: The Stomach
straight sinus
12.3: Circulation and the Central Nervous System
18.3: Circulatory Pathways
stratified columnar epithelium
3.3: Epithelial Tissue
stratified cuboidal epithelium
3.3: Epithelial Tissue
stratified squamous epithelium
3.3: Epithelial Tissue
stratum basale
4.2: Layers of the Skin
stratum corneum
4.2: Layers of the Skin
stratum granulosum
4.2: Layers of the Skin
stratum lucidum
4.2: Layers of the Skin
stratum spinosum
4.2: Layers of the Skin
stretch mark
4.4: Diseases, Disorders, and Injuries of the Integumentary System
striation
3.5: Muscle Tissue
striatum
12.2: The Central Nervous System

styloglossus
10.4: Axial Muscles of the Head, Neck, and Back
stylohyoid
10.4: Axial Muscles of the Head, Neck, and Back
styloid process
6.3: The Skull
styloid process of the radius
7.3: Bones of the Upper Limb
styloid process of the ulna
7.3: Bones of the Upper Limb
stylomastoid foramen
6.3: The Skull
subacromial bursa
8.7: Anatomy of Selected Synovial Joints
subarachnoid space
12.3: Circulation and the Central Nervous System
subclavian artery
18.3: Circulatory Pathways
subclavian vein
18.3: Circulatory Pathways
subclavius
10.6: Muscles of the Pectoral Girdle and Upper Limbs
subcortical nucleus
12.2: The Central Nervous System
subcutaneous bursa
8.5: Synovial Joints
sublingual gland
21.3: The Mouth, Pharynx, and Esophagus
submandibular gland
21.3: The Mouth, Pharynx, and Esophagus
submodality
13.2: Sensory Perception
submucosa
21.2: Overview of the Digestive System
submuscular bursa
8.5: Synovial Joints
subscapular bursa
8.7: Anatomy of Selected Synovial Joints
subscapular fossa
7.2: The Pectoral Girdle
subscapular vein
18.3: Circulatory Pathways
subscapularis
10.6: Muscles of the Pectoral Girdle and Upper Limbs
substantia nigra pars compacta
12.2: The Central Nervous System
substantia nigra pars reticulata
12.2: The Central Nervous System
subtalar joint
8.7: Anatomy of Selected Synovial Joints
subtendinous bursa
8.5: Synovial Joints
subthalamus
12.2: The Central Nervous System
sudoriferous gland
4.3: Accessory Structures of the Skin
sulcus
12.2: The Central Nervous System
17.2: Heart Anatomy
Superficial
1.4: Anatomical Terminology
superficial anterior compartment of the forearm
10.6: Muscles of the Pectoral Girdle and Upper Limbs
superficial posterior compartment of the forearm
10.6: Muscles of the Pectoral Girdle and Upper Limbs
superior
1.4: Anatomical Terminology
superior angle of the scapula
7.2: The Pectoral Girdle
superior articular process
6.4: The Vertebral Column
superior articular process of the sacrum
6.4: The Vertebral Column
superior border of the scapula
7.2: The Pectoral Girdle
superior cervical ganglion
14.2: Divisions of the Autonomic Nervous System
superior colliculus
12.2: The Central Nervous System
superior extensor retinaculum
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
superior gemellus
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
superior mesenteric artery
18.3: Circulatory Pathways
superior mesenteric ganglion
14.2: Divisions of the Autonomic Nervous System
superior nuchal line
6.3: The Skull
superior oblique
13.2: Sensory Perception
superior orbital fissure
6.3: The Skull
superior phrenic artery
18.3: Circulatory Pathways
superior rectus
13.2: Sensory Perception
superior rotation
8.6: Types of Body Movements
superior sagittal sinus
12.3: Circulation and the Central Nervous System
18.3: Circulatory Pathways
superior vena cava
17.2: Heart Anatomy
18.3: Circulatory Pathways
supinated position
8.6: Types of Body Movements
supination
8.6: Types of Body Movements
supinator
10.6: Muscles of the Pectoral Girdle and Upper Limbs
Supine
1.4: Anatomical Terminology
supportive connective tissue
3.4: Connective Tissue Supports and Protects
supraglenoid tubercle
7.2: The Pectoral Girdle
suprahyoid muscles
10.4: Axial Muscles of the Head, Neck, and Back
supraorbital foramen
6.3: The Skull
supraorbital margin
6.3: The Skull
suprascapular notch
7.2: The Pectoral Girdle
supraspinatus
10.6: Muscles of the Pectoral Girdle and Upper Limbs
supraspinous fossa
7.2: The Pectoral Girdle
supraspinous ligament
6.4: The Vertebral Column
surgical neck
7.3: Bones of the Upper Limb
suspensory ligaments
23.3: Anatomy and Physiology of the Female Reproductive System
sustentaculum tali
7.5: Bones of the Lower Limb
suture
6.3: The Skull
8.3: Fibrous Joints
sympathetic chain ganglia
12.4: The Peripheral Nervous System
14.2: Divisions of the Autonomic Nervous System
sympathetic division
14.2: Divisions of the Autonomic Nervous System
symphysis
8.4: Cartilaginous Joints
synapse
11.3: Nervous Tissue
synaptic cleft
9.3: Skeletal Muscle
synaptic end bulb
11.3: Nervous Tissue
synarthrosis
8.2: Classification of Joints
synchondrosis
8.4: Cartilaginous Joints
syndesmosis
8.3: Fibrous Joints
synergist
10.2: Interactions of Skeletal Muscles, Their Fascicle Arrangement, and Their Lever Systems
synostosis
8.3: Fibrous Joints
synovial fluid
8.5: Synovial Joints
synovial joint
8.2: Classification of Joints
synovial membrane
3.2: Types of Tissues
8.5: Synovial Joints
Systemic Anatomy
1.2: Overview of Anatomy and Physiology
systemic circuit
17.2: Heart Anatomy
systemic nerve
12.4: The Peripheral Nervous System

# T


T cell
19.2: Anatomy of the Lymphatic and Immune Systems
T lymphocytes
16.5: Leukocytes and Platelets
T wave
17.3: Cardiac Muscle
talocrural joint
8.7: Anatomy of Selected Synovial Joints
talus
7.5: Bones of the Lower Limb
target effector
14.2: Divisions of the Autonomic Nervous System
tarsal bone
7.5: Bones of the Lower Limb
taste buds
13.2: Sensory Perception
tectorial membrane
13.2: Sensory Perception
tectum
12.2: The Central Nervous System
tegmentum
12.2: The Central Nervous System
telogen
4.3: Accessory Structures of the Skin
telophase
2.5: Cell Growth and Division
temporal bone
6.3: The Skull
temporal fossa
6.3: The Skull
temporal lobe
12.2: The Central Nervous System
temporal process of the zygomatic bone
6.3: The Skull
temporal vein
18.3: Circulatory Pathways
temporalis
10.4: Axial Muscles of the Head, Neck, and Back
temporomandibular joint (TMJ)
8.7: Anatomy of Selected Synovial Joints
tendinous intersections
10.5: Axial Muscles of the Abdominal Wall and Thorax
tendon
8.5: Synovial Joints
tendon sheath
8.5: Synovial Joints
tenia coli
21.5: The Small and Large Intestines
tensor fascia lata
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
teres major
10.6: Muscles of the Pectoral Girdle and Upper Limbs
teres minor
10.6: Muscles of the Pectoral Girdle and Upper Limbs
terminal ganglia
14.2: Divisions of the Autonomic Nervous System
terminal ganglion
12.4: The Peripheral Nervous System
tertiary follicles
23.3: Anatomy and Physiology of the Female Reproductive System
testes
23.2: Anatomy and Physiology of the Male Reproductive System
testicular artery
18.3: Circulatory Pathways
testicular vein
18.3: Circulatory Pathways
thalamus
12.2: The Central Nervous System
thalassemia
16.4: Erythrocytes
theca cells
23.3: Anatomy and Physiology of the Female Reproductive System
thenar
10.6: Muscles of the Pectoral Girdle and Upper Limbs
thenar eminence
10.6: Muscles of the Pectoral Girdle and Upper Limbs
thermoreceptor
13.2: Sensory Perception
thick filament
9.3: Skeletal Muscle
thigh
7.5: Bones of the Lower Limb
thin filament
9.3: Skeletal Muscle
third ventricle
12.3: Circulation and the Central Nervous System
thoracic aorta
18.3: Circulatory Pathways
thoracic cage
6.2: Divisions of the Skeletal System
thoracic cavity
1.4: Anatomical Terminology
thoracic curve
6.4: The Vertebral Column
thoracic duct
19.2: Anatomy of the Lymphatic and Immune Systems
thoracic vertebrae
6.4: The Vertebral Column
thoracolumbar system
14.2: Divisions of the Autonomic Nervous System
thoroughfare channel
18.2: Structure of Blood Vessels
thrombocytes
16.5: Leukocytes and Platelets
thrombocytopenia
16.5: Leukocytes and Platelets
thrombocytosis
16.5: Leukocytes and Platelets
thrombopoietin
16.3: Production of the Formed Elements
thymocyte
19.2: Anatomy of the Lymphatic and Immune Systems
thymosins
15.9: Organs with Secondary Endocrine Functions
thymus
15.9: Organs with Secondary Endocrine Functions
19.2: Anatomy of the Lymphatic and Immune Systems
thyrocervical artery
18.3: Circulatory Pathways
thyrohyoid
10.4: Axial Muscles of the Head, Neck, and Back
thyroid cartilage
20.2: Organs and Structures of the Respiratory System
thyroid gland
15.4: The Thyroid Gland
thyroxine
15.4: The Thyroid Gland
tibia
7.5: Bones of the Lower Limb
tibial collateral ligament
8.7: Anatomy of Selected Synovial Joints
tibial nerve
12.4: The Peripheral Nervous System
tibialis anterior
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
tibialis posterior
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
tight junction
3.3: Epithelial Tissue
tissue
1.3: Structural Organization of the Human Body
3.2: Types of Tissues
tissue membrane
3.2: Types of Tissues
tongue
21.3: The Mouth, Pharynx, and Esophagus
tonsils
19.2: Anatomy of the Lymphatic and Immune Systems
topographical
13.2: Sensory Perception
totipotent
3.2: Types of Tissues
totipotent stem cell
16.3: Production of the Formed Elements
trabeculae
5.4: Bone Structure
trabeculae carneae
17.2: Heart Anatomy
trachea
20.2: Organs and Structures of the Respiratory System
trachealis muscle
20.2: Organs and Structures of the Respiratory System
tract
11.2: Basic Structures of the Nervous System
transduction
13.2: Sensory Perception
transient ischemic attack (TIA)
18.3: Circulatory Pathways
transitional epithelium
3.3: Epithelial Tissue
transverse colon
21.5: The Small and Large Intestines

transverse foramen
6.4: The Vertebral Column
Transverse Plane
1.4: Anatomical Terminology
transverse process
6.4: The Vertebral Column
transverse sinuses
12.3: Circulation and the Central Nervous System
18.3: Circulatory Pathways
transversus abdominis
10.5: Axial Muscles of the Abdominal Wall and Thorax
trapezium
7.3: Bones of the Upper Limb
trapezius
10.6: Muscles of the Pectoral Girdle and Upper Limbs
trapezoid
7.3: Bones of the Upper Limb
tri
10.3: Naming Skeletal Muscle
triad
9.3: Skeletal Muscle
triceps brachii
10.6: Muscles of the Pectoral Girdle and Upper Limbs
tricuspid valve
17.2: Heart Anatomy
trigeminal ganglion
12.4: The Peripheral Nervous System
trigeminal nerve
12.4: The Peripheral Nervous System
trigone
22.2: Gross Anatomy of Urine Transport
triiodothyronine
15.4: The Thyroid Gland
triquetrum
7.3: Bones of the Upper Limb
trochlea
7.3: Bones of the Upper Limb
13.2: Sensory Perception
trochlear nerve
12.4: The Peripheral Nervous System
trochlear notch
7.3: Bones of the Upper Limb
tropomyosin
9.3: Skeletal Muscle
troponin
9.3: Skeletal Muscle
true ribs
6.5: The Thoracic Cage
true vocal cord
20.2: Organs and Structures of the Respiratory System
trunk
18.3: Circulatory Pathways
tubercle of the rib
6.5: The Thoracic Cage
tunica externa
18.2: Structure of Blood Vessels
tunica intima
18.2: Structure of Blood Vessels
tunica media
18.2: Structure of Blood Vessels
tympanic membrane
13.2: Sensory Perception
type I alveolar cell
20.2: Organs and Structures of the Respiratory System
type II alveolar cell
20.2: Organs and Structures of the Respiratory System

## U

ulna
7.3: Bones of the Upper Limb
ulnar artery
18.3: Circulatory Pathways
ulnar collateral ligament
8.7: Anatomy of Selected Synovial Joints
ulnar nerve
12.4: The Peripheral Nervous System
ulnar notch of the radius
7.3: Bones of the Upper Limb
ulnar tuberosity
7.3: Bones of the Upper Limb
ulnar vein
18.3: Circulatory Pathways
Ultrasonography
1.5: Medical Imaging
umami
13.2: Sensory Perception
uniaxial joint
8.2: Classification of Joints
unipennate
10.2: Interactions of Skeletal Muscles, Their Fascicle Arrangement, and Their Lever Systems
unipolar
11.3: Nervous Tissue
upper esophageal sphincter
21.3: The Mouth, Pharynx, and Esophagus
urethra
22.2: Gross Anatomy of Urine Transport
urinary system
22: The Urinary System
urogenital triangle
10.5: Axial Muscles of the Abdominal Wall and Thorax
uterine tubes
23.3: Anatomy and Physiology of the Female Reproductive System
uterus
23.3: Anatomy and Physiology of the Female Reproductive System
utricle
13.2: Sensory Perception

## V

vagina
23.3: Anatomy and Physiology of the Female Reproductive System
vagus nerve
12.4: The Peripheral Nervous System
Valsalva’s maneuver
21.5: The Small and Large Intestines
valve
17.2: Heart Anatomy
varicosity
9.7: Smooth Muscle
14.2: Divisions of the Autonomic Nervous System
vasa vasorum
18.2: Structure of Blood Vessels
vascular shunt
18.2: Structure of Blood Vessels
vascular tunic
13.2: Sensory Perception
vasoconstriction
18.2: Structure of Blood Vessels
vasodilation
18.2: Structure of Blood Vessels
vasomotion
18.2: Structure of Blood Vessels
vastus lateralis
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
vastus medialis
10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs
vein
18.2: Structure of Blood Vessels
venous reserve
18.2: Structure of Blood Vessels
Ventral
1.4: Anatomical Terminology
ventral cavity
1.4: Anatomical Terminology
ventricle
17.2: Heart Anatomy
ventricles
12.3: Circulation and the Central Nervous System
venule
18.2: Structure of Blood Vessels
vertebra
6.2: Divisions of the Skeletal System
vertebral (spinal) canal
6.4: The Vertebral Column
vertebral arch
6.4: The Vertebral Column
vertebral artery
18.3: Circulatory Pathways
vertebral column
6.2: Divisions of the Skeletal System
vertebral foramen
6.4: The Vertebral Column
vertebral vein
18.3: Circulatory Pathways
Vesicle
2.2: The Cell Membrane
vestibular fold
20.2: Organs and Structures of the Respiratory System
vestibular ganglion
13.2: Sensory Perception
vestibule
13.2: Sensory Perception
villus
21.5: The Small and Large Intestines
visceral branches
18.3: Circulatory Pathways
visceral muscle
9.7: Smooth Muscle

visceral pleura
20.3: The Lungs
visceral reflex
14.3: Autonomic Reflexes and Homeostasis
visceral sense
13.2: Sensory Perception
vision
13.2: Sensory Perception
visual acuity
13.2: Sensory Perception
vitiligo
4.2: Layers of the Skin
vitreous humor
13.2: Sensory Perception
voluntary phase
21.3: The Mouth, Pharynx, and Esophagus
vomer bone
6.3: The Skull
vulva
23.3: Anatomy and Physiology of the Female Reproductive System

## W

white matter
11.2: Basic Structures of the Nervous System
white rami communicantes
14.2: Divisions of the Autonomic Nervous System
Wolffian duct
23.4: Development of the Male and Female Reproductive Systems

## Y

yellow marrow
5.2: The Functions of the Skeletal System

## Z

zona fasciculata
15.6: The Adrenal Glands
zona glomerulosa
15.6: The Adrenal Glands
zona reticularis
15.6: The Adrenal Glands
zone of calcified matrix
5.5: Bone Formation and Development
zone of maturation and hypertrophy
5.5: Bone Formation and Development
zonule fibers
13.2: Sensory Perception
zygapophysial joints
8.7: Anatomy of Selected Synovial Joints
zygomatic arch
6.3: The Skull
zygomatic bone
6.3: The Skull
zygomatic process of the temporal bone
6.3: The Skull

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    - 3.3: Epithelial Tissue - *CC BY 4.0*
    - 3.4: Connective Tissue Supports and Protects - *CC BY 4.0*
    - 3.5: Muscle Tissue - *CC BY 4.0*
    - 3.6: Nervous Tissue - *CC BY 4.0*
  - 4: The Integumentary System - *CC BY 4.0*
    - 4.1: Introduction - *CC BY 4.0*
    - 4.2: Layers of the Skin - *CC BY 4.0*
    - 4.3: Accessory Structures of the Skin - *CC BY 4.0*
    - 4.4: Diseases, Disorders, and Injuries of the Integumentary System - *CC BY 4.0*
  - 5: Bone Tissue and the Skeletal System - *CC BY 4.0*
    - 5.1: Introduction - *CC BY 4.0*
    - 5.2: The Functions of the Skeletal System - *CC BY 4.0*
    - 5.3: Bone Classification - *CC BY 4.0*
    - 5.4: Bone Structure - *CC BY 4.0*
    - 5.5: Bone Formation and Development - *CC BY 4.0*
    - 5.6: Fractures - Bone Repair - *CC BY 4.0*
  - 6: Axial Skeleton - *CC BY 4.0*
    - 6.1: Introduction to the Axial Skeleton - *CC BY 4.0*
    - 6.2: Divisions of the Skeletal System - *CC BY 4.0*
    - 6.3: The Skull - *CC BY 4.0*
    - 6.4: The Vertebral Column - *CC BY 4.0*
    - 6.5: The Thoracic Cage - *CC BY 4.0*
    - 6.6: Embryonic Development of the Axial Skeleton - *CC BY 4.0*
  - 7: The Appendicular Skeleton - *CC BY 4.0*
    - 7.1: Introduction - *CC BY 4.0*
    - 7.2: The Pectoral Girdle - *CC BY 4.0*
    - 7.3: Bones of the Upper Limb - *CC BY 4.0*
    - 7.4: The Pelvic Girdle and Pelvis - *CC BY 4.0*
    - 7.5: Bones of the Lower Limb - *CC BY 4.0*
  - 8: Joints - *CC BY 4.0*
    - 8.1: Introduction - *CC BY 4.0*
    - 8.2: Classification of Joints - *CC BY 4.0*
    - 8.3: Fibrous Joints - *CC BY 4.0*
    - 8.4: Cartilaginous Joints - *CC BY 4.0*
    - 8.5: Synovial Joints - *CC BY 4.0*
    - 8.6: Types of Body Movements - *CC BY 4.0*

- 8.7: Anatomy of Selected Synovial Joints - *CC BY 4.0*

- 9: Muscle Tissue - *CC BY 4.0*
  - 9.1: Prelude to Muscle Tissue - *CC BY 4.0*
  - 9.2: Overview of Muscle Tissues - *CC BY 4.0*
  - 9.3: Skeletal Muscle - *CC BY 4.0*
  - 9.4: Muscle Fiber Contraction and Relaxation - *CC BY 4.0*
  - 9.5: Types of Muscle Fibers - *CC BY 4.0*
  - 9.6: Cardiac Muscle Tissue - *CC BY 4.0*
  - 9.7: Smooth Muscle - *CC BY 4.0*
- 10: The Muscular System - *CC BY 4.0*
  - 10.1: Prelude to the Muscular System - *CC BY 4.0*
  - 10.2: Interactions of Skeletal Muscles, Their Fascicle Arrangement, and Their Lever Systems - *CC BY 4.0*
  - 10.3: Naming Skeletal Muscle - *CC BY 4.0*
  - 10.4: Axial Muscles of the Head, Neck, and Back - *CC BY 4.0*
  - 10.5: Axial Muscles of the Abdominal Wall and Thorax - *CC BY 4.0*
  - 10.6: Muscles of the Pectoral Girdle and Upper Limbs - *CC BY 4.0*
  - 10.7: Appendicular Muscles of the Pelvic Girdle and Lower Limbs - *CC BY 4.0*
- 11: The Nervous System and Nervous Tissue - *CC BY 4.0*
  - 11.1: Prelude to the Nervous System - *CC BY 4.0*
  - 11.2: Basic Structures of the Nervous System - *CC BY 4.0*
  - 11.3: Nervous Tissue - *CC BY 4.0*
- 12: Anatomy of the Nervous Tissue - *CC BY 4.0*
  - 12.1: Prelude Anatomy of the Nervous Tissue - *CC BY 4.0*
  - 12.2: The Central Nervous System - *CC BY 4.0*
  - 12.3: Circulation and the Central Nervous System - *CC BY 4.0*
  - 12.4: The Peripheral Nervous System - *CC BY 4.0*
- 13: The Somatic Nervous System - *CC BY 4.0*
  - 13.1: Prelude to The Somatic Nervous System - *CC BY 4.0*
  - 13.2: Sensory Perception - *CC BY 4.0*
- 14: The Autonomic Nervous System - *CC BY 4.0*
  - 14.1: Prelude to The Autonomic Nervous System - *CC BY 4.0*
  - 14.2: Divisions of the Autonomic Nervous System - *CC BY 4.0*
  - 14.3: Autonomic Reflexes and Homeostasis - *CC BY 4.0*
- 15: The Endocrine System - *CC BY 4.0*
  - 15.1: Prelude to the Endocrine System - *CC BY 4.0*
  - 15.2: An Overview of the Endocrine System - *CC BY 4.0*
  - 15.3: The Pituitary Gland and Hypothalamus - *CC BY 4.0*
  - 15.4: The Thyroid Gland - *CC BY 4.0*
  - 15.5: The Parathyroid Glands - *CC BY 4.0*
  - 15.6: The Adrenal Glands - *CC BY 4.0*
  - 15.7: The Pineal Gland - *CC BY 4.0*
  - 15.8: The Endocrine Pancreas - *CC BY 4.0*
  - 15.9: Organs with Secondary Endocrine Functions - *CC BY 4.0*
- 16: The Cardiovascular System - Blood - *CC BY 4.0*
  - 16.1: Prelude to Blood - *CC BY 4.0*
  - 16.2: An Overview of Blood - *CC BY 4.0*
  - 16.3: Production of the Formed Elements - *CC BY 4.0*
  - 16.4: Erythrocytes - *CC BY 4.0*
  - 16.5: Leukocytes and Platelets - *CC BY 4.0*
- 17: The Cardiovascular System - The Heart - *CC BY 4.0*
  - 17.1: Prelude to The Heart - *CC BY 4.0*
  - 17.2: Heart Anatomy - *CC BY 4.0*
  - 17.3: Cardiac Muscle - *CC BY 4.0*
- 18: The Cardiovascular System - Blood Vessels and Circulation - *CC BY 4.0*
  - 18.1: Introduction to the Cardiovascular System - Blood Vessels and Circulation - *CC BY 4.0*
  - 18.2: Structure of Blood Vessels - *CC BY 4.0*
  - 18.3: Circulatory Pathways - *CC BY 4.0*
- 19: The Lymphatic and Immune System - *CC BY 4.0*
  - 19.1: Introduction - *CC BY 4.0*
  - 19.2: Anatomy of the Lymphatic and Immune Systems - *CC BY 4.0*
- 20: The Respiratory System - *CC BY 4.0*
  - 20.1: Prelude to the Respiratory System - *CC BY 4.0*
  - 20.2: Organs and Structures of the Respiratory System - *CC BY 4.0*
  - 20.3: The Lungs - *CC BY 4.0*
- 21: The Digestive System - *CC BY 4.0*
  - 21.1: Introduction - *CC BY 4.0*
  - 21.2: Overview of the Digestive System - *CC BY 4.0*
  - 21.3: The Mouth, Pharynx, and Esophagus - *CC BY 4.0*
  - 21.4: The Stomach - *CC BY 4.0*
  - 21.5: The Small and Large Intestines - *CC BY 4.0*
  - 21.6: Accessory Organs in Digestion- The Liver, Pancreas, and Gallbladder - *CC BY 4.0*
- 22: The Urinary System - *CC BY 4.0*

- 22.1: Prelude to the Urinary System - *CC BY 4.0*
- 22.2: Gross Anatomy of Urine Transport - *CC BY 4.0*
- 22.3: Gross Anatomy of the Kidney - *CC BY 4.0*
- 22.4: Microscopic Anatomy of the Kidney - *CC BY 4.0*

- 23: The Reproductive System - *CC BY 4.0*
  - 23.1: Prelude to the Reproductive System - *CC BY 4.0*
  - 23.2: Anatomy and Physiology of the Male Reproductive System - *CC BY 4.0*
  - 23.3: Anatomy and Physiology of the Female Reproductive System - *CC BY 4.0*
  - 23.4: Development of the Male and Female Reproductive Systems - *CC BY 4.0*
- Back Matter - *Undeclared*
  - Index - *Undeclared*
  - Glossary - *CC BY-NC-SA 4.0*
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