# BIOL 106: ESSENTIALS OF ANATOMY AND PHYSIOLOGY



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# Essentials of Anatomy and Physiology BIOL 106

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Detailed Licensing

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# CHAPTER OVERVIEW

## 1: INTRODUCTION TO THE HUMAN BODY

This chapter outlines the organization of the human body and describes human cells, tissues, organs, organ systems, and body cavities. It also explains how organ systems interact and how feedback mechanisms maintain homeostasis in the body.


1.1: Case Study- Getting to Know Your Body
1.2: Organization of the Body
1.3: Human Cells and Tissues
1.4: Human Organs and Organ Systems
1.5: Human Body Cavities
1.6: Interaction of Organ Systems
1.7: Homeostasis and Feedback
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# 1.1: CASE STUDY- GETTING TO KNOW YOUR BODY

## CASE STUDY: UNDER PRESSURE

Looking at the photo of a football game in Figure **1.1.1**, you can see why it is so important that the players wear helmets because players may fall on their heads or on top of each other's heads. Football often involves forceful impact to the head as players tackle each other. This can cause damage to the brain — either temporarily as in the case of a concussion, or long-term and more severe types of damage. Helmets are critical to reducing the incidence of traumatic brain injuries (TBIs), but they do not fully prevent them.



Figure **1.1.1**:Football players

Take the example of 43-year-old Dayo. As a former professional football player who also played in college and high school, Dayo sustained many high-impact head injuries over the course of their football playing years. Dayo uses they/ them pronouns. A few years ago, Dayo began experiencing a variety of troubling symptoms, including the loss of bladder control (i.e. the involuntary leakage of urine), memory loss, and difficulty in walking. Symptoms such as these are often signs of damage to the nervous system, which includes the brain, spinal cord, and nerves, but they can result from many different types of injuries or diseases that affect the nervous system. In order to treat Dayo properly, their doctors needed to do several tests to determine the exact cause of their symptoms. These included a spinal tap to see if they had an infection, and an MRI (magnetic resonance imaging) to see if there were any problems with their brain structure.

The MRI revealed the cause of Dayo's symptoms. There are fluid-filled spaces within the brain called ventricles, and Dayo's ventricles were enlarged compared to normal ventricles. Based on this observation combined with the results of other tests, Dayo's doctor diagnosed them with hydrocephalus, a term that literally means "water head." Hydrocephalus occurs when the fluid that fills the ventricles, called cerebrospinal fluid, builds up excessively. This causes the ventricles to become enlarged and puts pressure on the brain, which can cause a variety of neurological symptoms including the ones Dayo was experiencing. You can see the difference between normal ventricles and ventricles that are enlarged due to hydrocephalus in the illustration below. Notice how the brain becomes "squeezed" due to hydrocephalus in the image on the right.

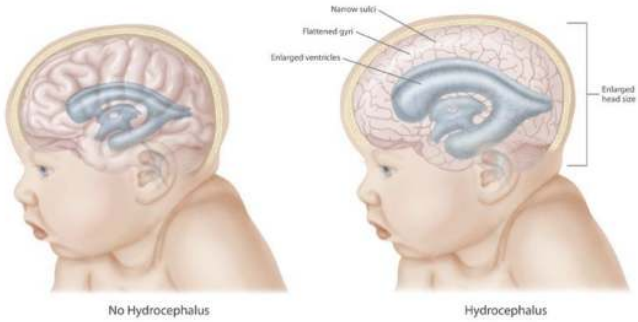



Figure **1.1.2**. Comparison of an infant with (on the right) and without hydrocephalus (on the left). The ventricles (shown in blue-gray) are located inside of the brain (shown in pink). Ventricles are enlarged in the infant with hydrocephalus.

Hydrocephalus often occurs at birth, due to genetic factors or events that occurred during fetal development. Because babies are born with skull bones that are not fully fused, the skull of a baby born with hydrocephalus can expand and relieve some of the pressure on the brain, as reflected in the enlarged head size shown above. But adults have fully fused, inflexible skulls, so when hydrocephalus occurs in an adult, the brain experiences all of the increased pressure.

Why did Dayo develop hydrocephalus? There are many possible causes of hydrocephalus in adults, including tumors, infections, hemorrhages, and TBIs. Given their repeated and long history of TBIs due to football, and the absence of any evidence of infection, tumor, or other cause, Dayo's doctor thinks their head injuries were most likely responsible for their hydrocephalus.

Although hydrocephalus is serious, there are treatments. Read the rest of this chapter to learn about the cells, tissues, organs, cavities, and systems of the body, how they are interconnected, and the importance of keeping the body in a state of homeostasis, or balance. The amount of cerebrospinal fluid in the ventricles is normally kept at a relatively steady level, and the potentially devastating symptoms of hydrocephalus are an example of what can happen when a system in the body becomes unbalanced. At the end of the chapter, you will learn about Dayo's treatment and prognosis.

## CHAPTER OVERVIEW: INTRODUCTION TO THE HUMAN BODY

In this chapter, you will learn about the general organization and functions of the human body. Specifically, you will learn about:

- The organization of the body from atoms and molecules up through cells, tissues, organs, and organ systems.
- How organ systems work together to carry out the functions of life.
- The variety of different specialized cell types in humans, the four major types of human tissues, and some of their functions.

- What organs are and the 11 major organ systems of the human body.
- Spaces in the body called body cavities, and the organs they hold and protect.
- The tissues and fluid that protect the brain and spinal cord.
- How organ systems communicate and interact in body processes such as cellular respiration, digestion, the fight-or-flight response to stressors, and physical activities such as sports.
- How homeostasis is maintained to keep the body in a relatively steady state, and the problems that can be caused by loss of homeostasis, such as diabetes.

As you read the chapter, think about the following questions:

1. What is the normal function of cerebrospinal fluid?
2. What is a spinal tap and how does it test for infection?
3. In Dayo's case, what organs and organ systems are probably affected by their hydrocephalus? What are some ways in which these organ systems interact?
4. The level of cerebrospinal fluid is normally kept in a state of homeostasis. What are other examples of types of homeostasis that keep your body functioning properly?

## ATTRIBUTIONS


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# 1.2: ORGANIZATION OF THE BODY

## A FANTASTIC MACHINE

This six-legged robot in Figure **1.2.1** was created for research, but it looks like it might be fun to play with. It's obviously a complex machine. Think about some other, more familiar machines, such as power drills, washing machines, and lawnmowers. Each machine consists of many parts, and each part does a specific job, yet all the parts work together to perform certain functions. Many people have compared the human body to a machine, albeit an extremely complex one. Like real machines, the human body also consists of many parts that work together to perform certain functions, which in the case of the human body include keeping the organism alive. The human body may be the most fantastic machine on Earth, as you will discover when you learn more about it in this concept.



Figure **1.2.1**: Six-legged walking robot LAURON IV

## WHAT THE HUMAN MACHINE CAN DO

Imagine a machine that has all of the following attributes. It can generate a "wind" of 166 km/hr (100 mi/hr), and it can relay messages faster than 400 km/hr (249 mi/hr). It contains a pump that moves about a million barrels of fluid over its lifetime, and it has a control center that contains billions of individual components. The machine in question can even repair itself if necessary and not wear out for up to a century or more. It has all these abilities, and yet it consists mainly of water. What is it? It is the human body.

## ORGANIZATION OF THE HUMAN BODY

The human body is a complicated, highly organized structure that consists of trillions of parts that function together to achieve all the functions needed to maintain life. The biology of the human body incorporates the body's structure, the study of which is called anatomy, and the body's functioning, the study of which is called physiology.

The organization of the human body can be seen as a hierarchy of increasing size and complexity, starting at the level of atoms and molecules and ending at the level of the entire organism, which is an individual living thing. You can see the intervening levels of organization in Figure **1.2.2** and read about them in the figure and the sections that follow.

To study the smallest level of organization, scientists consider the simplest building blocks of matter: atoms and molecules. The chemical level of organization considers these two building blocks as atoms bond to form molecules with three-dimensional structures.

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

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

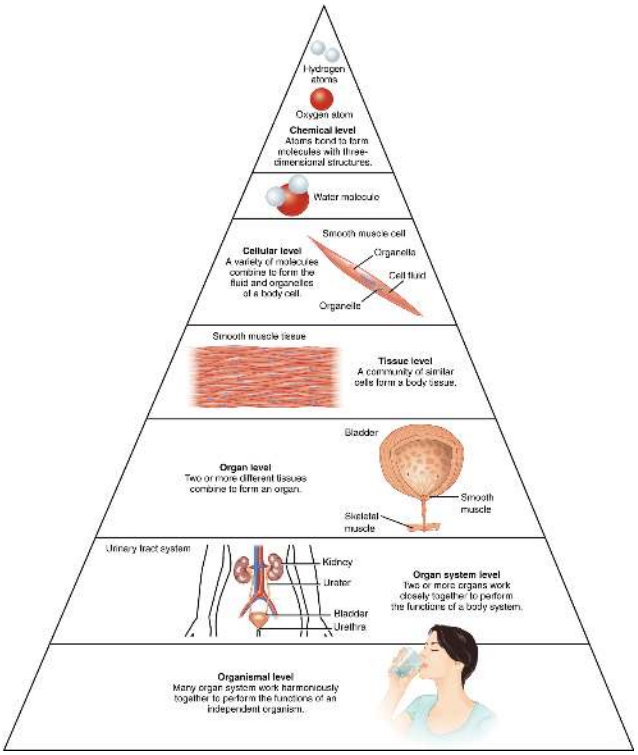



Figure **1.2.2**: This diagram shows the levels of organization of the human body, from atoms to the whole organism.

The tissue level can be studied when a community of similar cells forms a body tissue. A tissue is a group of many similar cells (though sometimes composed of a few related types) that work together to perform a specific function. For example, when many smooth muscle cells come together both structurally and functionally, these cells collectively form a layer of smooth muscle tissue.

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

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

## CELLS

The basic units of structure and function of the human body, as in all living things, are cells — an amazing 37 trillion of them by the time the average person reaches adulthood! Each cell carries out basic life processes that allow the body to survive. In addition, most human cells are specialized in structure and function to carry out other specific roles. In fact, the human body may consist of as many as 200 different types of cells, each of which has a special job to do. Just a few of these different human cell types are pictured in Figure **1.2.3**. The cells in the figure have obvious differences in structure that reflect their different functions. For example, nerve cells have long projections sticking out from the body of the cell. These projections help them carry electrical messages to other cells.

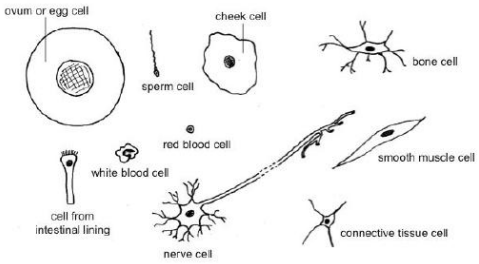



Figure **1.2.3**: A few of the many different types of cells in the human body are illustrated here. Each type of cell is specialized for a particular role in the body.

## TISSUES

After the cell, the tissue is the next level of organization in the human body. A **tissue** is a group of connected cells that have a similar function. There are four basic types of human tissues: connective, epithelial, muscle, and nervous tissues. These four tissue types, which are shown in Figure **1.2.4**, make up all the organs of the human body. Connective tissue is composed of cells that are suspended in a matrix. Epithelial tissue is mostly composed of cells that are tightly packed together in sheets. Muscle tissue is also composed of tightly packed cells and some types of muscle, such as the skeletal muscle shown in Figure **1.2.4** contains striation due to the organization of muscle fibers. Nervous tissue is composed of cells with long extensions.

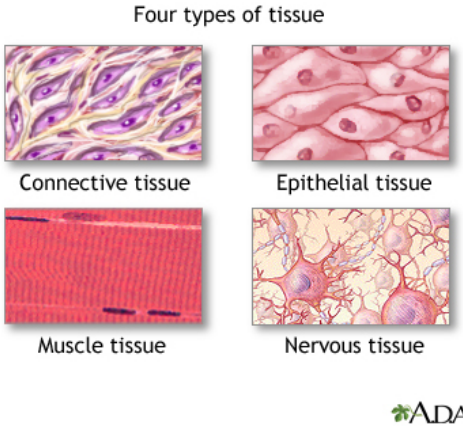



Figure **1.2.4**: Four types of tissues: Connective tissue, Epithelial tissue, Muscle tissue, Nervous tissue

## ORGANS AND ORGAN SYSTEMS

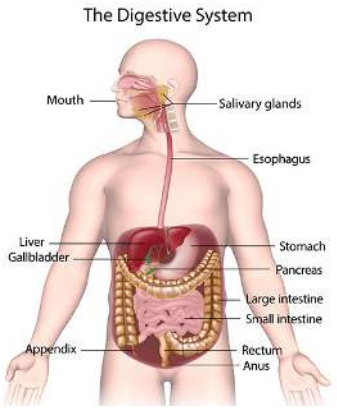



Figure **1.2.5**: A sample organ system (the digestive system) showing the organs within the system (mouth, salivary glands, esophagus, stomach, pancreas, large intestine, small intestine, liver, gallbladder, appendix, rectum, anus).

After tissues, organs are the next level of the organization of the human body. An organ is a structure that consists of two or more types of tissues that work together to do the same job. Examples of human organs include the heart, brain, lungs, skin, and kidneys. Human organs are organized into organ systems; the digestive system is shown in figure Figure **1.2.5**. An organ system is a group of organs that work together to carry out a complex overall function. Each organ of the system does part of the larger job.

## A WELL-OILED MACHINE

All of the organs and organ systems of the human body normally work together like a well-oiled machine. This is because they are closely regulated by the nervous and endocrine systems. The nervous system controls virtually all body activities, and the endocrine system secretes hormones that help to regulate these activities. Functioning together, the organ systems supply body cells with all the substances they need and eliminate their wastes. They also keep temperature, pH, and other conditions at just the right levels to support life.

## REVIEW

1. How is the human body like a complex machine?
2. Compare and contrast human anatomy and human physiology.
3. Summarize the hierarchical organization of the human body.
4. Relate cell structure to cell function, and give examples of specific cell types in the human body.
5. Define tissue, and identify the four types of tissues that make up the human body.
6. What is an organ? Give three examples of organs in the human body.
7. Define organ system, and name five organ systems in the human body.
8. True or False. How cells use oxygen is an example of physiology.
9. The organ system that secretes hormones is called the _____ system.
10. A neuron is a:
    A. specialized cell
    B. unspecialized cell
    C. an organ
    D. an organ system
11. Which organ system's function is to provide structure to the body and protect internal organs?
12. How is the human body regulated so all of its organs and organ systems work together
13. *True or False.* Organs consist of one or more types of tissue.
14. Give one example of how the respiratory and circulatory systems work together.

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# 1.3: HUMAN CELLS AND TISSUES

## DUST MOP

This photo in Figure **1.3.1** looks like a close-up of an old-fashioned dust mop, and the object it shows has a somewhat similar function. However, the object is greatly enlarged in the photo. Can you guess what it is? The answer may surprise you. It is a scanning electron micrograph of human epithelial cells that line the bronchial passages. The floppy, dust-mop-like extensions are actually microscopic structures called cilia projecting from the outer surface of the epithelial cells. The function of the cilia is to trap dust, pathogens, and other particles in the air before it enters the lungs. The cilia also sway back and forth to sweep the trapped particles upward toward the throat, from which they can be expelled from the body.

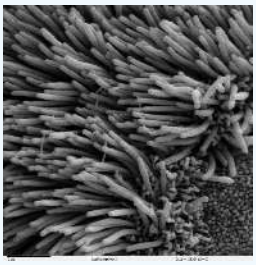


Figure **1.3.1**: Scanning electron microscope image of lung trachea epithelium. There are both ciliated and on-ciliated cells in this epithelium. Note the difference in size between the cilia and the microvilli (on the non-ciliated cell surface)

## HUMAN CELLS

Like the ciliated bronchial cells in the micrograph above, many other cells in the human body are very distinctive and well suited for special functions. To perform their special functions, cells may vary in a number of ways.

### VARIATION IN HUMAN CELLS

Some cells act as individual cells and are not attached to one another. Red blood cells are a good example. Their main function is to transport oxygen to other cells throughout the body, so they must be able to move freely through the circulatory system. Many other cells, in contrast, act together with other similar cells as part of the same tissue, so they are attached to one another and cannot move freely. For example, epithelial cells lining the respiratory tract are attached to each other to form a continuous surface that protects the respiratory system from particles and other hazards in the air.

Many cells can divide readily and form new cells. Skin cells are constantly dying and being shed from the body and replaced by new skin cells, and bone cells can divide to form new bone for growth or repair. Some other cells, in contrast, such as certain nerve cells, can divide and form new cells only under exceptional circumstances. That's why nervous system injuries such as a severed spinal cord generally cannot heal by the production of new cells, resulting in a permanent loss of function.

Many human cells have the primary job of producing and secreting a particular substance, such as a hormone or an enzyme. For example, special cells in the pancreas produce and secrete the hormone insulin, which regulates the level of glucose in the blood. Some of the epithelial cells that line the bronchial passages produce mucus, a sticky substance that helps trap particles in the air before it passes into the lungs.

### DIFFERENT BUT IDENTICAL

All the different cell types within an individual human organism are genetically identical, so no matter how different the cells are, they all have the same genes. How can such different types of cells arise? The answer is the differential regulation of genes. Cells with the same genes can be very different because different genes are expressed depending on the cell type.

### EXAMPLES OF HUMAN CELL TYPES

Many common types of human cells — such as bone cells and white blood cells — actually consist of several subtypes of cells. Each subtype, in turn, has a special structure and function. A closer look at these cell types will give you a better appreciation for the diversity of structures and functions of human cells.

#### *BONE CELLS*

There are four main subtypes of bone cells, as shown in Figure **1.3.2**. Each type has a different form and function:

1. Osteocytes are star-shaped bone cells that make up the majority of bone tissue. They are the most common cells in mature bone and can live as long as the organism itself. They also control the function of bone cells called osteoblasts and osteoclasts.
2. Osteoblasts are cells with single nuclei that synthesize new bone. They function in organized groups of connected cells called osteons to form the organic and mineral matrix of bone.
3. Osteogenic cells are undifferentiated stem cells that differentiate to form osteoblasts in the tissue that covers the outside of the bone.
4. Osteoclasts are very large, multinucleated cells that are responsible for the breakdown of bones through resorption. The breakdown of bone is very important in bone health because it allows for bone remodeling.

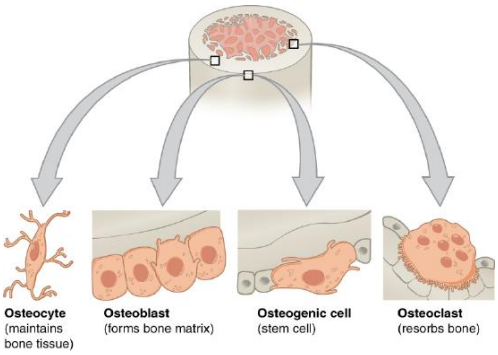



Figure **1.3.2**: Four sub-types of bone cells in the human skeletal system: Osteocytes (maintain bone tissues), Osteoblast (form bone matrix), Osteogenic cells (stem cell), Osteoclasts (reabsorb bone)

### *WHITE BLOOD CELLS*

White blood cells (also called leukocytes) are even more variable than bone cells. Five subtypes of white blood cells are shown in Figure **1.3.3**. All of them are immune system cells involved in defending the body, but each subtype has a different function. They also differ in the normal proportion of all leukocytes they make up.

1. Monocytes make up about 5 percent of leukocytes. They are the biggest cells with extensions and a kidney-shaped nucleus. They engulf and destroy (phagocytize) pathogens in tissues.
2. Eosinophils make up about 2 percent of leukocytes. They have and a bilobed nucleus. They attack larger parasites and set off allergic responses.
3. Basophils make up less than 1 percent of leukocytes. Like eosinophils, these cells also have granules and a bilobed nucleus. They release proteins called histamines that are involved in inflammation.
4. Lymphocytes make up about 30 percent of leukocytes. These are small cells with a large circular nucleus. They include B cells and T cells. B cells produce antibodies against non-self antigens, and T cells destroy virus-infected cells and cancer cells.
5. Neutrophils are the most numerous white blood cells, making up about 62 percent of leukocytes. They have granules and a multilobed nucleus. They phagocytize single-celled bacteria and fungi in the blood.

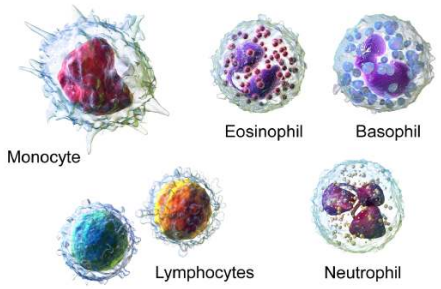



Figure **1.3.3**: Five sub-types of human white blood cells in the human immune system: monocyte, eosinophil, basophil, lymphocyte, neutrophil

## TISSUES

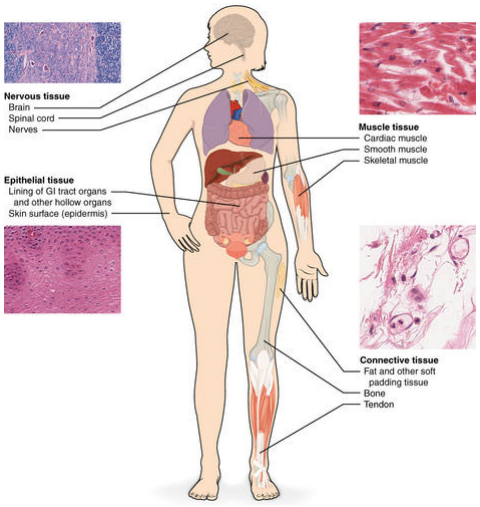



Figure **1.3.4**: There are 4 different types of tissues in our body. Nervous tissue is found in the brain, spinal cord, and nerves. Muscular tissue such as cardiac, smooth, and skeletal muscle. Epithelial tissue lines the GI tract organs and other hollow organs and is found on the skin surface (epidermis). Connective tissue such as fat and other soft padding tissue, bone, and tendon.

Groups of connected cells form tissues. The cells in a tissue may all be the same type or they may be of multiple types. In either case, the cells in the tissue work together to carry out a specific function. There are four main types of human tissues: connective, epithelial, muscle, and nervous tissues.

## CONNECTIVE TISSUE

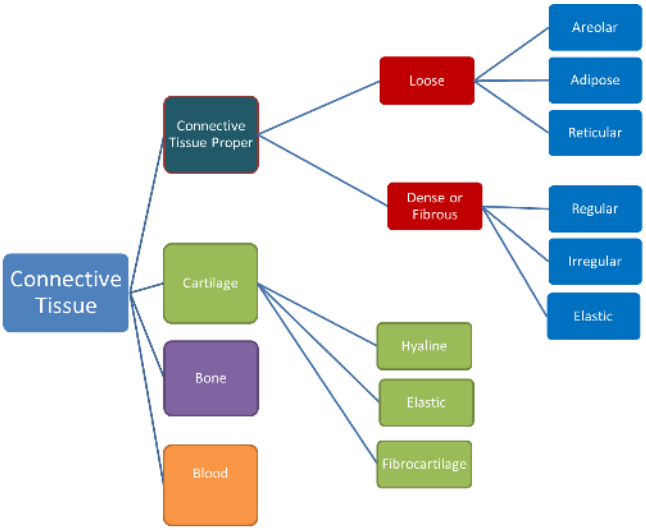



Figure **1.3.5**: The image summarizes the various categories of connective tissues found in the human body. Connective tissue can be classified as connective tissue proper, cartilage, bone, or blood. Cartilage can be classified as hyaline cartilage, elastic cartilage, or fibrocartilage. Connective tissue proper can be classified as loose and dense or fibrous. Loose connective tissue can be classified as areolar, adipose, or reticular. Dense or fibrous connective tissue can be classified as regular, irregular, and elastic.

The most diverse and abundant of all tissues, connective tissue holds cells together and supports the body. Connective tissue is made up of cells suspended in a non-cellular matrix. The matrix (also known as

ground substance) is secreted by the connective tissue cells and determines the characteristics of the connective tissue. It is the consistency of the matrix that determines the function of the connective tissue. The matrix can be liquid, gel-like or solid, all depending on the type of connective tissue. For example, the extracellular matrix of bone is a rigid mineral framework. The extracellular matrix of blood is liquid plasma. Connective tissues such as bone and cartilage generally form the body's structure. There are many sub-types of the four major types of tissues in a human body, see the flow chart in Figure **1.3.5**.

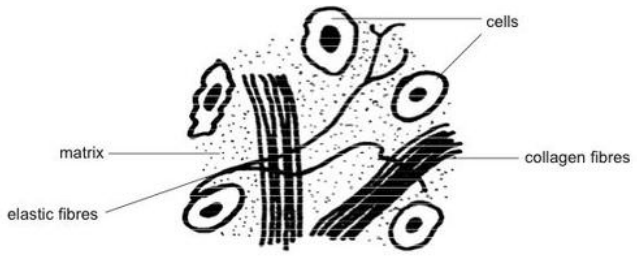



Figure **1.3.6**: General features of connective tissues. The Matrix of most connective tissues is made up of ground substance and protein fibers. There are cells suspended in the matrix.

### *CONNECTIVE TISSUE PROPER*

**Fibroblast cells** are responsible for synthesizing protein fibers for the matrix. **Collagen fibers** are strong, **elastic fibers** are flexible and **reticular fibers** form a supportive framework for organs and basement membranes. There are two subcategories of connective tissue proper.

## LOOSE CONNECTIVE TISSUE

Thin and soft, this tissue contains many collagen and elastic fibers in a jell-like matrix. The cells in loose connective tissue are not close together. This tissue functions in binding the skin to underlying structures. There are three types of loose connective tissue.

1. **Areolar connective tissue** is a common form of loose connective tissue. It is found in the skin and mucous membranes, where it binds the skin or membrane to underlying tissues such as muscles. It is also found around blood vessels and internal organs where it links and supports them.
2. **Adipose connective tissue** is commonly known as fat. This tissue contains fat cells that are specialized for lipid storage. In addition to storing energy, this tissue also cushions and protects the organs.
3. **Reticular connective tissue** is mostly composed of reticular protein fibers which make a skeleton, known as stroma, for the lymphatic and white blood cells. This type of tissue is found in the spleen and other lymphatic system structures.

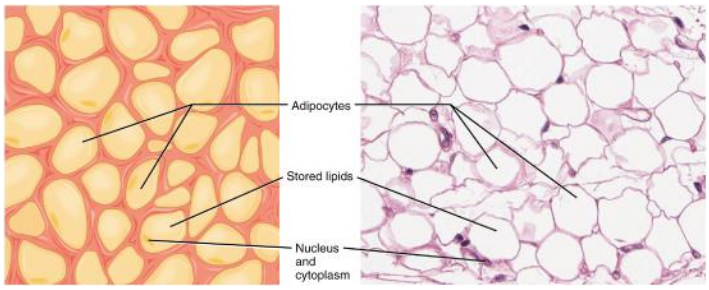



Figure **1.3.7**: Adipose Connective Tissue consists of fat cells (adipocytes with a nucleus and stored lipids in their cytoplasm) with a little extracellular matrix. It stores fat for energy and provides insulation.

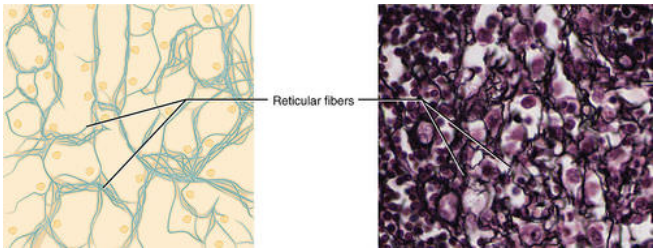



Figure **1.3.8**: Reticular Connective Tissue. This is a loose connective tissue made up of a network of reticular fibers that provides a supportive framework for soft organs

## DENSE CONNECTIVE TISSUE PROPER

This tissue consists of three categories, dense regular connective tissue, dense irregular connective tissue, and elastic connective tissue. These tissues differ on the arrangement and composition of the fibrous elements of the extracellular matrix.

1. **Dense regular connective tissue** has extracellular fibers that all run in the same direction and plane. Muscle tendons are a type of dense regular connective tissue.
2. **Dense irregular connective tissue** contains collagen and elastic fibers which are found running in all different directions and planes. The dermis of the skin is composed of dense irregular connective tissue.
3. **Elastic connective tissue**: Made up of freely branching elastic fibers with fibroblasts in the spaces between the fibers, this tissue allows the kind of stretch that is found in the walls of arteries.

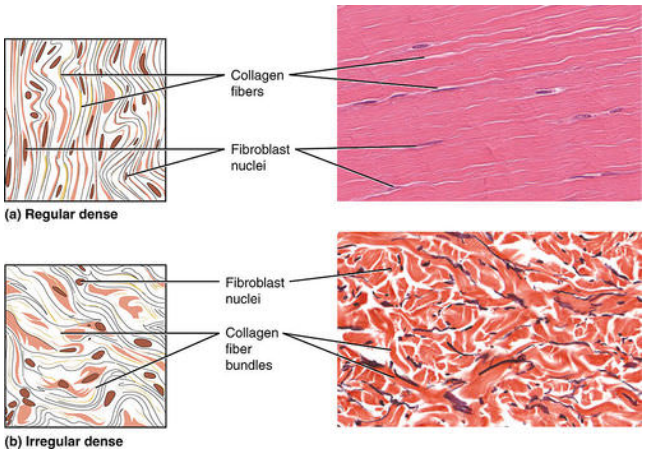



Figure **1.3.9**: (a) Dense regular connective tissue consists of collagen fibers packed into parallel bundles. (b) Dense irregular connective tissue consists of collagen fibers interwoven into a mesh-like network..

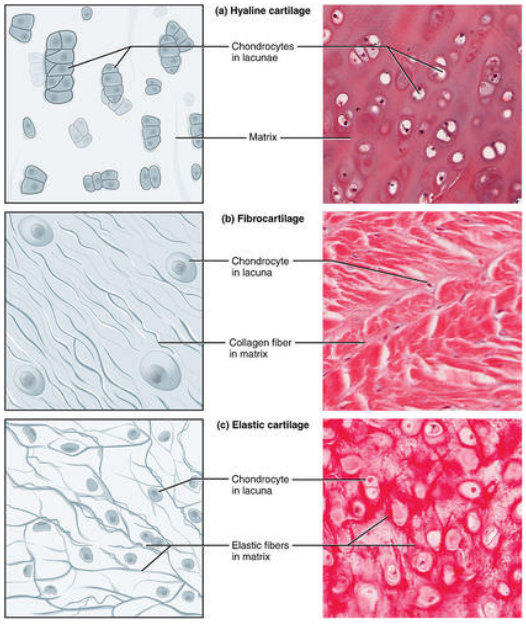



Figure 1.3.10: Cartilage is a connective tissue consisting of collagenous fibers embedded in a firm matrix of chondroitin sulfates. (a) Hyaline cartilage has chondrocytes in lacunae within a matrix. (b) Fibrocartilage has chondrocytes in lacunae within collage fibers in a matrix. (c) Elastic cartilage has chondrocytes in lacunae within elastic fibers in a matrix.

### *CARTILAGE*

This connective tissue is relatively solid and is a non-vascularized tissue (does not have a blood supply). The matrix is produced by cells called chondroblasts. When these cells slow down, they reside is small spaces called lacunae. These mature cells in the lacunae are called chondrocytes. There are three types of cartilage: hyaline cartilage, elastic cartilage, and fibrocartilage.

1. **Hyaline cartilage** is the most common type of cartilage, contains many collagen fibers and is found in many places including the nose, between the ribs and the sternum and in the rings of the trachea.
2. **Elastic cartilage** has many elastic fibers in the matrix and supports the shape of the ears and forms part of the larynx.
3. **Fibrocartilage** is tough and contains many collagen fibers and is responsible for cushioning the knee joint and for forming the disks between the vertebrae.

### *BONE*

Bone is a hard, mineralized tissue found in the skeleton. The bone matrix contains many collagen fibers as well as inorganic mineral salts, calcium carbonate, and calcium phosphate, all features that make it a very rigid structure. Bone cells, called **osteoblasts**, secrete the osteoid substance that eventually hardens around the cells to form an ossified matrix. The **osteon** forms the basic unit of compact bone. Within the

osteon, the osteocytes (mature bone cells) are located in lacunae. Because the bone matrix is very dense, the osteocytes get their nutrition from the central canal via tiny canals called canaliculi.

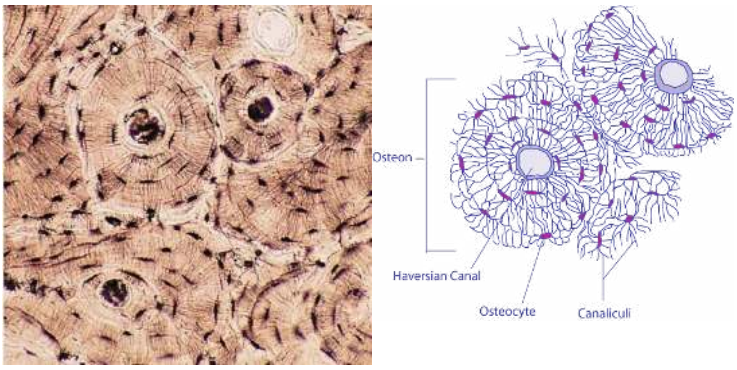



Figure **1.3.11**: The image shows a micrograph as well as an illustration of the cross-section of the compact bone tissue. The osteons are concentric structures that are composed of osteocytes in the lacunae and central (Haversian) canal. The small tunnels, canaliculi, connect osteocytes in the different layers of an osteon.

### *BLOOD*

**Blood is c**onsidered a type of fluid connective tissue because the matrix of blood is not solid. The fluid matrix is called plasma, and formed elements of this tissue include white blood cells, red blood cells, and platelets. Read more about the composition and function of blood in the cardiovascular system chapter.

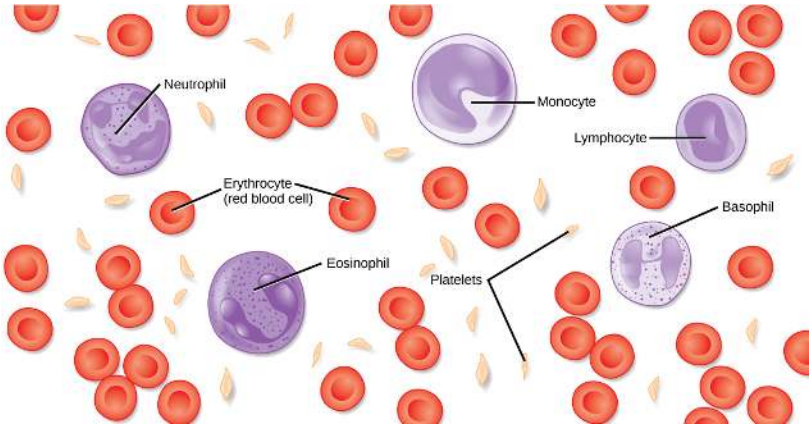



Figure **1.3.12**: The cells and cellular components of human blood are shown. Red blood cells deliver oxygen to the cells and remove carbon dioxide. White blood cells (including neutrophils, monocytes, lymphocytes, eosinophils, and basophils) are involved in the immune response. Platelets form clots that prevent blood loss after injury.

## EPITHELIAL TISSUE

**Epithelial tissue** is made up of cells that line inner and outer body surfaces, such as the skin and the inner surface of the digestive tract. Epithelial tissue that lines inner body surfaces and body openings is called **mucous membrane.** This type of epithelial tissue produces **mucus**, a slimy substance that coats mucous membranes and traps pathogens, particles, and debris. Epithelial tissue protects the body and its internal organs, secretes substances such as hormones in addition to mucus, and absorbs substances such as nutrients.

### *EPITHELIAL CELL CLASSIFICATION*

Most epithelial tissue is described with two names. The first name describes the number of cell layers present and the second describes the shape of the cells. One layer of epithelial cells is called simple and more than one layer of epithelial cells is called stratified. There are three basic shapes of epithelial cells, squamous, cuboidal, and columnar. Squamous cells are thin and flat; cuboidal cells have a shape of a cube; columnar cells have a shape of a pillar. For example, simple squamous epithelial tissue describes a single layer of cells that are flat and scale-like in shape.

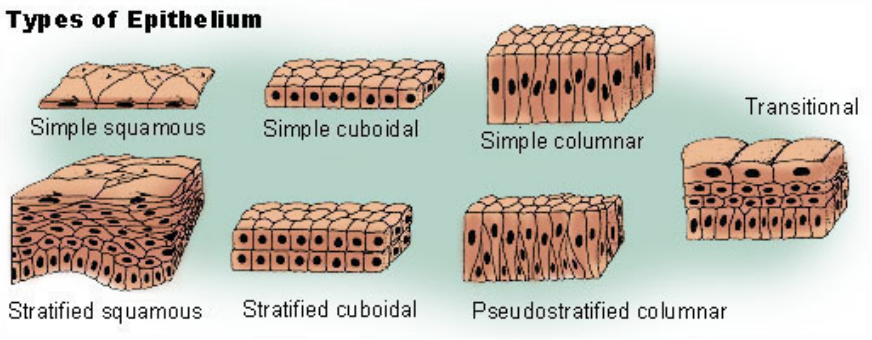



Figure **1.3.13**: Classification of Epithelial Tissues

### *LOCATIONS AND FUNCTIONS OF EPITHELIAL TISSUES*

These tissues are found at various locations in our body and they have many functions. Some locations and functions are listed below:

- Simple squamous epithelium: This tissue is located in the sacs of the lungs and kidney where the exchange of nutrients and gas is essential.
- Simple cuboidal epithelium: This tissue is located in the glands and their ducts and kidneys. The main function of this tissue is secretion.
- Simple Columnar epithelium: This tissue lines the Gastrointestinal tract. The main function of this tissue is absorption and secretion.
- Pseudostratified epithelium: This is a simple tissue with the appearance of stratification. This tissue is located in the respiratory tract. This tissue may contain cilia to move mucus.
- Stratified squamous epithelium: This tissue is located where protection is needed such as skin.
- Stratified cuboidal epithelium: This tissue is located in the sweat glands for protection.
- Stratified columnar epithelium: This tissue is located in some sweat glands. The main function is to protect and secrete sweat components.
- Transitional epithelium: This tissue lines bladder, urethra, and ureters. The tissue allows the urinary organs to expand and stretch.

## MUSCLE TISSUE

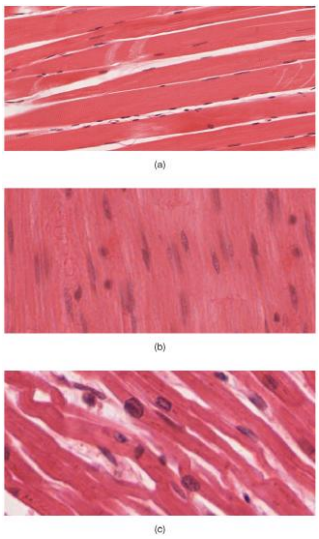



Figure **1.3.14**: The body contains three types of muscle tissue: (a) skeletal muscle, (b) smooth muscle, and (c) cardiac muscle.

**Muscle tissue** is made up of cells that have the unique ability to contract or become shorter. There are three major types of muscle tissue, as pictured in Figure **1.3.14**: skeletal, smooth, and cardiac muscle tissues.

1. **Skeletal muscles** are striated, or striped in appearance, because of their internal structure. Skeletal muscles are attached to bones, and when they pull on the bones, they enable the body to move. Skeletal muscles are under voluntary control.
2. **Smooth muscles** are nonstriated muscles. They are found in the walls of blood vessels and in the reproductive, gastrointestinal, and respiratory tracts. Smooth muscles are not under voluntary control.
3. **Cardiac muscles** are striated and found only in the heart. Their contractions cause the heart to beat. Cardiac muscles are not under voluntary control.

## NERVOUS TISSUE

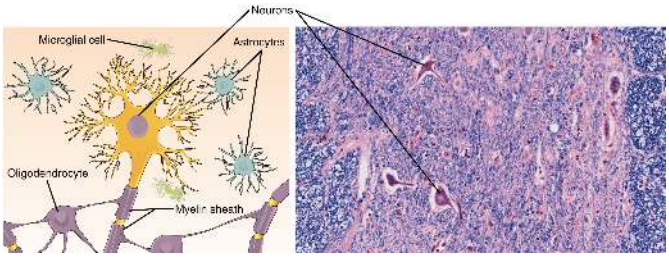



Figure **1.3.15**. This diagram shows some of the cell types that make up nervous tissues.

**Nervous tissue** is made up of neurons and other types of cells generally called glial cells (Figure **1.3.15**). Neurons are composed of cell body and extensions. The cell body contains the nucleus and the extensions make connections with the other tissues and neurons. Neurons transmit electrical messages and the glial cells play supporting roles. Nervous tissue makes up the central nervous system (mainly the brain and spinal cord) and peripheral nervous system (the network of nerves that runs throughout the rest of the body).

### FEATURE: MY HUMAN BODY

If you are a blood donor, then you have donated tissue. Blood is a tissue that you can donate when you are alive. You may have indicated on your driver's license application that you wish to be a tissue donor in the event of your death. Deceased people can donate many different tissues, including skin, bone, heart valves, and the corneas of the eyes. If you are not already registered as a tissue donor, the information below may help you decide if you would like to register.

Each year, approximately 30,000 people donate tissues, which supply tissues for up to 1 million tissue transplants. One tissue donor can enhance or save the life of more than 50 people! Unlike organs, which generally must be transplanted immediately after the donor dies, donated tissues can be processed and stored for a long time for later use. Donated tissues can be used to replace burned skin and damaged bone and to repair ligaments. Corneal tissues can be used for corneal transplants that restore sight in blind people. In fact, each year 48,000 patients have their sight restored with corneal transplants. Unfortunately, there are not enough tissues to go around, and the need for donated tissues keeps rising.

## REVIEW

1. Give an example of cells that function individually and move freely, and give an example of cells that act together and are attached to other cells of the same type.
2. What are examples of cells that can readily divide and cells that can divide only under rare circumstances?
3. Identify a type of cell that secretes an important substance and name the substance it secretes.
4. Explain how different cell types come about when all the cells in an individual human being are genetically identical.
5. Compare and contrast four subtypes of human bone cells.
6. Identify three types of human white blood cells, and state their functions.
7. Why are bone and blood both classified as connective tissues?
8. Name another type of connective tissue, and describe its role in the human body.
9. Based on the information in the table above of types of epithelial tissues, list four general functions of this type of tissue in the human body.
10. Compare and contrast the three types of muscle tissues.
11. Identify the four types of nervous tissues, where each type is found, and its basic function.
12. Of the main types of human tissue, name two that can secrete hormones.
13. Cells in a particular tissue:
    A. Are all of the same type
    B. Have different genes from cells in other tissues
    C. Work together to carry out a function
    D. Are always connected physically to each other
14. Why are mucous membranes often located in regions that interface between the body and the outside world?
15. Skin is a type of _____ tissue.
16. Body fat is a type of _____ tissue.

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# 1.4: HUMAN ORGANS AND ORGAN SYSTEMS

## "ACHY BREAKY HEART"

Billy Ray Cyrus's song "Achy Breaky Heart" has lyrics suc as: Heartache, heartbreak...it all has to do with love. Did you ever wonder why the heart is associated with love? The heart was once thought to be the center of all thought processes, as well as the site of all emotions. This notion may have stemmed from very early anatomical dissections that found many nerves can be traced to the region of the heart. The fact that the heart may start racing when one is excited or otherwise emotionally aroused may have contributed to this idea as well. In fact, the heart is not the organ that controls thoughts or emotions. The organ that controls those functions is the brain. In this concept, you'll be introduced to the heart, brain, and other major organs of the human body.



Figure **1.4.1**: Twemoji

## HUMAN ORGANS

An organ is a collection of tissues joined in a structural unit to serve a common function. Organs exist in most multicellular organisms, including not only humans and other animals but also plants. In single-celled organisms such as bacteria, the functional equivalent of an organ is an organelle.

### TISSUES IN ORGANS

Although organs consist of multiple tissue types, many organs are composed of the main tissue that is associated with the organ's major function and other tissues that play supporting roles. The main tissue may be unique to that specific organ. For example, the main tissue of the heart is the cardiac muscle, which performs the heart's major function of pumping blood and is found only in the heart. The heart also includes nervous and connective tissues that are required for it to perform its major function. For example, nervous tissues control the beating of the heart, and connective tissues make up heart valves that keep blood flowing in just one direction through the heart.

### VITAL ORGANS

The human body contains five organs that are considered vital for survival. They are the heart, brain, kidneys, liver, and lungs. The locations of these five organs and several other internal organs are shown in Figure **1.4.2**. If any of the five vital organs stops functioning, the death of the organism is imminent without medical intervention.

1. The heart is located in the center of the chest, and its function is to keep blood flowing through the body. Blood carries substances to cells that they need and also carries away wastes from cells.
2. The brain is located in the head and functions as the body's control center. It is the seat of all thoughts, memories, perceptions, and feelings.
3. The two kidneys are located in the back of the abdomen on either side of the body. Their function is to filter blood and form urine, which is excreted from the body.
4. The liver is located on the right side of the abdomen. It has many functions, including filtering blood, secreting bile that is needed for digestion, and producing proteins necessary for blood clotting.
5. The two lungs are located on either side of the upper chest. Their main function is exchanging oxygen and carbon dioxide with the blood.

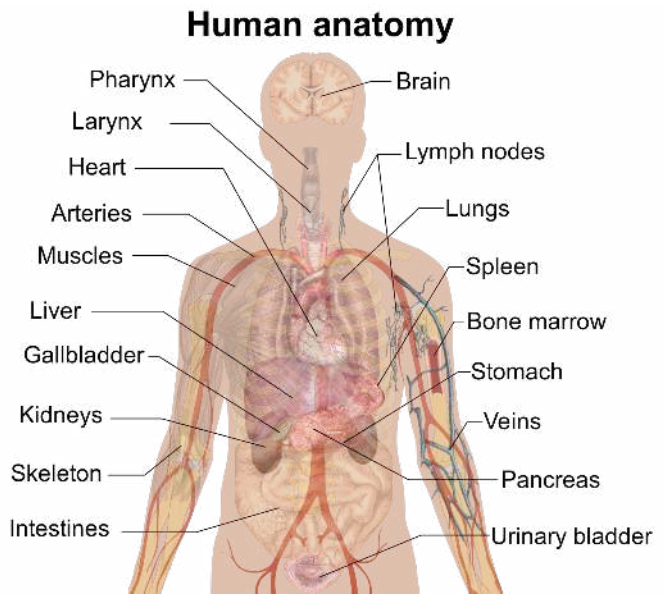



Figure **1.4.2**: Use this shadow diagram of human anatomy to locate the five organs described above: heart, brain, kidneys, liver, and lungs. Do you know the functions of any of the other organs in the diagram?

## HUMAN ORGAN SYSTEMS

Functionally related organs often cooperate to form whole organ systems. Figure **1.4.3** and Figure **1.4.4** show 11 human organ systems, including separate diagrams for the male and female reproductive systems. Some of the organs and functions of the organ systems are identified in the figure. Each system is also described in more detail in the text that follows. Most of these human organ systems are also the subject of separate chapters in this book.

### INTEGUMENTARY SYSTEM

Organs of the integumentary system include the skin, hair, and nails. The skin is the largest organ in the body. It encloses and protects the body and is the site of many sensory receptors. The skin is the body's first defense against pathogens, and it also helps regulate body temperature and eliminate wastes in sweat.

## SKELETAL SYSTEM

The skeletal system consists of bones, joints, teeth. The bones of the skeletal system are connected by tendons, ligaments, and cartilage. Functions of the skeletal system include supporting the body and giving it shape. Along with the muscular system, the skeletal system enables the body to move. The bones of the skeletal system also protect internal organs, store calcium, and produce red and white blood cells.

## MUSCULAR SYSTEM

The muscular system consists of three different types of muscles, including skeletal muscles, which are attached to bones by tendons and allow for voluntary movements of the body. Smooth muscle tissues control the involuntary movements of internal organs, such as the organs of the digestive system, allowing food to move through the system. Smooth muscles in blood vessels allow vasoconstriction and vasodilation and thereby help regulate body temperature. Cardiac muscle tissues control the involuntary beating of the heart, allowing it to pump blood through the blood vessels of the cardiovascular system.

## NERVOUS SYSTEM

The nervous system includes the brain and spinal cord, which make up the central nervous system, and nerves that run throughout the rest of the body, which make up the peripheral nervous system. The nervous system controls both voluntary and involuntary responses of the human organism and also detects and processes sensory information.

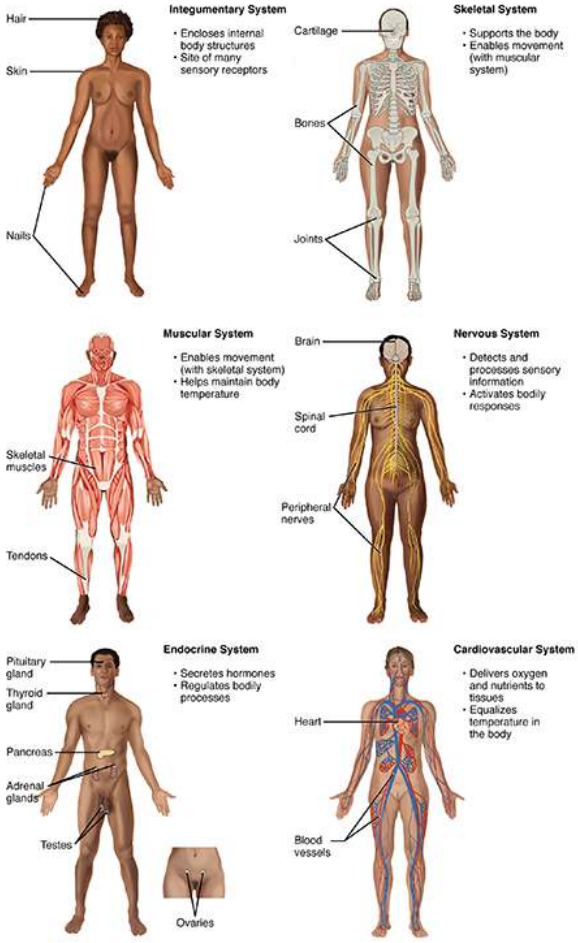



Figure **1.4.3**: Organ systems: Integumentary, Skeletal, Muscular, Nervous, Endocrine, and Cardiovascular

## ENDOCRINE SYSTEM

The endocrine system is made up of glands that secrete hormones into the blood, which carries the hormones throughout the body. Endocrine hormones are chemical messengers that control many body functions, including metabolism, growth, and sexual development. The master gland of the endocrine system is the pituitary gland, which produces hormones that control other endocrine glands. Some of the other endocrine glands include the pancreas, thyroid gland, and adrenal glands.

## CARDIOVASCULAR SYSTEM

The cardiovascular system (also called the circulatory system) includes the heart, blood, and three types of blood vessels: arteries, veins, and capillaries. The heart pumps blood, which travels through the blood vessels. The main function of the cardiovascular system is transport. Oxygen from the lungs and nutrients from the digestive system are transported to cells throughout the body. Carbon dioxide and other waste materials are picked up from the cells and transported to organs such as the lungs and kidneys for elimination from the body. The cardiovascular system also equalizes body

temperature and transports endocrine hormones to cells in the body where they are needed.

## URINARY SYSTEM

The urinary system includes the pair of kidneys, which filter excess water and a waste product called urea from the blood and form urine. Two tubes called ureters carry the urine from the kidneys to the urinary bladder, which stores the urine until it is excreted from the body through another tube named the urethra. The kidneys also produce an enzyme called renin and a variety of hormones. These substances help regulate blood pressure, the production of red blood cells, and the balance of calcium and phosphorus in the body.

## RESPIRATORY SYSTEM

Organs and other structures of the respiratory system include the nasal passages, lungs, and a long tube called the trachea, which carries air between the nasal passages and lungs. The main function of the respiratory system is to deliver oxygen to the blood and remove carbon dioxide from the body. Gases are exchanged between the lungs and blood across the walls of capillaries lining tiny air sacs (alveoli) in the lungs.

## LYMPHATIC SYSTEM

The lymphatic system is sometimes considered to be part of the immune system. It consists of a network of lymph vessels and ducts that collect excess fluid (called lymph) from extracellular spaces in tissues and transport the fluid to the bloodstream. The lymphatic system also includes many small collections of tissue, called lymph nodes, and an organ called the spleen, both of which remove pathogens and cellular debris from the lymph or blood. In addition, the thymus gland in the lymphatic system produces some types of white blood cells (lymphocytes) that fight infections.

## DIGESTIVE SYSTEM

The digestive system consists of several main organs — including the mouth, esophagus, stomach, and small and large intestines — that form a long tube called the gastrointestinal (GI) tract. Food moves through this tract where it is digested, its nutrients absorbed, and its waste products excreted. The digestive system also includes accessory organs (such as the pancreas and liver) that produce enzymes and other substances needed for digestion but through which food does not actually pass.

## MALE AND FEMALE REPRODUCTIVE SYSTEMS

The reproductive system is the only body system that differs substantially between individuals. There is a range of Biological sex, but most books divide them into male and female. We will discuss the Biology of sex in detail in the reproductive and development chapters.

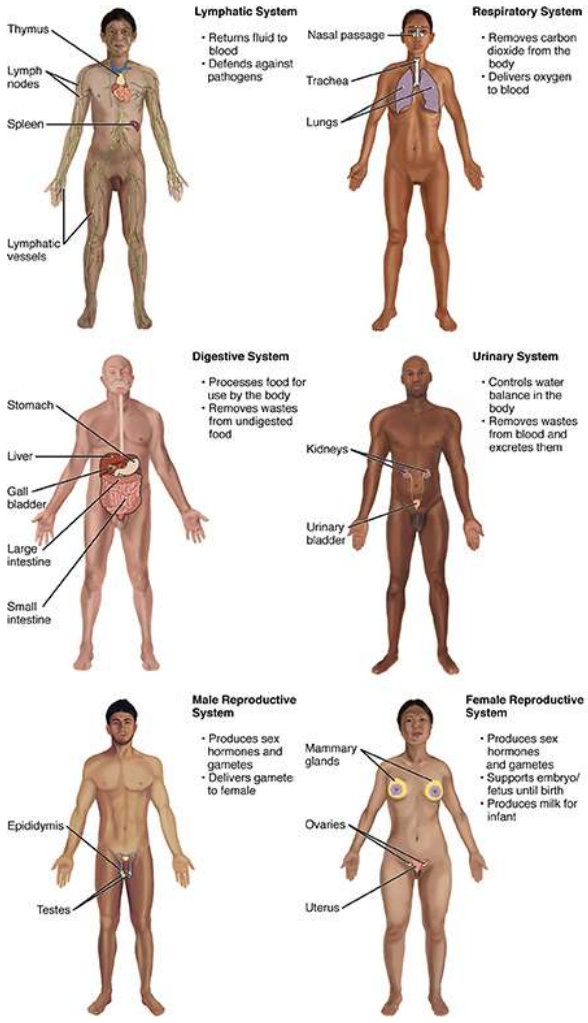



Figure **1.4.4**: Organ Systems: Lymphatic, Respiratory, Digestive, Urinary, male and female reproductive

### FEATURE: HUMAN BIOLOGY IN THE NEWS

Organ transplantation has been performed by surgeons for more than six decades, and you've no doubt heard of people receiving heart, lung, and kidney transplants. However, you may have never heard of a penis transplant. The first U.S. penis transplant was performed in May of 2016 at Massachusetts General Hospital in Boston. The 15-hour procedure involved a team of more than 50 physicians, surgeons, and nurses. The patient was a 64-year-old man who had lost his penis to cancer in 2012. The surgical milestone involved grafting microscopic blood vessels and nerves of the donor organ to those of the recipient. As with most transplant patients, this patient will have to take immunosuppressing drugs for the rest of his life so his immune system will not reject the organ. The transplant team said that their success with this transplant "holds promise for patients with devastating genitourinary injuries and disease." They also hope their experiences will be helpful for gender reassignment surgery.

## REVIEW

1. What is the main tissue in the heart, and what is its role?
2. What non-muscle tissues are found in the heart? What are their functions?
3. Identify two vital organs in the human body. Identify their locations and functions.
4. List three human organ systems. For each organ system, identify some of its organs and functions.
5. Compare and contrast the male and female reproductive systems.
6. For each of the following pairs of organ systems, describe one way in which they work together and/or overlap.
   A. Skeletal system and muscular system
   B. Muscular system and digestive system
   C. Endocrine system and reproductive system
   D. Cardiovascular system and urinary system
7. What is the largest organ of the human body?
8. What are the three organ systems involved in regulating human body temperature?
9. Teeth are part of which system?
   A. Integumentary
   B. Skeletal
   C. Nervous
   D. A and B
10. Hair is part of which organ system?
11. *True or False.* Organs only exist in animals.
12. *True or False.* The respiratory system helps to remove wastes from the body.

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# 1.5: HUMAN BODY CAVITIES

## CONTAIN THE BRAIN

The brain is a delicate organ that regulates the physiology of the whole body. Figure **1.5.1** shows the brain with its superficial structures. Brain coverings and the skull provide protection to the brain. The space where the brain is located in the skull is called the cranial cavity.

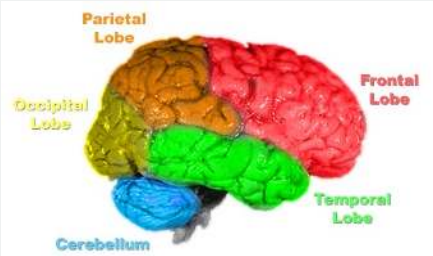



Figure **1.5.1**: Human Brain lateral view

## WHAT ARE BODY CAVITIES?

The human body, like that of many other multicellular organisms, is divided into a number of body cavities. A **body cavity** is a fluid-filled space inside the body that holds and protects internal organs. Human body cavities are separated by membranes and other structures. The two largest human body cavities are the ventral cavity and the dorsal cavity. These two body cavities are subdivided into smaller body cavities. Both the dorsal and ventral cavities and their subdivisions are shown in Figure **1.5.2**.

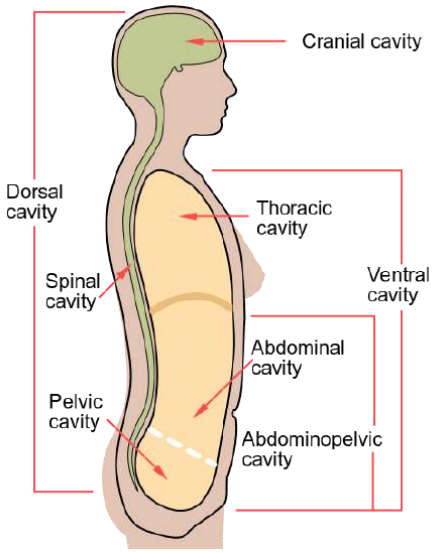



Figure **1.5.2**: The ventral cavity includes the thoracic and abdominopelvic cavities and their subdivisions. The abdominopelvic cavity is further divided into abdominal and pelvic cavities. The dorsal cavity includes the cranial and spinal cavities.

## VENTRAL CAVITY

The **ventral cavity** is at the anterior, or front, of the trunk. Organs contained within this body cavity include the lungs, heart, stomach, intestines, and reproductive organs. You can see some of the organs in the ventral cavity in Figure **1.5.3**. The ventral cavity allows for considerable changes in the size and shape of the organs within it as they perform their functions. For example, organs such as the lungs, stomach, or uterus can expand or contract without distorting other tissues or disrupting the activities of nearby organs.

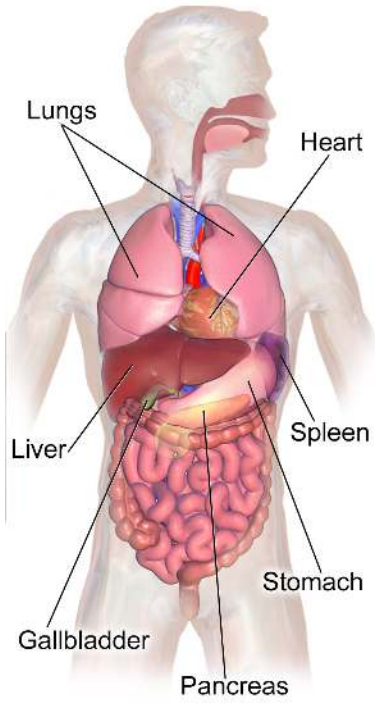



Figure **1.5.3**: Some of the major organs such as the spleen, stomach, pancreas, gallbladder, liver, lungs, and heart inside the ventral cavity of the human body

The ventral cavity is subdivided into the thoracic and abdominopelvic cavities.

- The **thoracic cavity** fills the chest and is subdivided into two pleural cavities and the pericardial cavity. The pleural cavities hold the lungs, and the pericardial cavity holds the heart.
- The **abdominopelvic cavity** fills the lower half of the trunk and is subdivided into the abdominal cavity and the pelvic cavity. The abdominal cavity holds digestive organs and the kidneys, and the pelvic cavity holds reproductive organs and organs of excretion.

## DORSAL CAVITY

The **dorsal cavity** is at the posterior, or back, of the body, including both the head and the back of the trunk. The dorsal cavity is subdivided into the cranial and spinal cavities.

- The **cranial cavity** fills most of the upper part of the skull and contains the brain.
- The **spinal cavity** is a very long, narrow cavity inside the vertebral column. It runs the length of the trunk and contains the spinal cord.

The brain and spinal cord are protected by the bones of the skull and the vertebrae of the spine. They are further protected by the **meninges,** a three-layer membrane that encloses the brain and spinal cord. A thin layer of **cerebrospinal fluid** is maintained between two of the meningeal layers. This clear fluid is produced by the brain, and it provides extra protection and cushioning for the brain and spinal cord.

### FEATURE: MY HUMAN BODY

The meninges membranes that protect the brain and spinal cord inside their cavities may become inflamed, generally due to a bacterial or viral infection. This condition is called meningitis. Meningitis can lead to serious long-term consequences such as deafness, epilepsy, or cognitive deficits, especially if not treated quickly. Meningitis can also rapidly become life-threatening, so it is classified as a medical emergency.

Learning the symptoms of meningitis may help you or a loved one get prompt medical attention if you ever develop the disease. Common symptoms include fever, headache, and neck stiffness. Other symptoms may include confusion or altered consciousness, vomiting, and an inability to tolerate light or loud noises. Young children often exhibit less specific symptoms, such as irritability, drowsiness, or poor feeding.

Meningitis is diagnosed with a lumbar puncture (commonly known as a "spinal tap"), in which a needle is inserted into the spinal canal to collect a sample of cerebrospinal fluid. The fluid is analyzed for the presence of pathogens in a medical lab. If meningitis is diagnosed, treatment consists of antibiotics and sometimes antiviral drugs. Corticosteroids may also be administered to reduce inflammation and the risk of complications such as brain damage. Supportive measures such as IV fluids may also be provided.

Some types of meningitis can be prevented with a vaccine. Ask your health care professional whether you have had the vaccine or should get it. Giving antibiotics to people who have had significant exposure to certain types of meningitis may reduce their risk of developing the disease. If someone you know is diagnosed with meningitis, see your doctor for advice if you are concerned about contracting the disease.

## REVIEW

1. What is a body cavity?
2. Compare and contrast ventral and dorsal body cavities.
3. Identify the subdivisions of the ventral cavity and the organs each contains.
4. Describe the subdivisions of the dorsal cavity and its contents.
5. Identify and describe all the tissues that protect the brain and spinal cord.
6. What do you think might happen if fluid were to build up excessively in one of the body cavities?
7. Explain why a woman's body can accommodate a full-term fetus during pregnancy, without damage to her internal organs.
8. Which body cavity does the needle enter in a lumbar puncture?
9. What are the names given to the three body cavity divisions where the heart is located?
10. What are the names given to the three body cavity divisions where the kidneys are located?
11. *True or False.* The stomach is located in the dorsal cavity.
12. *True or False.* A body cavity must open to the outside world.
13. *True or False.* The vertebral column surrounds the spinal cavity.
14. The _____ cavity is directly below the thoracic cavity.
15. What is the name of the fluid that protects the brain and spinal cord?

    A. meningeal
    B. cerebrospinal
    C. lumbar
    D. cranial

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# 1.6: INTERACTION OF ORGAN SYSTEMS

## TEAMWORK

Every player on a softball team has a special job to perform. Each of the orange team's players in Figure **1.6.1** has his part of the infield or outfield covered if the ball comes his way. Other players on the orange team cover other parts of the field or pitch or catch the ball. Playing softball clearly requires teamwork. The human body is like a softball team in that regard. All the organ systems of the human body must work together as a team to keep the body alive and well. Teamwork within the body begins with communication.



Figure **1.6.1**: Softball

## COMMUNICATION AMONG ORGAN SYSTEMS

Communication among organ systems is vital if they are to work together as a team. They must be able to respond to each other and change their responses as needed to keep the body in balance. Communication among organ systems is controlled mainly by the autonomic nervous system and the endocrine system.

The autonomic nervous system is the part of the nervous system that controls involuntary functions. For example, the autonomic nervous system controls heart rate, blood flow, and digestion. You don't have to tell your heart to beat faster or to consciously squeeze muscles to push food through the digestive system. In fact, you don't have to even think about these functions at all. The autonomic nervous system orchestrates all the signals needed to control them. It sends messages between parts of the nervous system and between the nervous system and other organ systems via chemical messengers called neurotransmitters.

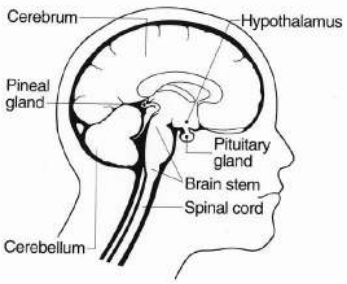



Figure **1.6.2**: The figure illustrates the hypothalamus, pituitary gland, brain stem, spinal cord, cerebellum, pineal gland, and cerebrum.

The endocrine system is the system of glands that secrete hormones directly into the bloodstream. Once in the blood, endocrine hormones circulate to cells everywhere in the body. The endocrine system is under the control of the hypothalamus, a part of the brain. The hypothalamus secretes hormones that travel directly to cells of the pituitary gland, which is located beneath it. The pituitary gland is the master gland of the endocrine system. Most of its hormones either turn on or turn off other endocrine glands. For example, if the pituitary gland secretes thyroid stimulating hormone, the hormone travels through the circulation to the thyroid gland, which is stimulated to secrete thyroid hormone. Thyroid hormone then travels to cells throughout the body, where it increases their metabolism.

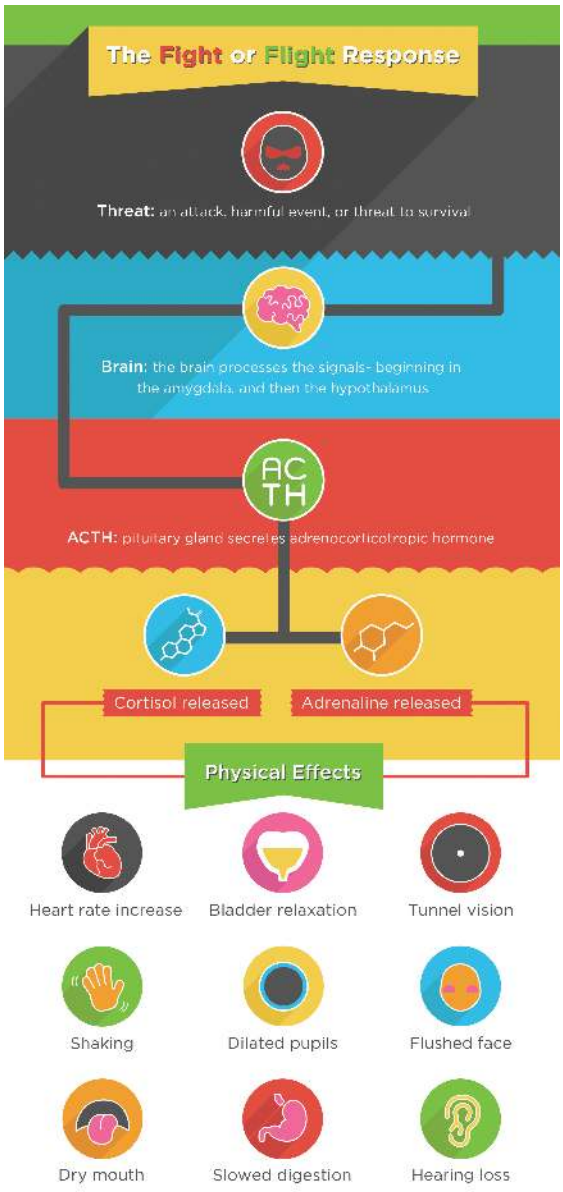



Figure **1.6.3**: The image shows a concept map of how the fight-or-flight response occurs. A treat (an attack, harmful event, or threat to survive) leads to the brain processing the signals - beginning in the amygdala, and then the hypothalamus. ACTH (adrenocorticotropic hormone) is released by the pituitary gland. This causes cortisol and adrenaline to be released. The physical effects include heart rate increase, bladder relaxation, tunnel vision, shaking, dilated pupils, flushed face, dry mouth, slowed digestion, and hearing loss.

## EXAMPLES OF ORGAN SYSTEM INTERACTIONS

An increase in cellular metabolism requires more cellular respiration. Cellular respiration is a good example of organ system interactions because it is a basic life process that occurs in all living cells.

### CELLULAR RESPIRATION

Cellular respiration is the intracellular process that breaks down glucose with oxygen to produce carbon dioxide and energy in the form of ATP molecules. It is the process by which cells obtain usable energy to power other cellular processes. Which organ systems are involved in cellular respiration? The glucose needed for cellular respiration comes from the digestive system via the cardiovascular system. The oxygen needed for cellular respiration comes from the respiratory system also via the cardiovascular system. The carbon dioxide produced in cellular respiration leaves the body by the opposite route. In short, cellular respiration requires at a minimum the digestive, cardiovascular, and respiratory systems.

### FIGHT-OR-FLIGHT RESPONSE

The well-known **fight-or-flight response** is a good example of how the nervous and endocrine systems control other organ system responses. The fight-or-flight response begins when the nervous system perceives sudden danger, as shown in Figure **1.6.2**. The brain sends a message to the endocrine system (via the pituitary gland) for the adrenal glands to secrete their hormones cortisol and adrenaline. These hormones flood the circulation and affect other organ systems throughout the body, including the cardiovascular, urinary, sensory, and digestive systems. Specific responses include increased heart rate, bladder relaxation, tunnel vision, and a shunting of blood away from the digestive system and toward the muscles, brain, and other vital organs needed to fight or flee.

### DIGESTING FOOD

Digesting food requires teamwork between the digestive system and several other organ systems, including the nervous, cardiovascular, and muscular systems. When you eat a meal, the organs of the digestive system need more blood to perform their digestive functions. Food entering the digestive systems causes nerve impulses to be sent to the brain; in response, the brain sends messages to the cardiovascular system to increase heart rate and dilate blood vessels in the digestive organs. Food passes through the organs of the digestive tract by rhythmic contractions of smooth muscles in the walls of the organs, so the muscular system is also needed for digestion. After food is digested, nutrients from the food are absorbed into the blood of the vessels lining the small intestine. Any remaining food waste is excreted through the large intestine.

### PLAYING SOFTBALL

The men playing softball in Figure **1.6.1** are using multiple organ systems in this voluntary activity. Their nervous systems are focused on observing and preparing to respond to the next play. Their other systems are being controlled by the autonomic nervous system. Organ systems they are using include the muscular, skeletal, respiratory, and cardiovascular systems. Can you explain how each of these organ systems is involved in playing softball?

### FEATURE: RELIABLE SOURCES

Teamwork among organ systems allows the human organism to work like a finely tuned machine. Or at least it does until one of the organ systems fails. When that happens, other organ systems interacting in the same overall process will also be affected. This is especially likely if the system affected plays a controlling role in the process. An example is type 1 diabetes.

This disorder occurs when the pancreas does not secrete the endocrine hormone insulin. Insulin normally is secreted in response to an increasing level of glucose in the blood, and it brings the level of glucose back to normal by stimulating body cells to take up insulin from the blood.

Learn more about type 1 diabetes. Use several reliable Internet sources to answer the following questions:

1. What causes the endocrine system to fail to produce insulin in type 1 diabetes?
2. Which organ systems are affected by high blood glucose levels if type 1 diabetes is not controlled? What are some of the specific effects?
3. How can blood glucose levels be controlled in patients with type 1 diabetes?

## REVIEW

1. What is the autonomic nervous system?
2. How do the autonomic nervous system and endocrine system communicate with other organ systems so the systems can interact?
3. Explain how the brain communicates with the endocrine system.
4. What is the role of the pituitary gland in the endocrine system?
5. Identify organ systems that play a role in cellular respiration.
6. How does the hormone adrenaline prepare the body to fight or flee? What specific physiological changes does it bring about?
7. Explain the role of the muscular system in the digestion of food.
8. Describe how three different organ systems are involved when a player makes a particular play in softball, such as catching a fly ball.
9. *True or False*. The autonomic nervous system controls conscious movements.
10. *True or False*. Hormones travel throughout the body.
11. *True or False*. The pituitary gland directly secretes thyroid hormone.
12. What are two types of molecules that the body uses to communicate between organ systems?
13. Explain why hormones can have such a wide variety of effects on the body.
14. Heart rate can be affected by:
    A. Hormones
    B. Neurotransmitters
    C. The fight-or-flight response
    D. All of the above
15. Which gland secretes the hormone cortisol?

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# 1.7: HOMEOSTASIS AND FEEDBACK

## STEADY AS SHE GOES

This device looks simple, but it controls a complex system that keeps a home at a steady temperature. The device is an old-fashioned thermostat. The dial shows the current temperature in the room and also allows the occupant to set the thermostat to the desired temperature. A thermostat is a commonly cited model of how living systems, including the human body, maintain a steady state called homeostasis.




Figure **1.7.1**: Thermostat for a building

## WHAT IS HOMEOSTASIS?

Homeostasis is the condition in which a system such as the human body is maintained in a more-or-less steady state. It is the job of cells, tissues, organs, and organ systems throughout the body to maintain many different variables within narrow ranges that are compatible with life. Keeping a stable internal environment requires continuous monitoring of the internal environment and constantly making adjustments to keep things in balance.

### SETPOINT AND NORMAL RANGE

For any given variable, such as body temperature or blood glucose level, there is a particular **setpoint** that is the physiological optimum value. For example, the setpoint for human body temperature is about 37 ºC (98.6 ºF). As the body works to maintain homeostasis for temperature or any other internal variable, the value typically fluctuates around the set point. Such fluctuations are normal as long as they do not become too extreme. The spread of values within which such fluctuations are considered insignificant is called the **normal range**. In the case of body temperature, for example, the normal range for an adult is about 36.5 to 37.5 ºC (97.7 to 99.5 ºF).

### MAINTAINING HOMEOSTASIS

Homeostasis is normally maintained in the human body by an extremely complex balancing act. Regardless of the variable being kept within its normal range, maintaining homeostasis requires at least four interacting components: stimulus, sensor, control center, and effector.

1. The **stimulus** is provided by the variable that is being regulated. Generally, the stimulus indicates that the value of the variable has moved away from the set point or has left the normal range.
2. The **sensor** monitors the values of the variable and sends data on it to the control center.
3. The **control center** matches the data with normal values. If the value is not at the set point or is outside the normal range, the control center sends a signal to the effector.
4. The **effector** is an organ, gland, muscle, or other structure that acts on the signal from the control center to move the variable back toward the set point.

Each of these components is illustrated in Figure **1.7.2**. The diagram on the left is a general model showing how the components interact to maintain homeostasis. The stimulus activates the sensor. The sensor activates the control system that regulates the effector. The diagram on the right shows the example of body temperature. From the diagrams, you can see that maintaining homeostasis involves feedback, which is data that feeds back to control a response. High body temperature may stimulate the temperature regulatory center of the brain to activate the sweat glands to bring the body temperature down. When body temperature reaches normal range, it acts as negative feedback to stop the process. Feedback may be negative or positive. All the feedback mechanisms that maintain homeostasis use negative feedback. Biological examples of positive feedback are much less common.

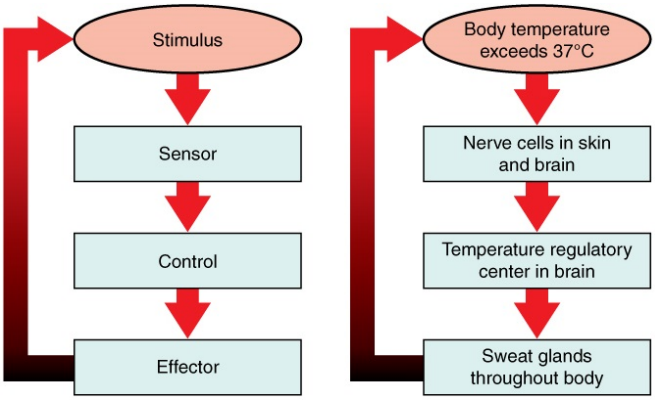



Figure **1.7.2**: Maintaining homeostasis through feedback requires a stimulus, sensor, control center, and effector

## NEGATIVE FEEDBACK

In a **negative feedback loop**, feedback serves to reduce an excessive response and keep a variable within the normal range. Examples of processes controlled by negative feedback include body temperature regulation and control of blood glucose.

### BODY TEMPERATURE

Body temperature regulation involves negative feedback whether it lowers the temperature or raises it (Figure **1.7.3**).

## COOLING DOWN

The human body's temperature regulatory center is the hypothalamus in the brain. When the hypothalamus receives data from sensors in the skin and brain that body temperature is higher than the setpoint, it sets into motion the following responses:

- Blood vessels in the skin dilate (vasodilation) to allow more blood from the warm body core to flow close to the surface of the body, so heat can be radiated into the environment.
- As blood flow to the skin increases, sweat glands in the skin are activated to increase their output of sweat (diaphoresis). When the sweat evaporates from the skin surface into the surrounding air, it takes the heat with it.
- Breathing becomes deeper, and the person may breathe through the mouth instead of the nasal passages. This increases heat loss from the lungs.

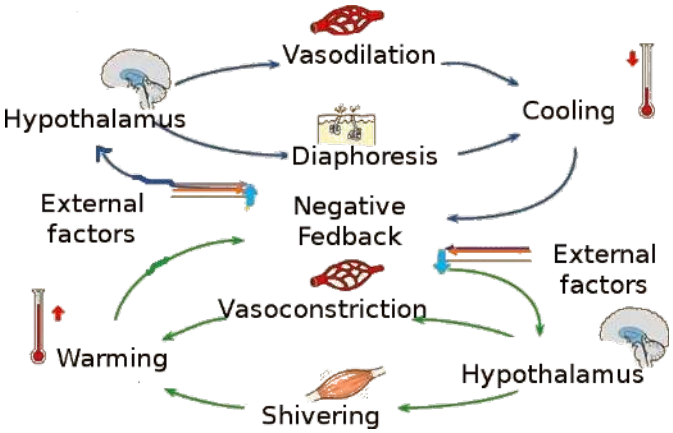



Figure **1.7.3**: The hypothalamus plays a major role in temperature regulation

## HEATING UP

When the brain's temperature regulatory center receives data that body temperature is lower than the setpoint, it sets into motion the following responses:

- Blood vessels in the skin contract (vasoconstriction) to prevent blood from flowing close to the surface of the body. This reduces heat loss from the surface.
- As the temperature falls lower, random signals to skeletal muscles are triggered, causing them to contract. This causes shivering, which generates a small amount of heat.
- The thyroid gland may be stimulated by the brain (via the pituitary gland) to secrete more thyroid hormones. This hormone increases metabolic activity and heat production in cells throughout the body.
- The adrenal glands may also be stimulated to secrete the hormone adrenaline. This hormone causes the breakdown of glycogen (the carbohydrate used for energy storage in animals) to glucose, which can be used as an energy source. This catabolic chemical process is exothermic, or heat producing.

## BLOOD GLUCOSE

In the control of the blood glucose level, certain endocrine cells in the pancreas called alpha and beta cells, detect the level of glucose in the blood. Then they respond appropriately to keep the level of blood glucose within the normal range.

- If the blood glucose level rises above the normal range, pancreatic beta cells release the hormone insulin into the bloodstream. Insulin signals cells to take up the excess glucose from the blood until the level of blood glucose decreases to the normal range.
- If the blood glucose level falls below the normal range, pancreatic alpha cells release the hormone **glucagon** into the bloodstream. Glucagon signals cells to break down stored glycogen to glucose and release the glucose into the blood until the level of blood glucose increases to the normal range.

# POSITIVE FEEDBACK

In a **positive feedback loop**, feedback serves to intensify a response until an endpoint is reached. Examples of processes controlled by positive feedback in the human body include blood clotting and childbirth.

## BLOOD CLOTTING

When a wound causes bleeding, the body responds with a positive feedback loop to clot the blood and stop blood loss. Substances released by the injured blood vessel wall begin the process of blood clotting. Platelets in the blood start to cling to the injured site and release chemicals that attract additional platelets. As the platelets continue to amass, more of the chemicals are released and more platelets are attracted to the site of the clot. The positive feedback accelerates the process of clotting until the clot is large enough to stop the bleeding.

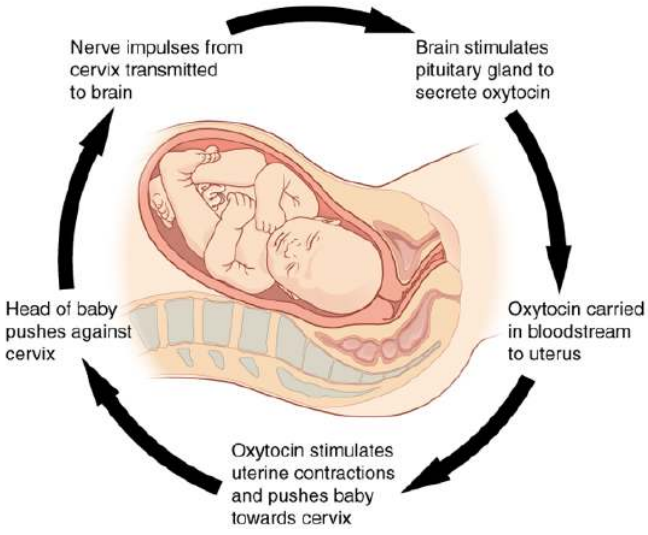



Figure **1.7.4**: Normal childbirth is driven by a positive feedback loop. Positive feedback causes an increasing deviation from the normal state to a fixed endpoint rather than a return to a normal set point as in homeostasis

### CHILDBIRTH

Figure **1.7.4** shows the positive feedback loop that controls childbirth. The process normally begins when the head of the infant pushes against the cervix. This stimulates nerve impulses, which travel from the cervix to the hypothalamus in the brain. In response, the hypothalamus sends the hormone **oxytocin** to the pituitary gland, which secretes it into the bloodstream so it can be carried to the uterus. Oxytocin stimulates uterine contractions, which push the baby harder against the cervix. In response, the cervix starts to dilate in preparation for the passage of the baby. This cycle of positive feedback continues, with increasing levels of oxytocin, stronger uterine contractions, and wider dilation of the cervix until the baby is pushed through the birth canal and out of the body. At that point, the cervix is no longer stimulated to send nerve impulses to the brain, and the entire process stops.

## WHEN HOMEOSTASIS FAILS

Homeostatic mechanisms work continuously to maintain stable conditions in the human body. Sometimes, however, the mechanisms fail. When they do, **homeostatic imbalance** may result, in which cells may not get everything they need or toxic wastes may accumulate in the body. If homeostasis is not restored, the imbalance may lead to disease or even death. Diabetes is an example of a disease caused by homeostatic imbalance. In the case of diabetes, blood glucose levels are no longer regulated and may be dangerously high. Medical intervention can help restore homeostasis and possibly prevent permanent damage to the organism.

### FEATURE: MY HUMAN BODY

Diabetes is diagnosed in people who have abnormally high levels of blood glucose after fasting for at least 12 hours. A fasting level of blood glucose below 100 is normal. A level between 100 and 125 places you in the pre-diabetes category, and a level higher than 125 results in a diagnosis of diabetes.

Of the two types of diabetes, type 2 diabetes is the most common, accounting for about 90 percent of all cases of diabetes in the United States. Type 2 diabetes typically starts after the age of 40. However, because of the dramatic increase in recent decades in obesity in younger people, the age at which type 2 diabetes is diagnosed has fallen. Even children are now being diagnosed with type 2 diabetes. Today, about 30 million Americans have type 2 diabetes, and another 90 million have pre-diabetes.

You are likely to have your blood glucose level tested during a routine medical exam. If your blood glucose level indicates that you have diabetes, it may come as a shock to you because you may not have any symptoms of the disease. You are not alone, because as many as one in four diabetics does not know they have the disease. Once the diagnosis of diabetes sinks in, you may be devastated by the news. Diabetes can lead to heart attacks, strokes, blindness, kidney failure, and loss of toes or feet. The risk of death in adults with diabetes is 50 percent greater than it is in adults without diabetes, and diabetes is the seventh leading cause of death in adults. In addition, controlling diabetes usually requires frequent blood glucose testing, watching what and when you eat and taking medications or even insulin injections. All of this may seem overwhelming.

The good news is that changing your lifestyle may stop the progression of type 2 diabetes or even reverse it. Here's how:

- Lose weight. Any weight loss is beneficial. Losing as little as seven percent of your weight may be all that is needed to stop diabetes in its tracks. It is especially important to eliminate excess weight around your waist.
- Exercise regularly. You should try to exercise five days a week for at least 30 minutes. This will not only lower your blood sugar and help your insulin work better; it will also lower your blood pressure and improve your heart health. Another bonus of exercise is that it will help you lose weight by increasing your basal metabolic rate.
- Adopt a healthy diet. Decrease your consumption of refined carbohydrates such as sweets and sugary drinks. Increase your intake of fiber-rich foods such as fruits, vegetables, and whole grains. About a quarter of each meal should consist of high-protein foods, such as fish, chicken, dairy products, legumes, or nuts.
- Control stress. Stress can increase your blood glucose and also raise your blood pressure and risk of heart disease. When you feel stressed out, do breathing exercises or take a brisk walk or jog. Also, try to replace stressful thoughts with more calming ones.
- Establish a support system. Enlist the help and support of loved ones as well as medical professionals such as a nutritionist and diabetes educator. Having a support system will help ensure that you are on the path to wellness and that you can stick to your plan.

## REVIEW

1. What is homeostasis?
2. Define the setpoint and normal range for physiological measures.
3. Identify and define the four interacting components that maintain homeostasis in feedback loops.
4. Compare and contrast negative and positive feedback loops.
5. Explain how negative feedback controls body temperature.
6. Give two examples of physiological processes that are controlled by positive feedback loops.
7. A negative feedback loop:
   A. brings a variable's level back to a normal range
   B. can lower, but not raise, body temperature
   C. is the type of feedback involved in blood clotting
   D. A and B
8. During breastfeeding, the stimulus of the baby sucking on the nipple increases the amount of milk produced by the mother. The more sucking, the more milk is usually produced.

A. Is this an example of negative or positive feedback? Explain your answer.
B. What do you think might be the evolutionary benefit of the milk production regulation mechanism described in part a?

9. Explain why homeostasis is regulated by negative feedback loops, rather than positive feedback loops.
10. A setpoint is usually:
    A. the top of a normal range
    B. the bottom of a normal range
    C. in the middle of a normal range
    D. the point at which changes can no longer occur
11. The level of a sex hormone, testosterone (T), is controlled by negative feedback. Another hormone, gonadotropin-releasing hormone (GnRH), is released by the hypothalamus of the brain, which triggers the pituitary gland to release luteinizing hormone (LH). LH stimulates the gonads to produce T. When there is too much T in the bloodstream, it feeds back on the hypothalamus, causing it to produce less GnRH. While this does not describe all the feedback loops involved in regulating T, answer the following questions about this particular feedback loop.
    A. What is the stimulus in this system? Explain your answer.
    B. What is the control center in this system? Explain your answer.
    C. What is the pituitary considered in this system: stimulus, sensor, control center, or effector? Explain your answer.

## EXPLORE MORE

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## ATTRIBUTIONS


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# 1.8: CASE STUDY CONCLUSION- PRESSURE AND CHAPTER SUMMARY

## CASE STUDY CONCLUSION: UNDER PRESSURE

As you learned in this chapter, the human body consists of many complex systems that normally work together efficiently like a well-oiled machine to carry out life's functions. For example, Figure 1.8.1 illustrates how the brain and spinal cord are protected by layers of membrane called meninges and fluid that flows between the meninges and in spaces called ventricles inside the brain. This fluid is called **cerebrospinal fluid (CSF)** and as you have learned, one of its important functions is to cushion and protect the brain and spinal cord, which make up most of the central nervous system (CNS). CSF additionally circulates nutrients and removes waste products from the CNS. CSF is produced continually in the ventricles, circulates throughout the CNS, and then is reabsorbed by the bloodstream. If too much CSF is produced, its flow blocked, or if not enough is reabsorbed, the system becomes out of balance, and CSF can build up in the ventricles. This causes an enlargement of the ventricles called hydrocephalus that can put pressure on the brain, resulting in the types of neurological problems that former professional football player, Dayo, described at the beginning of this chapter, is suffering from.

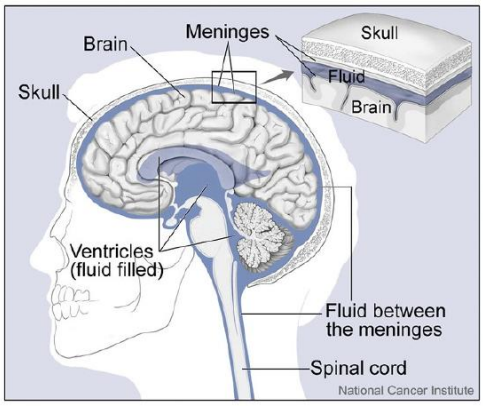



Figure 1.8.1: The brain and nearby structures (including the skull, meninges, ventricles, and spinal cord). An enlarged inset shows the skull, fluid, and brain.

Recall that Dayo's symptoms included loss of bladder control, memory loss, and difficulty walking. The cause of their symptoms was not immediately clear, although their doctors suspected that it related to the nervous system since the nervous system acts as the control center of the body, controlling and regulating many other organ systems. Dayo's memory loss directly implicated the involvement of the brain, since that is the site of thoughts and memory. The urinary system is also controlled in part by the nervous system, and the inability to hold urine appropriately can be a sign of a neurological issue. Dayo's trouble walking involved the muscular system, which works alongside the skeletal system to enable movement of the limbs. In turn, the contraction of muscles is regulated by the nervous system. You can see why a problem in the nervous system can cause a variety of different symptoms by affecting multiple organ systems in the human body.

To try to find the exact cause of Dayo's symptoms, their doctors performed a lumbar puncture, or spinal tap, which is the removal of some CSF through a needle inserted into the lower part of the spinal canal. Doctors then analyzed Dayo's CSF for the presence of pathogens such as bacteria to determine whether an infection was the cause of their neurological symptoms. When no evidence of infection was found, Doctors used an MRI to observe the structures of Dayo's brain. This is when Doctors discovered Dayo's enlarged ventricles, which are a hallmark of hydrocephalus.

To treat Dayo's hydrocephalus, a surgeon implanted a device called a shunt in Dayo's brain to remove the excess fluid (Figure 1.8.2). One side of the shunt consists of a small tube, called a **catheter**, which was inserted into Dayo's ventricles. Excess CSF is then drained through a one-way valve to the other end of the shunt, which was threaded under their skin to their abdominal cavity, where the CSF is released and can be reabsorbed by the bloodstream.

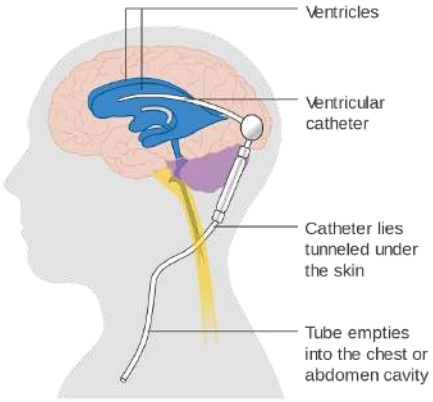



Figure 1.8.2: Tube empties CSF into the abdominal cavity.

Implantation of a shunt is the most common way to treat hydrocephalus, and for some people, it can allow them to recover almost completely. However, there can be complications associated with a brain shunt. The shunt can have mechanical problems or cause an infection. Also, the rate of draining must be carefully monitored and adjusted to balance the rate of removal of CSF with the rate of its production. If it is drained too fast, it is called overdraining, and if it is drained too slowly, it is called **underdraining**. In the case of underdraining, the pressure on the brain and associated neurological symptoms will persist. In the case of overdraining, the ventricles can collapse, which can cause serious problems such as the tearing of blood vessels and hemorrhaging. To avoid these problems, some shunts have an adjustable pressure valve where the rate of draining can be adjusted by placing a special magnet over the scalp. You can see how the proper balance between CSF production and removal is so critical – both in the causes of hydrocephalus and in its treatment.

In what other ways does your body regulate balance, or maintain a state of homeostasis? In this chapter, you learned about the feedback loops that keep body temperature and blood glucose within normal

ranges. Other important examples of homeostasis in the human body are the regulation of the pH in the blood and the balance of water in the body. You will learn more about homeostasis in different body systems in the coming chapters.

Thanks to Dayo's shunt, their symptoms are starting to improve, but they have not fully recovered. Time may tell whether the removal of the excess CSF from their ventricles will eventually allow them to recover normal functioning or whether permanent damage to their nervous system has already been done. The flow of CSF might seem simple but when it gets out of balance, it can easily wreak havoc on multiple organ systems because of the intricate interconnectedness of the systems within the human "machine."

## CHAPTER SUMMARY

This chapter provided an overview of the organization and functioning of the human body. You learned that:

- The human body consists of multiple parts that function together to maintain life. The biology of the human body incorporates the body's structure, or anatomy, and the body's functioning, or physiology.
- The organization of the human body is a hierarchy of increasing size and complexity, starting at the level of atoms and molecules and ending at the level of the entire organism.
- Cells are the level of organization above atoms and molecules, and they are the basic units of structure and function of the human body. Each cell carries out basic life functions as well as other specific roles. Cells of the human body show a lot of variation.
  - Variations in cell function are generally reflected in variations in cell structure.
  - Some cells are unattached to other cells and can move freely; others are attached to each other and cannot move freely. Some cells can divide readily and form new cells; others can divide only under exceptional circumstances. Many cells are specialized to produce and secrete particular substances.
  - All the different cell types within an individual have the same genes. Cells can vary because different genes are expressed depending on the cell type.
  - Many common types of human cells consist of several subtypes of cells, each of which has a special structure and function. For example, subtypes of bone cells include osteocytes, osteoblasts, osteogenic cells, and osteoclasts.
- A tissue is a group of connected cells that have a similar function. There are four basic types of human tissues that make up all the organs of the human body: epithelial, muscle, nervous, and connective tissues.
  - Connective tissues, such as bone and blood, are made up of cells that are separated by non-living material, called the extracellular matrix.
  - Epithelial tissues, such as skin and mucous membranes, protect the body and its internal organs and secrete or absorb substances.
  - Muscle tissues are made up of cells that have the unique ability to contract. They include skeletal, smooth, and cardiac muscle tissues.
  - Nervous tissues are made up of neurons, which transmit electrical messages, and glial cells of various types, which play supporting roles. Types of nervous tissues include gray matter, white matter, nerves, and ganglia.
- An organ is a structure that consists of two or more types of tissues that work together to do the same job. Examples include the brain and heart.
  - Many organs are composed of a major tissue that performs the organ's main function, as well as other tissues that play supporting roles.
  - The human body contains five organs that are considered vital for survival. They are the heart, brain, kidneys, liver, and lungs. If any of these five organs stops functioning, the death of the organism is imminent without medical intervention.
- An organ system is a group of organs that work together to carry out a complex overall function. For example, the skeletal system provides structure to the body and protects internal organs.
  - There are 11 major organ systems in the human organism. They are the integumentary, skeletal, muscular, nervous, endocrine, cardiovascular, lymphatic, respiratory, digestive, urinary, and reproductive systems. Only the reproductive system varies significantly between males and females.
- The human body is divided into a number of body cavities. A body cavity is a fluid-filled space in the body that holds and protects internal organs. The two largest human body cavities are the ventral cavity and the dorsal cavity.
  - The ventral cavity is at the anterior, or front, of the trunk. It is subdivided into the thoracic cavity and abdominopelvic cavity.
  - The dorsal cavity is at the posterior, or back, of the body, and includes the head and the back of the trunk. It is subdivided into the cranial cavity and spinal cavity.
- Organ systems of the human body must work together to keep the body alive and functioning normally. This requires communication among organ systems. This is controlled by the autonomic nervous system and endocrine system. The autonomic nervous controls involuntary body functions, such as heart rate and digestion. The endocrine system secretes hormones into the blood that travel to body cells and influence their activities.
  - Cellular respiration is a good example of organ system interactions because it is a basic life process that occurs in all living cells. It is the intracellular process that breaks down glucose with oxygen to produce carbon dioxide and energy. Cellular respiration requires the interaction of the digestive, cardiovascular, and respiratory systems.
  - The fight-or-flight response is a good example of how the nervous and endocrine systems control other organ system responses. It is triggered by a message from the brain to the endocrine system and prepares the body for flight or a fight.

Many organ systems are stimulated to respond, including the cardiovascular, respiratory, and digestive systems.
    - Digesting food requires teamwork between the digestive system and several other organ systems, including the nervous, cardiovascular, and muscular systems.
    - Playing softball or doing other voluntary physical activities may involve the interaction of nervous, muscular, skeletal, respiratory, and cardiovascular systems.
- Homeostasis is the condition in which a system such as the human body is maintained in a more-or-less steady state. It is the job of cells, tissues, organs, and organ systems throughout the body to maintain homeostasis.
    - For any given variable, such as body temperature, there is a particular set point that is the physiological optimum value. The spread of values around the setpoint that is considered insignificant is called the normal range.
    - Homeostasis is generally maintained by a negative feedback loop that includes a stimulus, sensor, control center, and effector. Negative feedback serves to reduce an excessive response and to keep a variable within the normal range. Negative feedback loops control body temperature and blood glucose level.
    - Sometimes homeostatic mechanisms fail, resulting in homeostatic imbalance. Diabetes is an example of a disease caused by homeostatic imbalance. Aging can bring about a reduction in the efficiency of the body's control system, making the elderly more susceptible to disease.
- Positive feedback loops are not common in biological systems. Positive feedback serves to intensify a response until an endpoint is reached. Positive feedback loops control blood clotting and childbirth.

The severe and broad impact of hydrocephalus on the body's systems highlights the importance of the nervous system and its role as the master control system of the body. In the next chapter, you will learn much more about the structures and functioning of this fascinating and important system.

## CHAPTER SUMMARY REVIEW

1. Compare and contrast tissues and organs.
2. Osteocyte cells are part of which type of tissue and organ system?
3. Adipose tissue, or body fat, is the same general type of tissue as:
    A. mucous membranes
    B. gray matter
    C. skin
    D. blood
4. Which type of tissue lines the inner and outer surfaces of the body?
5. *True or False.* The extracellular matrix that surrounds cells is always solid.
6. *True or False.* Skin is an organ.
7. What is a vital organ? What happens if a vital organ stops working?
8. Name three organ systems that transport or remove wastes from the body.
9. Name two types of tissue in the digestive system.
10. For each of the following body functions, choose the organ system that is most associated with the function. Organ systems: integumentary; skeletal; muscular; nervous; endocrine; cardiovascular; lymphatic; respiratory; digestive; urinary; reproductive
    A. Processes sensory information
    B. Secretes hormones
    C. Releases carbon dioxide from the body to the outside world
    D. Produces gametes
    E. Controls water balance in the body
11. The spleen is part of which organ system?
    A. Digestive
    B. Lymphatic
    C. Integumentary
    D. Urinary
12. Describe one way in which the integumentary and cardiovascular systems work together to regulate homeostasis in the human body.
13. Name the two largest body cavities in humans and describe their general locations.
14. What are the names given to the three body cavity divisions where the reproductive organs are located?
15. *True or False.* There are two pleural cavities.
16. *True or False.* Body cavities are filled with air.
17. The pituitary gland is in which organ system? Describe how the pituitary gland increases metabolism.
18. When the level of thyroid hormone in the body gets too high, it acts on other cells to reduce the production of more thyroid hormone. What type of feedback loop does this represent?
19. Hypothetical organ A is the control center in a feedback loop that helps maintain homeostasis. It secretes molecule A1 which reaches organ B, causing organ B to secrete molecule B1. B1 negatively feeds back onto organ A, reducing the production of A1 when the level of B1 gets too high.
    A. What is the stimulus in this feedback loop?
    B. If the level of B1 falls significantly below the setpoint, what do you think happens to the production of A1? Why?
    C. What is the effector in this feedback loop?
    D. If organs A and B are part of the endocrine system, what type of molecules do you think A1 and B1 are likely to be?
20. What are the two main systems that allow various organ systems to communicate with each other?
21. The hypothalamus is part of the:
    A. spinal cord
    B. thoracic cavity
    C. kidneys
    D. brain

22. What are two functions of the hypothalamus that you learned about in this chapter?

## ATTRIBUTIONS

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# CHAPTER OVERVIEW

## 2: CHEMISTRY OF LIFE

This chapter provides the chemistry background needed to understand the human body, its functions, and its processes. The chapter describes biochemical compounds and reactions as well as the significance of water to life.


2.1: Case Study- Chemistry and Your Life
2.2: Elements and Compounds
2.3: Chemical Bonding
2.4: Biochemical Compounds
2.5: Carbohydrates
2.6: Lipids
2.7: Proteins
2.8: Nucleic Acids
2.9: Energy in Chemical Reactions
2.10: Chemical Reactions in Living Things
2.11: Biochemical Properties of Water
2.12: Acids and Bases
2.13: Case Study Conclusion- Diet and Chapter Summary



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# 2.1: CASE STUDY- CHEMISTRY AND YOUR LIFE

## CASE STUDY: DIET DILEMMA

Mohinder is a college student who has watched their father suffer from complications of type 2 diabetes over the past few years. Mohinder likes to use gender-neutral pronouns, such as they, them, and their's. In type 2 diabetes, the hormone insulin does not transmit its signal sufficiently. Because insulin normally removes sugar from the bloodstream and brings it into the body's cells, diabetes causes blood sugar levels to not be regulated properly. This can cause damage to the cells of the body.



Figure **2.1.1**: Diabetes Detritus

Diabetes can be treated with insulin injections, as shown above, as well as dietary modifications, but sometimes complications can still occur. Mohinder's father has some nerve damage, or neuropathy, in his feet due to his diabetes. This made his feet numb and so he didn't notice when he got minor injuries to his feet, which led to some serious infections.

Mohinder is obese and knows that their weight plus a family history of diabetes increases their risk of getting diabetes themselves. They want to avoid the health issues that their father has suffered. Mohinder begins walking every day for exercise and starts to lose some weight. They also want to improve their diet in order to lose more weight, lower their risk of diabetes, and improve their general health, but they are overwhelmed with all the different dietary advice they read online and hear from their friends and family.

Mohinder's father tells them to limit refined carbohydrates, such as white bread and rice because that is what he does to help keep his blood sugar at an acceptable level. But Mohinder's friend tells them that eating a diet high in carbohydrates and low in fat is a good way to lose weight. Mohinder reads online that "eating clean" by eating whole, unprocessed foods and avoiding food with "chemicals" can help with weight loss. One piece of advice that everyone seems to agree on is that drinking enough water is good for overall health.

All of this dietary advice may sound confusing, but you can better understand health conditions such as diabetes and the role of diet and nutrition by understanding chemistry. Chemistry is so much more than reactions in test tubes in a lab — it is the atoms, molecules, and reactions that make us who we are and keep us alive and functioning properly. Our diets are one of the main ways our bodies take in raw materials that are needed for the important chemical reactions that take place inside of us.

## CHAPTER OVERVIEW: CHEMISTRY OF LIFE

As you read this chapter, you will learn more about how chemistry relates to our lives, health, and the foods we eat. Specifically, you will learn:

- The nature of chemical substances, including elements and compounds and their component atoms and molecules.
- The types and mechanisms of the formation of chemical bonds.
- The structures and functions of biochemical compounds including carbohydrates, lipids, proteins, and nucleic acids such as DNA and RNA.
- What chemical reactions are, how energy is involved in chemical reactions, how enzymes assist in chemical reactions, and what some types of biochemical reactions in living organisms are.
- Properties of water and the importance of water for most biochemical processes.
- What pH is and why maintaining a proper pH in the body is important for biochemical reactions.

As you read the chapter, think about the following questions regarding Mohinder's situation and how diabetes and diet relate to the chemistry of life.

1. Why do you think Mohinder's father having diabetes increases his risk of getting diabetes?
2. What is the difference between refined (simple) carbohydrates and complex carbohydrates? Why are refined carbohydrates particularly problematic for people with diabetes?
3. Insulin is a peptide hormone. In which class of biochemical compounds would you categorize insulin?
4. Why is drinking enough water important for overall health? Can you drink too much water?
5. Sometimes "eating clean" is described as avoiding "chemicals" in food. Think about the definition of "chemicals" and how it relates to what we eat.

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# 2.2: ELEMENTS AND COMPOUNDS

## WHAT ARE YOU MADE OF?

If you look at your hand, what do you see? Of course, you see skin, which consists of cells. But what are skin cells made of? Like all living cells, they are made of matter. In fact, all things are made of matter. **Matter** is anything that takes up space and has mass. Matter, in turn, is made up of chemical substances. A chemical substance is a matter that has a definite composition and the same composition throughout. A chemical substance may be either an element or a compound.



Figure **2.2.1**: Diversity and Unity

## ELEMENTS AND ATOMS

An **element** is a pure substance. It cannot be broken down into other types of substances. Each element is made up of just one type of atom.

### PERIODIC TABLE OF THE ELEMENTS

There are almost 120 known elements. As you can see in the Periodic Table of the Elements shown in Figure **2.2.3**, the majority of elements are metals. Examples of metals are iron (Fe) and copper (Cu). Metals are shiny and good conductors of electricity and heat. Nonmetal elements are far fewer in number. They include hydrogen (H) and oxygen (O). They lack the properties of metals. The element most important to life is Carbon (C). Find carbon in the table. What type of element is it, metal or nonmetal?

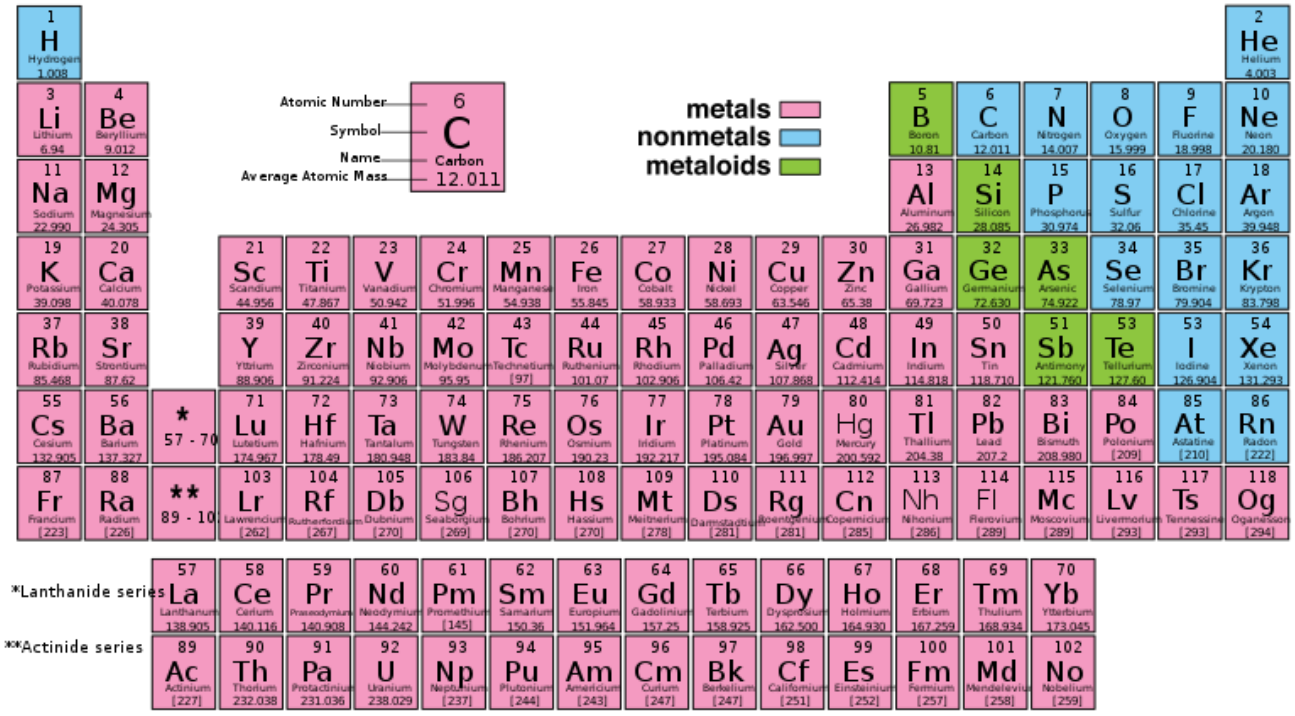



Figure **2.2.3**: Periodic Table of the Elements. The periodic table of the elements arranges elements in groups based on their properties. You may prefer to use an interactive periodic table or an accessible periodic table.

### STRUCTURE OF AN ATOM

An **atom** is the smallest particle of an element that still has the properties of that element. Every substance is composed of atoms. Atoms are extremely small, typically about a ten-billionth of a meter in diameter. However, atoms do not have well-defined boundaries, as suggested by the atomic model shown in figure **2.2.2**. An atom is composed of many **subatomic particles.** We will only discuss **protons**, **neutrons**, and **electrons**.

Table **2.2.1**: Subatomic Particles

| Particle | Proton | Neutron | Electron |
|---|---|---|---|
| Electric Charge | +1 | 0 | -1 |
| Location | Nucleus | Nucleus | Outside the nucleus |
| Mass | 1 amu | 1 amu | ~0 amu |

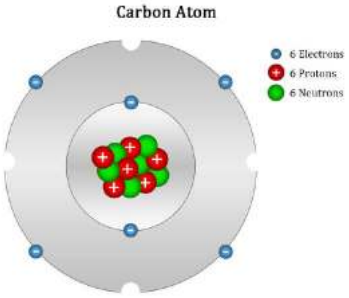



Figure **2.2.2**: A model of a Carbon atom. Carbon has 6 protons and 6 neutrons (found in the nucleus). The image also shows the 6 electrons outside of the nucleus in 2 separate orbitals.

If the number of protons and electrons in an atom are equal, then an atom is electrically neutral because the positive and negative charges cancel out. If an atom has more or fewer electrons than protons, then it has an overall negative or positive charge, respectively, and it is called an **ion.**

The negatively charged electrons of an atom are attracted to the positively charged protons in the nucleus by a force called **electromagnetic force,** for which opposite charges attract. Electromagnetic force between protons in the nucleus causes these subatomic particles to repel each other because they have the same charge. However, the protons and neutrons in the nucleus are attracted to each other by a different force, called **nuclear force,** which is usually stronger than the electromagnetic force repelling the positively charged protons from each other.

## COMPOUNDS AND MOLECULES

A **compound** is a unique substance that consists of two or more elements combined in fixed proportions. This means that the composition of a compound is always the same. The smallest particle of most compounds in living things is called a **molecule.** Consider water as an example. A molecule of water always contains one atom of oxygen and two atoms of hydrogen. The composition of water is expressed by the chemical formula $H_2O$. A model of a water molecule is shown in Figure **2.2.4**. Notice that molecules can be drawn in different ways, but represent the same molecule. In this case, a molecule made of one oxygen and two hydrogens.

What causes the atoms of a water molecule to “stick” together? The answer is chemical bonds. A chemical bond is a force that holds together the atoms of molecules. Bonds in molecules involve atoms sharing electrons. New chemical bonds form when substances react with one another.

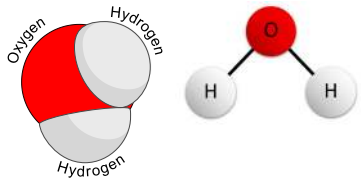



Figure **2.2.4**: Water Molecule. A water molecule always has this composition, one atom of oxygen, and two atoms of hydrogen.

## REVIEW

1. What is an element? Give three examples.
2. Define compound. Explain how compounds form.
3. Compare and contrast atoms and molecules.
4. The compound called water can be broken down into its constituent elements by applying an electric current to it. What ratio of elements is produced in this process?
5. Relate ions to elements and atoms.
6. What is the most important element of life?
7. Iron oxide is often known as rust — the reddish substance you might find on corroded metal. The chemical formula for this type of iron oxide is Fe2O3. Answer the following questions about iron oxide and briefly explain each answer.
   A. Is iron oxide an element or a compound?
   B. Would one particle of iron oxide be considered a molecule or an atom?
   C. Describe the relative proportion of atoms in iron oxide.
   D. What causes the Fe and O to stick together in iron oxide?
   E. Is iron oxide made of metal atoms, metalloid atoms, nonmetal atoms, or a combination of any of these?
8. Explain why ions have a positive or negative charge.
9. Name the three subatomic particles described in this section.

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# 2.3: CHEMICAL BONDING

## CHEMICAL BONDING

When you think of bonding, you may not think of ions. Like most of us, you probably think of bonding between people. Like people, molecules bond — and some bonds are stronger than others. It's hard to break up a mother and baby, or a molecule made up of one oxygen and two hydrogen atoms! A chemical bond is a force of attraction between atoms or ions. Bonds form when atoms share or transfer valence electrons. Valence electrons are the electrons in the outer energy level of an atom that may be involved in chemical interactions. Valence electrons are the basis of all chemical bonds.



Figure **2.3.1**: Mother and daughter

## WHY BONDS FORM

To understand why chemical bonds form, consider the common compound known as water, or $H_2O$. It consists of two hydrogen (H) atoms and one oxygen (O) atom. As you can see in the on the left side of the Figure **2.3.2** below, each hydrogen atom has just one electron, which is also its sole valence electron. The oxygen atom has six valence electrons. These are the electrons in the **outer energy level** of the oxygen atom.

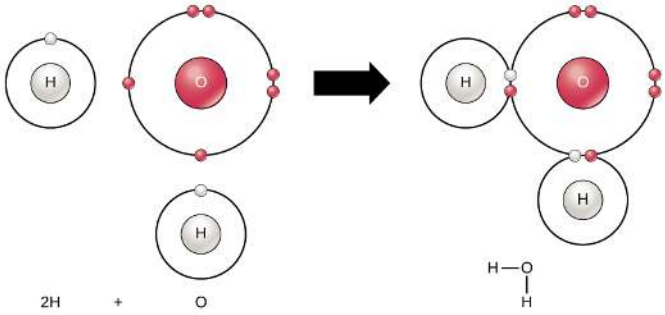



Figure **2.3.2**: Bonds between hydrogen and oxygen atoms in a water molecule. Electrons are drawn as spheres on the circle indicating an electron orbit. The nucleus is shown as the big sphere in the center of the atom.

In the water molecule on the right in Figure **2.3.2**, each hydrogen atom shares a pair of electrons with the oxygen atom. By sharing electrons, each atom has electrons available to fill its sole or outer energy level. The hydrogen atoms each have a pair of shared electrons, so their first and only energy level is full. The oxygen atom has a total of eight **valence electrons**, so its outer energy level is full. A full outer energy level is the most stable possible arrangement of electrons. It explains why elements form chemical bonds with each other.

## TYPES OF CHEMICAL BONDS

Not all chemical bonds form in the same way as the bonds in water. There are actually four different types of chemical bonds that we will discuss here are non-polar covalent, polar covalent, hydrogen, and ionic bonding. Each type of bond is described below.

### NON-POLAR COVALENT BONDS

For methane ($CH_4$) in Figure **2.3.3**, the carbon atom (with four electrons in its outermost valence energy shell) shares a single electron from each of the four hydrogens. Hydrogen has one valence electron in its first energy shell. Covalent bonding is prevalent in organic compounds. In fact, your body is held together by electrons shared by carbons and hydrogens! The electrons are equally shared in all directions; therefore, this type of covalent bond is referred to as non-polar.

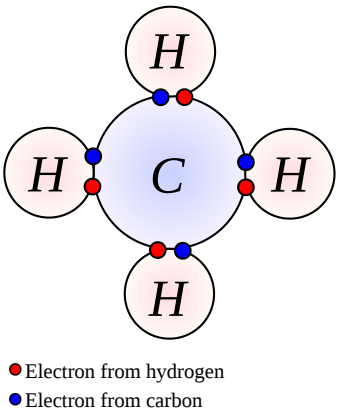



Figure **2.3.3**: Methane is formed when four hydrogens and one carbon covalently bond.

### POLAR COVALENT BONDS AND HYDROGEN BONDS

A covalent bond is the force of attraction that holds together two nonmetal atoms that share a pair of electrons. One electron is provided by each atom, and the pair of electrons is attracted to the positive nuclei of both atoms. The water molecule represented in Figure **2.3.4** contains polar covalent bonds.

The attractive force between water molecules is a dipole interaction. The hydrogen atoms are bound to the highly electronegative oxygen atom (which also possesses two lone pair sets of electrons, making for a very polar bond. The partially positive hydrogen atom of one molecule is then attracted to the partially negative oxygen atom of a nearby water molecule as shown in Figure **2.3.4** ).

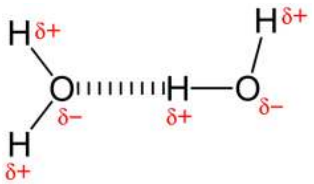



Figure **2.3.4**: A hydrogen bond in water occurs between the hydrogen atom of one water molecule and the lone pair of electrons on an oxygen atom of a neighboring water molecule

A **hydrogen bond** is an intermolecular and intramolecular attractive force in which a hydrogen atom that is covalently bonded to a highly **electronegative** atom is attracted to a lone pair of electrons on an atom or a partially negative atom in a neighboring polar molecule. Hydrogen bonds are also found intramolecularly in the tertiary and quaternary structures of protein and DNA strands.

Hydrogen bonding occurs only in molecules where hydrogen is covalently bonded to one of three elements: fluorine, oxygen, or nitrogen. These three elements are so electronegative that they withdraw the majority of the electron density in the covalent bond with hydrogen, leaving the H atom very electron-deficient. The H atom nearly acts as a bare proton, leaving it very attracted to lone pair electrons on a nearby atom.

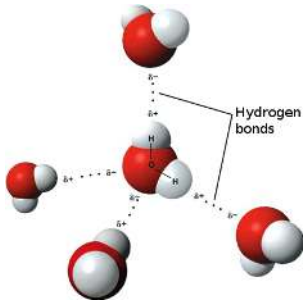



Figure **2.3.5**: Multiple hydrogen bonds occur simultaneously in water because of its bent shape and the presence of two hydrogen atoms per molecule.

The hydrogen bonding that occurs in water leads to some unusual, but very important properties. Most molecular compounds that have a mass similar to water are gases at room temperature. Because of the strong hydrogen bonds, water molecules are able to stay condensed in the liquid state. Figure **2.3.5** shows how the bent shape and two hydrogen atoms per molecule allow each water molecule to be able to hydrogen bond to two other molecules.

In the liquid state, the hydrogen bonds of water can break and reform as the molecules flow from one place to another. When water is cooled, the molecules begin to slow down. Eventually, when water is frozen to ice, the hydrogen bonds form a very specific network shown on the right side of Figure **2.3.6**. When water is liquid, the molecules are more motile and don't produce this rigid structure.

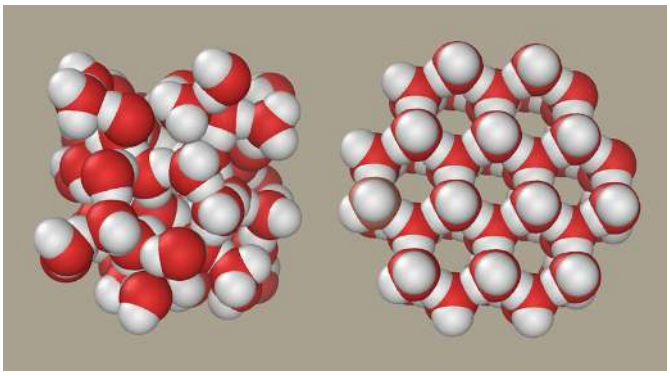


Figure **2.3.6**: When water freezes to ice, the hydrogen bonding network becomes more stable. Each oxygen atom has an approximately tetrahedral geometry – two covalent bonds and two hydrogen bonds.

## IONIC BONDS

Electrons are transferred between atoms. An ion will give one or more electrons to another ion. Table salt, sodium chloride (NaCl), is a common example of an ionic compound. Note that sodium is on the left side of the periodic table and that chlorine is on the right side of the periodic table. In Figure **2.3.7**, an atom of lithium donates an electron to an atom of fluorine to form an ionic compound. This happens to full fill their outermost valence shell. The transfer of the electron gives the lithium ion a net charge of +1, and the fluorine ion a net charge of -1. These ions bond because they experience an attractive force due to the difference in sign of their charges.

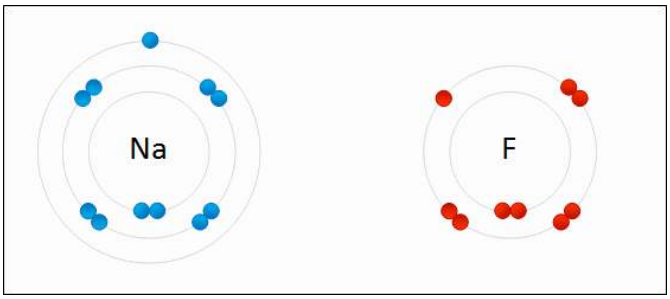



Figure **2.3.7**: Sodium (left) and fluorine (right) form an ionic compound called Sodium fluoride. The animation shows sodium (Na) losing an electron. This electron is taken by fluorine (F). This makes Na positively charged and F negatively charged. These ions are then attracted to each other.

## REVIEW

1. How is a covalent bond different from an ionic bond?
2. Why is a hydrogen bond a relatively weak bond?
3. Diagram the polarity of a water molecule.
4. What is a chemical bond?
5. Explain why hydrogen and oxygen atoms are more stable when they form bonds in a water molecule.
6. How many valence electrons does sodium have? How many valence electrons does chlorine have? How does a chlorine atom bonds with sodium? What is the charge on a sodium ion? What about the chlorine ion?
7. When does covalent bonding occur? How does it work?
8. How many valence electrons does oxygen have?

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# 2.4: BIOCHEMICAL COMPOUNDS

## CARBS GALORE

What do all these foods have in common? All of them consist mainly of large compounds called carbohydrates, often referred to as "carbs." Contrary to popular belief, carbohydrates are an important part of a healthy diet. They are also one of four major classes of biochemical compounds.



Figure **2.4.1**: Grain product food

## CHEMICAL COMPOUNDS IN LIVING THINGS

The compounds found in living things are known as **biochemical compounds.** Biochemical compounds make up the cells and other structures of organisms and carry out life processes. Carbon is the basis of all biochemical compounds, so carbon is essential to life on Earth. Without carbon, life as we know it could not exist.

Why is carbon so basic to life? The reason is carbon's ability to form stable bonds with many elements, including itself. This property allows carbon to form a huge variety of very large and complex molecules. In fact, there are nearly 10 million carbon-based compounds in living things!

Most biochemical compounds are very large molecules called polymers. A **polymer** is built of repeating units of smaller compounds called **monomers.** Monomers are like the individual beads on a string of beads, and the whole string is the polymer. The strings of beads pictured below are simple models of polymers in biochemical compounds.



Figure **2.4.2**: A Fio de conta: Beads on a string are similar to the formation of polymers from repeating units called monomers.

## CLASSES OF BIOCHEMICAL COMPOUNDS

Although there are millions of different biochemical compounds in Earth's living things, all biochemical compounds contain the elements carbon, hydrogen, and oxygen. Some contain only these elements; others contain additional elements as well. The vast number of biochemical compounds can be grouped into just four major classes: carbohydrates, lipids, proteins, and nucleic acids.

### CARBOHYDRATES

Carbohydrates include sugars and starches. These compounds contain only the elements carbon, hydrogen, and oxygen. Functions of carbohydrates in living things include providing energy to cells, storing energy, and forming certain structures, such as the cell walls of plants. The monomer that makes up large carbohydrate compounds is called a monosaccharide. The sugar glucose, represented by the chemical model below, is a monosaccharide. It contains six carbon atoms (C) and several atoms of hydrogen (H) and oxygen (O). Thousands of glucose molecules can join together to form a polysaccharide such as starch.

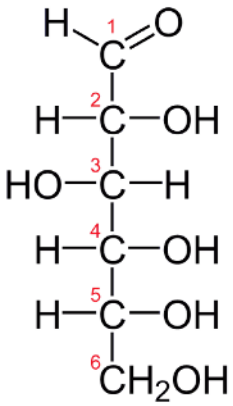



Figure **2.4.3**: Model of a monosaccharide (glucose) molecule. Glucose has 6 carbons forming a backbone. Each carbon has a total of 4 bonds. Each bond connects carbon to a carbon, hydrogen, or oxygen atom.

### LIPIDS

Lipids include fats and oils. They contain primarily the elements carbon, hydrogen, and oxygen, although some lipids contain additional elements such as phosphorus. Functions of lipids in living

things include storing energy, forming cell membranes, and carrying messages. Lipids consist of repeating units that join together to form chains called fatty acids. Most naturally occurring fatty acids have an unbranched chain of an even number (generally from 4 to 28) of carbon atoms.

### PROTEINS

Proteins include enzymes, antibodies, and many other important compounds in living things. They contain the elements carbon, hydrogen, oxygen, nitrogen, and sulfur. The functions of proteins are very numerous. They include helping cells keep their shape, making up muscles, speeding up chemical reactions, and carrying messages and materials. The monomers that make up large protein compounds are called amino acids. There are 23 different amino acids that combine into long chains (called polypeptides) to form the building blocks of a vast array of proteins in living things.

### NUCLEIC ACIDS

Nucleic acids include the molecules DNA (deoxyribonucleic acid) and RNA (ribonucleic acid). They contain the elements carbon, hydrogen, oxygen, nitrogen, and phosphorus. Their functions in living things are to encode instructions for making proteins, to help make proteins, and to pass the instructions from parents to offspring. The monomer that makes up nucleic acids is the nucleotide. All nucleotides are the same except for a component called a nitrogen base. There are four different nitrogen bases, and each nucleotide contains one of these four bases. The sequence of nitrogen bases in the chains of nucleotides in DNA and RNA makes up the code for protein synthesis, called the genetic code. The animation below represents the very complex structure of DNA, which consists of two chains of nucleotides.

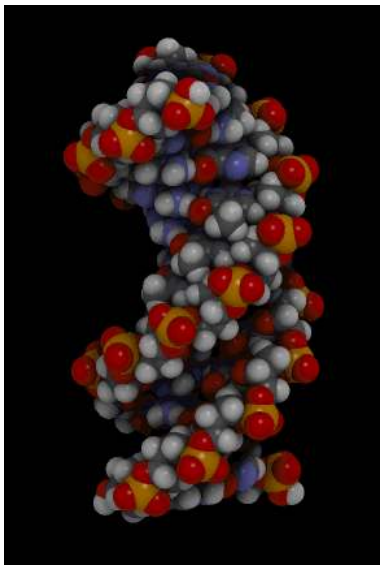


Figure **2.4.4**: This rotating DNA model shows the complexity of this two-stranded nucleic acid. There are many different atoms making the double helix structure.

## REVIEW

1. Why is carbon so important to life on Earth?
2. What are the biochemical compounds?
3. Describe the diversity of biochemical compounds, and explain how they are classified.
4. Identify two types of carbohydrates. What are the main functions of this class of biochemical compounds?
5. What roles are played by lipids in living things?
6. The enzyme amylase is found in saliva. It helps break down starches in foods into simpler sugar molecules. What type of biochemical compound do you think amylase is?
7. Explain how DNA and RNA contain the genetic code.
8. What are the three elements present in every class of biochemical compound?
9. For each of the following terms (nucleic acid; amino acid; monosaccharide; protein; nucleotide; polysaccharide)
   A. Determine whether it is a monomer or a polymer.
   B. Match each monomer with its correct polymer.
   C. Identify which class of biochemical compound is represented by each monomer/polymer pair.
10. Is glucose a monomer or a polymer? Explain your answer.
11. What is one element contained in proteins and nucleic acids, but not in carbohydrates?
12. Describe the relationship between proteins and nucleic acids.
13. Why do you think it is important to eat a diet that contains a balance of carbohydrates, proteins, and fats?

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# 2.5: CARBOHYDRATES

## THE CELLULOSE OF OUR LIVES

Where would we be without our jeans? They have been the go-to pants for many people for decades, and they are still as popular as ever. Jeans are made of denim, a type of cotton fabric. Cotton is a soft, fluffy fiber that grows in a protective case around the seeds of cotton plants. The fiber is almost pure cellulose. Cellulose is the single most abundant biochemical compound found in Earth's living things and one of several types of carbohydrates.



Figure 2.5.1: Body paint and jeans

## WHAT ARE CARBOHYDRATES?

**Carbohydrates** are the most common class of biochemical compounds. They include sugars and starches. Carbohydrates are used to provide or store energy, among other uses. Like most biochemical compounds, carbohydrates are built of small repeating units, or monomers, which form bonds with each other to make larger molecules, called polymers. In the case of carbohydrates, the small repeating units are known as **monosaccharides.** Each monosaccharide consists of six carbon atoms, as shown in the model of the monosaccharide glucose below.

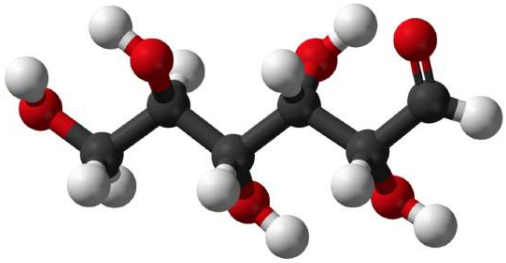


Figure 2.5.2: The six black balls in this model of the monosaccharide glucose represent carbon atoms. These six carbons make up the backbone in the center of glucose. The red balls are oxygen, and the white ones are hydrogen.

## SUGARS

**Sugars** are the general name for sweet, short-chain, soluble carbohydrates, which are found in many foods. Their function in living things is to provide energy. The simplest sugars consist of a single monosaccharide. They include glucose, fructose, and galactose. **Glucose** is a simple sugar that is used for energy by the cells of living things. Fructose is a simple sugar found in fruits, and galactose is a simple sugar found in milk.

Other sugars contain two monosaccharide molecules and are called **disaccharides.** An example is sucrose or table sugar. It is composed of one fructose molecule and one glucose molecule. Other disaccharides include maltose (two glucose molecules) and lactose (one glucose molecule and one galactose molecule). Lactose occurs naturally in milk. Some people can't digest lactose. If they drink milk, it causes gas, cramps, and other unpleasant symptoms unless the milk has been processed to remove the lactose.

## COMPLEX CARBOHYDRATES

The simple sugars form the foundation of more complex carbohydrates. The cyclic forms of two sugars can be linked together by means of a condensation reaction. The figure below shows how a glucose molecule and a fructose molecule combine to form a sucrose molecule. A hydrogen atom from one molecule and a hydroxyl group from the other molecule are eliminated as water, with a resulting covalent bond linking the two sugars together at that point.

Glucose and fructose combine to produce the disaccharide sucrose in a condensation reaction as shown in Figure 2.5.3. Sucrose, commonly known as table sugar, is an example of a disaccharide.

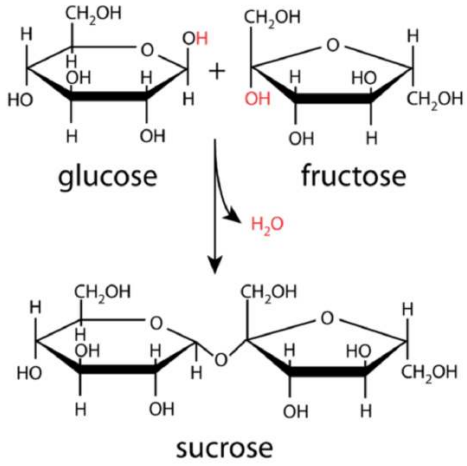



Figure 2.5.3: Glucose and fructose combine to produce the disaccharide sucrose in a condensation reaction. The diagram shows how water is produced when the reaction occurs. This is because the oxygen in glucose binds to the carbon in fructose. That removes an oxygen and two hydrogens from the new molecule.

A **disaccharide** is a carbohydrate formed by the joining of two monosaccharides. Other common disaccharides include lactose and maltose. Lactose, a component of milk, is formed from glucose and galactose, while maltose formed from two glucose molecules. During digestion, these disaccharides are hydrolyzed in the small intestine to form the component monosaccharides, which are then

absorbed across the intestinal wall and into the bloodstream to be transported to the cells.

Some carbohydrates consist of hundreds or even thousands of monosaccharides bonded together in long chains. These carbohydrates are called **polysaccharides** ("many saccharides"). Polysaccharides are also referred to as **complex carbohydrates.** Complex carbohydrates that are found in living things include starch, glycogen, cellulose, and chitin. Each type of complex carbohydrate has different functions in living organisms but they generally either store energy or make up certain structures of living things.



Figure **2.5.4**: (left) Potatoes are starch-filled tubers of potato plants. They are harvested by digging them up from underground. (center) Cotton fibers represent the purest natural form of cellulose, containing more than 90 percent of this polysaccharide. (right) The tough outer skeleton (exoskeleton) of this ten-lined beetle is made partly of the complex carbohydrate chitin.

## STARCH

**Starch** is a complex carbohydrate that is made by plants to store energy. For example, the potatoes pictured below are packed full of starches that consist mainly of repeating units of glucose and other simple sugars. The leaves of potato plants make sugars by photosynthesis, and the sugars are carried to underground tubers where they are stored as starch. When we eat starchy foods such as potatoes, the starches are broken down by our digestive system to sugars, which provide our cells with energy. Starches are easily and quickly digested with the help of digestive enzymes such as amylase, which is found in the saliva. If you chew a starchy saltine cracker for several minutes, you may start to taste the sugars released as the starch is digested.

## GLYCOGEN

Animals do not store energy as starch. Instead, animals store the extra energy as the complex carbohydrate glycogen. **Glycogen** is a polysaccharide of glucose. It serves as a form of energy storage in fungi as well as animals and is the main storage form of glucose in the human body. In humans, glycogen is made and stored primarily in the cells of the liver and the muscles. When energy is needed from either storage depot, the glycogen is broken down to glucose for use by cells. Muscle glycogen is converted to glucose for use by muscle cells, and liver glycogen is converted to glucose for use throughout the rest of the body. Glycogen forms an energy reserve that can be quickly mobilized to meet a sudden need for glucose, but one that is less compact than the energy reserves of lipids, which are the primary form of energy storage in animals.

Glycogen plays a critical part in the homeostasis of glucose levels in the blood. When blood glucose levels rise too high, excess glucose can be stored in the liver by converting it to glycogen. When glucose levels in the blood fall too low, glycogen in the liver can be broken down into glucose and released into the blood.

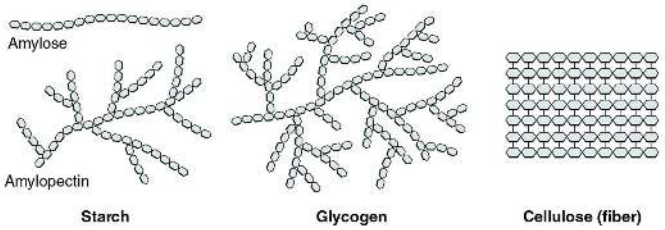



Figure **2.5.5**: Starch, Glycogen, and Cellulose have different arrangements of monosaccharides.

## CELLULOSE

**Cellulose** is a polysaccharide consisting of a linear chain of several hundred to many thousands of linked glucose units. Cellulose is an important structural component of the cell walls of plants and many algae. Human uses of cellulose include the production of cardboard and paper, which consist mostly of cellulose from wood and cotton. The cotton fibers pictured below are about 90 percent cellulose.

Certain animals, including termites and ruminants such as cows, can digest cellulose with the help of microorganisms that live in their gut. Humans cannot digest cellulose, but it nonetheless plays an important role in our diet. It acts as a water-attracting bulking agent for feces in the digestive tract and is often referred to as "dietary fiber."

## CHITIN

**Chitin** is a long-chain polymer of a derivative of glucose. It is found in many living things. For example, it is a component of the cell walls of fungi, the exoskeletons of arthropods such as crustaceans and insects (including the beetle pictured in Figure **2.5.7**), and the beaks and internal shells of animals such as squids and octopuses. The structure of chitin is similar to that of cellulose.

### FEATURE: MY HUMAN BIOLOGY



Figure **2.5.6**: Beans are an excellent source of both soluble and insoluble fiber.

You probably know that you should eat plenty of fiber, but do you know how much fiber you need, how fiber contributes to good health, or which foods are good sources of fiber? Dietary fiber consists mainly of cellulose, so it is found primarily in plant-based foods, including fruits, vegetables, whole grains, and legumes. Dietary fiber can't be broken down and absorbed by your digestive system. Instead, it passes relatively unchanged through your gastrointestinal tract and is excreted in feces. That's how it helps keep you healthy.

The fiber in food is commonly classified as either soluble or insoluble fiber.

- Soluble fiber dissolves in water to form a gel-like substance as it passes through the gastrointestinal tract. Its health benefits include lowering blood levels of cholesterol and glucose. Good sources of soluble fiber include whole oats, peas, beans, and apples.
- Insoluble fiber does not dissolve in water. This type of fiber increases the bulk of feces in the large intestine and helps keep food wastes moving through, which may help prevent or correct constipation. Good sources of insoluble fiber include whole wheat, wheat bran, beans, and potatoes.

How much fiber do you need for good health? That depends on your age and gender. The Institute of Medicine recommends the daily fiber intake for adults shown in the table below. Most dietitians further recommend a ratio of about 3 parts insoluble fiber to 1 part soluble fiber each day. Most fiber-rich foods contain both types of fiber, so it usually isn't necessary to keep track of the two types of fiber as long as your overall fiber intake is adequate.

Use food labels and online fiber counters to find out how much total fiber you eat in a typical day. Are you consuming enough fiber for good health? If not, consider ways to increase your intake of this important substance. For example, substitute whole grains for refined grains, eat more legumes such as beans, and try to consume at least five servings of fruits and vegetables each day.

Table **2.5.1**: Recommended Daily Fiber Intake for Males and Females

| Gender | Age 50 or Younger | Age 51 or Older |
|---|---|---|
| Male | 38 grams | 30 grams |
| Female | 25 grams | 21 grams |

## SUMMARY

- Carbohydrates are the most common class of biochemical compounds. The basic building block of carbohydrates is the monosaccharide, which consists of six carbon atoms.
- Sugars are sweet, short-chain, soluble carbohydrates that are found in many foods and supply us with energy. Simple sugars, such as glucose, consist of just one monosaccharide. Some sugars, such as sucrose, or table sugar, consist of two monosaccharides and are called disaccharides.
- Complex carbohydrates, or polysaccharides, consist of hundreds or even thousands of monosaccharides. They include starch, glycogen, cellulose, and chitin. They generally either store energy or form structures, such as cell walls, in living things.
- Starch is a complex carbohydrate that is made by plants to store energy. Potatoes are a good food source of dietary starch, which is readily broken down to its component sugars during digestion.
- Glycogen is a complex carbohydrate that is made by animals and fungi to store energy. Glycogen plays a critical part in the homeostasis of blood glucose levels in humans.
- Cellulose is the single most common biochemical compound in living things. It forms the cell walls of plants and certain algae. Like most other animals, humans cannot digest cellulose, but it makes up most of the crucial dietary fiber in the human diet.
- Chitin is a complex carbohydrate, similar to cellulose, that makes up organic structures such as the cell walls of fungi and the exoskeletons of insects and other arthropods.

## REVIEW

1. What are carbohydrates? Describe their structure.
2. Compare and contrast sugars and complex carbohydrates.
3. Identify the four main types of complex carbohydrates and their functions.
4. If you chew on a starchy food such as a saltine cracker for several minutes, it may start to taste sweet. Explain why.
5. *True or False.* Glucose is mainly stored by lipids in the human body.
6. Put the following carbohydrates in order from smallest to largest: cellulose; fructose; sucrose
7. Name three carbohydrates that contain glucose as a monomer.
8. Jeans are made of tough, durable cotton. Explain how you think this fabric gets its tough qualities, based on what you know about the structure of carbohydrates.
9. Which do you think is faster to digest — simple sugars or complex carbohydrates? Explain your answer.
10. *True or False.* Cellulose is broken down in the human digestive system into glucose molecules.
11. Which type of fiber dissolves in water? Which type does not dissolve in water?
12. What are the similarities and differences between muscle glycogen and liver glycogen?
13. Which carbohydrate is used directly by the cells of living things for energy?
14. Which of the following is *not* a complex carbohydrate?

A. chitin
B. starch
C. disaccharide
D. none of the above

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# 2.6: LIPIDS

YUM!

It glistens with fat, from the cheese to the steak. You may never have visited Philadelphia, but you probably know about its famous gastronomic delight, the Philly cheesesteak, pictured here. Both cheese and steak are typically high-fat foods, so this sandwich is definitely not recommended if you are following a low-fat diet. We need some fats in our diet for good health, but too much of a good thing can be harmful to our health, no matter how good it tastes. What are fats? And why do we have such a love-hate relationship with them? Read on to find out.



Figure **2.6.1**: Philly Cheesesteak Sandwich

## LIPIDS AND FATTY ACIDS

Fats are actually a type of lipid. **Lipids** are a major class of biochemical compounds that includes oils as well as fats. Organisms use lipids to store energy and for many other uses.

Lipid molecules consist mainly of repeating units called **fatty acids.** There are two types of fatty acids: saturated fatty acids and unsaturated fatty acids. Both types consist mainly of simple chains of carbon atoms bonded to one another and to hydrogen atoms. The two types of fatty acids differ in how many hydrogen atoms they contain.

### SATURATED FATTY ACIDS

In saturated fatty acids, carbon atoms are bonded to as many hydrogen atoms as possible. All the carbon-to-carbon atoms share just single bonds between them. This causes the molecules to form straight chains, as shown in Figure **2.6.2**. The straight chains can be packed together very tightly, allowing them to store energy in a compact form. Saturated fatty acids have relatively high melting points, explaining why they are solids at room temperature. Animals use saturated fatty acids to store energy.

### UNSATURATED FATTY ACIDS

In **unsaturated fatty acids**, some carbon atoms are not bonded to as many hydrogen atoms as possible. Instead, they form double or even triple bonds with other carbon atoms. This causes the chains to bend (see Figure **2.6.2**). The bent chains cannot be packed together very tightly. Unsaturated fatty acids have relatively low melting points, which explains why they are liquids at room temperature. Plants use unsaturated fatty acids to store energy.

Monounsaturated fatty acids contain one less hydrogen atom than the same-length saturated fatty acid chain. Monounsaturated fatty acids are liquids at room temperature but start to solidify at refrigerator temperatures. Good food sources of monounsaturated fats include olive and peanut oils and avocados.

Polyunsaturated fatty acids contain at least two fewer hydrogen atoms than the same-length saturated fatty acid chain. Polyunsaturated fatty acids are liquids at room temperature and remain in the liquid state in the refrigerator. Good food sources of polyunsaturated fats include safflower and soybean oils and many nuts and seeds.

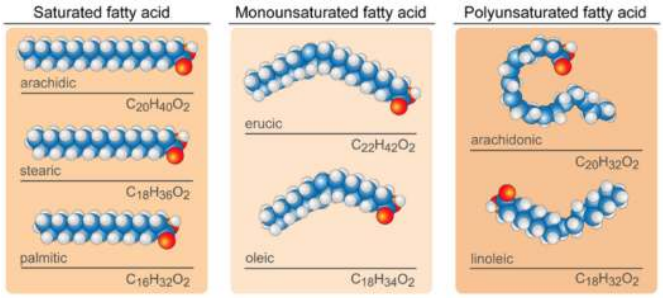



Figure **2.6.2**: Fatty Acids models. The blue balls, white balls, and red balls represent carbon, hydrogen, and oxygen, respectively. Saturated fatty acids, such as arachidic, stearic and palmitic, have straight chains. Unsaturated fatty acids have bent chains. Monounsaturated fatty acids, such as erucic and oleic have a single double bond between carbons creating a single bend in the chain. Polyunsaturated fatty acids, such as arachidoic and linoleic, have multiple carbon-carbon double bonds creating multiple bends.

## TYPES OF LIPIDS

Lipids may consist of fatty acids alone, or they may contain other molecules as well. For example, some lipids contain alcohol or phosphate groups. Types of lipids include triglycerides, phospholipids, and steroids. Each type has different functions in living things.

### TRIGLYCERIDES

**Triglycerides** are formed by combining a molecule of glycerol with three fatty acid molecules. Glycerol (also called glycerine) is a simple compound known as a sugar alcohol. It is a colorless, odorless liquid that is sweet tasting and nontoxic. Triglycerides are the main constituent of body fat in humans and other animals. They are also found in fats derived from plants. There are many different types of triglycerides, with the main division being between those that contain saturated fatty acids and those that contain unsaturated fatty acids.

In the human bloodstream, triglycerides play an important role in metabolism as energy sources and transporters of dietary fat. They contain more than twice as much energy as carbohydrates, the other major source of energy in the diet. When you eat, your body converts any calories it doesn't need to use right away into triglycerides, which are stored in your fat cells. When you need energy between meals, hormones trigger the release of some of these stored triglycerides back into the bloodstream.

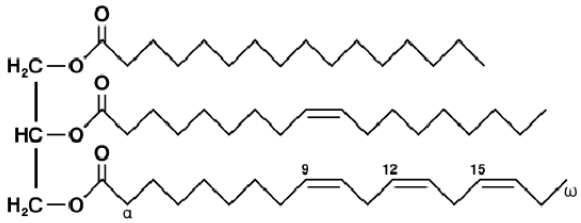



Figure 2.6.3: Triglyceride Molecule. The left part of this triglyceride molecule represents glycerol. Each of the three long chains on the right represents a different fatty acid. From top to bottom, the fatty acids are palmitic acid, oleic acid, and alpha-linolenic acid. These fatty acids are shown in Figure 2.6.2. The chemical formula for this triglyceride is $C_{55}H_{98}O_6$. KEY: H=hydrogen, C=carbon, O=oxygen.

## PHOSPHOLIPIDS

**Phospholipids** are a major component of the cell membranes of all living things. Each phospholipid molecule has a "tail" consisting of two long fatty acids and a "head" consisting of a phosphate group and glycerol molecule (see diagram below). The phosphate group is a small negatively charged molecule. The phospholipid head is **hydrophilic** or attracted to water. The fatty acid tail of the phospholipid is **hydrophobic** or repelled by water. These properties allow phospholipids to form a two-layer, or bilayer, cell membrane.

As shown in the diagram below, a phospholipid bilayer forms when many phospholipid molecules line up tail to tail, forming an inner and outer surface of hydrophilic heads. The hydrophilic heads point toward both the watery extracellular space and the watery intracellular space (lumen) of the cell.

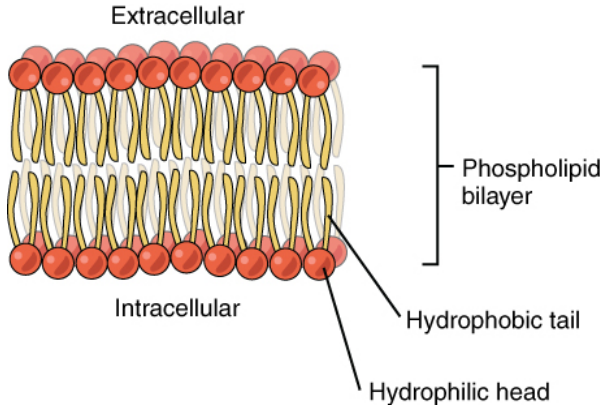



Figure 2.6.4: The phospholipid bilayer consists of two adjacent sheets of phospholipids, arranged tail to tail. The hydrophobic tails associate with one another, forming the interior of the membrane. The polar heads contact the fluid inside and outside of the cell.

## STEROIDS

**Steroids** are lipids with a ring structure. Each steroid has a core of seventeen carbon atoms arranged in four rings of five or six carbons each (see model pictured below). Steroids vary by the other components attached to this four-ring core. Hundreds of steroids are found in plants, animals, and fungi, but most steroids have one of just two principal biological functions: some steroids, such as cholesterol, are important components of cell membranes; many other steroids are hormones, which are messenger molecules. In humans, steroid hormones include cortisone, a fight-or-flight hormone; and the sex hormones estrogen and testosterone.

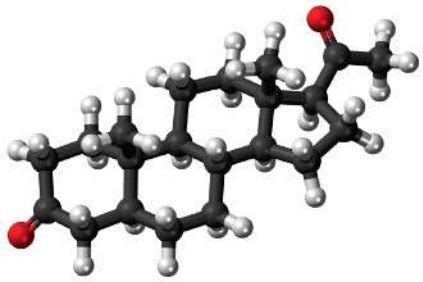


Figure 2.6.5: Each steroid molecule consists of a four-ring core of 17 carbon atoms (black balls in the model). The red balls are representing oxygen and the white balls are representing hydrogen in the model. The components of the molecule may vary and determine the steroid's function.

### FEATURE: MY HUMAN BODY

During a routine checkup with your family doctor, your blood was collected for a lipid profile. The results are back, and your triglyceride level is 180 mg/dL. Your doctor says this is a little high. A blood triglyceride level of 150 mg/dL or lower is considered normal. Higher levels of triglycerides in the blood have been linked to increased risk of atherosclerosis, heart disease, and stroke.

If a blood test reveals that you have high triglycerides, the levels can be lowered through healthy lifestyle choices and/or prescription medications. Healthy lifestyle choices to control triglyceride levels include:

- losing weight. If you are overweight, losing even 5 or 10 pounds may help lower your triglyceride level.
- cutting back on calories. Extra calories are converted to triglycerides and stored as fat, so reducing your calories should also reduce your triglyceride level.
- avoiding sugary and refined foods. Simple carbohydrates, such as sugars and foods made with white flour, can increase triglyceride levels.
- choosing healthier fats. Trade saturated fats found in animal foods for healthier unsaturated fats found in plants and oily fish. For example, substitute olive oil for butter and salmon for red meat.
- limiting alcohol consumption. Alcohol is high in calories and sugar and has a strong effect on triglyceride levels.
- exercising regularly. Aim for at least 30 minutes of physical activity on most or all days of the week to lower triglyceride levels.

If healthy lifestyle changes aren't enough to bring down high triglyceride levels, drugs prescribed by your doctor are likely to help.

## REVIEW

1. What are lipids?
2. Compare and contrast saturated and unsaturated fatty acids.
3. Identify three major types of lipids, and describe differences in their structures.
4. How do triglycerides play an important role in human metabolism?
5. Explain how phospholipids form cell membranes.
6. What is cholesterol, and what is its major function?
7. Give three examples of steroid hormones in humans.
8. Which type of fatty acid do you think is predominant in the steak and cheese of the cheesesteak shown above? Explain your answer.
9. Which type of fat would be the most likely to stay liquid in colder temperatures — bacon fat, olive oil, or soybean oil? Explain your answer.
10. Why do you think that the shape of the different types of fatty acid molecules affects how easily they solidify?
11. High cholesterol levels in the bloodstream can cause negative health effects but explain why we wouldn't want to get rid of *all* the cholesterol in our bodies.
12. Name two types of lipids that are part of the cell membrane.
13. *True or False.* Fatty acids are made up of triglycerides.
14. Which type of lipid often functions as chemical messenger molecules?

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# 2.7: PROTEINS

## PROTEIN SHAKE

Drinks like this shake contain a lot of protein. Such drinks are popular with people who want to build muscle because muscle tissue consists mainly of protein. Making up muscles is just one of a plethora of functions of this amazingly diverse class of biochemicals.



Figure 2.7.1: Protein shake

## WHAT ARE PROTEINS?

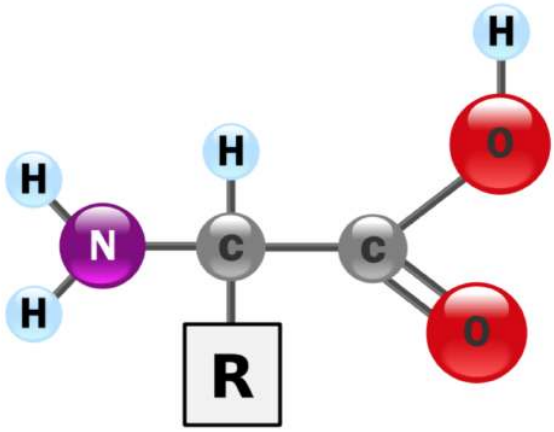



Figure 2.7.2: General Structure of Amino Acids. This model shows the general structure of all amino acids. Only the side chain, R, varies from one amino acid to another. For example, in the amino acid glycine, the side chain is simply hydrogen (H). In glutamic acid, in contrast, the side chain is $CH_2CH_2COOH$ CH2CH2COOH. Variable side chains give amino acids different chemical properties. The order of amino acids, together with the properties of the amino acids, determines the shape of the protein, and the shape of the protein determines the function of the protein. KEY: H = hydrogen, N = nitrogen, C = carbon, O = oxygen, R = variable side chain.

**Proteins** are organic compounds that contain carbon, hydrogen, oxygen, nitrogen, and, in some cases, sulfur. These compounds have many essential functions within the cell (see below). Proteins are made of smaller units called **amino acids**. There are 20 different common amino acids needed to make proteins. All amino acids have the same basic structure, which is shown in Figure 2.7.3. Only the side chain (labeled R in the figure) differs from one amino acid to another. These side chains can vary in size from just one hydrogen atom in glycine to a large heterocyclic group in tryptophan. The variable side chain gives each amino acid unique properties. The side chains can also characterize the amino acid as (1) nonpolar or hydrophobic, (2) neutral (uncharged) but polar, (3) acidic, with a net negative charge, and (4) basic, with a net positive charge at neutral pH.

Proteins can differ from one another in the number and sequence (order) of amino acids. It is because of the side chains of the amino acids that proteins with different amino acid sequences have different shapes and different chemical properties. Small proteins can contain just a few hundred amino acids. Yeast proteins average 466 amino acids. The largest known proteins are the titins, found in muscle, which are composed of over 27,000 amino acids.

## PROTEIN STRUCTURE

Amino acids join together to form a molecule called a dipeptide. The –OH from the carboxyl group of one amino acid combines with a hydrogen atom from the amino group of the other amino acid to produce water. This is called a **condensation reaction** - a reaction in which two molecules combine to form a single molecule with a release of water. Figure 2.7.3) shows this process. The top part of the image shows two amino acids; note the -OH in amino acid 1 and the -H in amino acid two are highlighted. These are the atoms that will be removed from the amino acids to form water. This allows a covalent bond forms between the carboxyl carbon of one amino acid and the amine nitrogen of the second amino acid. This reaction forms a molecule called a dipeptide and the carbon-nitrogen covalent bond is called a **peptide bond**. When repeated numerous times, a lengthy molecule called a **polypeptide** is eventually produced. Very lengthy polypeptides with functional configuration are called **proteins.**

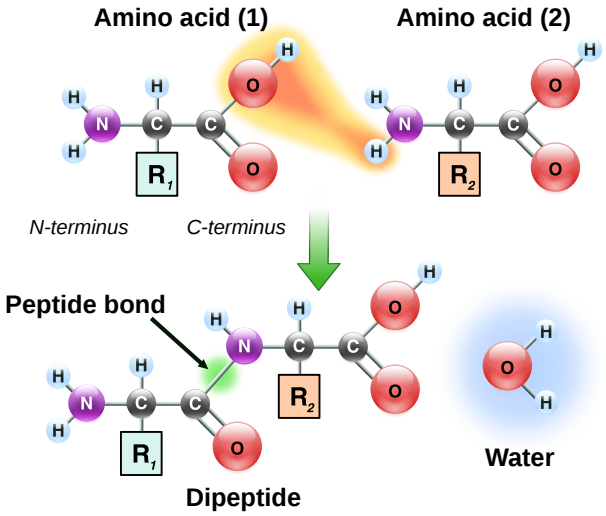



Figure 2.7.3: Amino acids join together to form a molecule called a dipeptide. The C–N bond is called a peptide bond. The order of amino acids is by convention shown with the free amino group on the left and the free carboxyl group on the right.

Proteins may have up to four levels of structure, from primary to quaternary, as described and shown in the diagram below, giving them the potential for tremendous diversity:

- A protein's primary structure is the sequence of amino acids in its polypeptide chain(s). This sequence of amino acids determines the higher levels of protein structure and is encoded in genes.
- A protein's secondary structure consists of regularly repeating local structures stabilized by hydrogen bonding between the carboxylic and amino groups of the backbone. The most common secondary structures include the alpha-helix and beta-sheet. Because secondary structures are local, many regions of different secondary structures can be present in the same protein molecule.
- A protein's tertiary structure refers to the overall three-dimensional shape of a single protein molecule. It is determined by the spatial relationship of non-covalent and covalent bonds between the "R" groups of distant amino acids in a polypeptide. The tertiary structure is what controls the basic function of the protein.
- Not all proteins have a final, quaternary structure. This is a structure formed by several protein molecules that function together as a single protein complex.

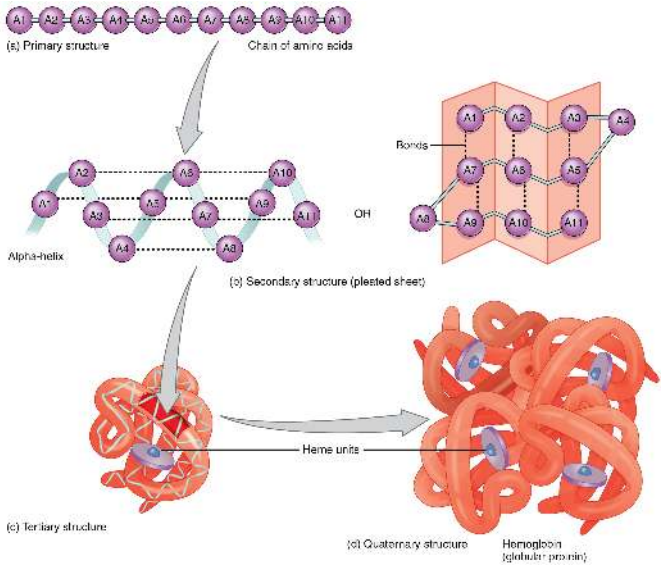



Figure **2.7.4**: The levels of structure of a protein called hemoglobin.

## FUNCTIONS OF PROTEINS

The diversity of protein structures explains how this class of biochemical compounds can play so many important roles in living things. What are the roles of proteins?

- Some proteins have structural functions. They may help cells keep their shape or make up muscle tissues.
- Many proteins are enzymes that speed up chemical reactions in cells. Enzymes are usually highly specific and accelerate only one or a few chemical reactions. Thousands of different biochemical reactions are known to be catalyzed by enzymes, including most of the reactions involved in metabolism. A reaction without an enzyme might take millions of years to complete, whereas, with the proper enzyme, it may take just a few milliseconds!
- Other proteins are antibodies. These are proteins that bind to specific foreign substances, such as proteins on the surface of bacterial cells. This targets the cells for destruction.
- Still, other proteins carry messages or materials. For example, a protein called myoglobin is an oxygen-binding protein found in the muscle tissues of most mammals including humans. You can see a model of the tertiary structure of myoglobin in the figure below.

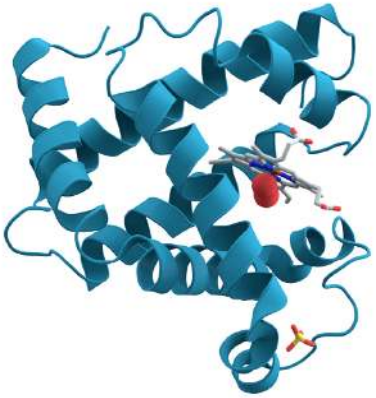


Figure **2.7.5**: Myoglobin is a protein found in the muscle tissues of most mammals. It binds with oxygen to supply the cells with this element. The modle shows the 3D structure of the protein.

The chief characteristic of proteins that allows their diverse set of functions is their ability to bind other molecules specifically and tightly. For example, myoglobin can bind specifically and tightly with oxygen. The region of a protein responsible for binding with another molecule is known as the **binding site.** This site is often a depression on the molecular surface, determined largely by the tertiary structure of the protein.

## PROTEIN CONSUMPTION, DIGESTION, AND SYNTHESIS

Proteins are necessary for the diets of humans and other animals. We cannot make all the different amino acids we need, so we must obtain some of them from the foods we consume. Through the process of digestion, we break down the proteins in food into free amino acids that can then be used to synthesize our own proteins. Protein synthesis from amino acid monomers takes place in all cells and is controlled by genes. Once new proteins are synthesized, they generally do not last very long before they are degraded and their amino acids are recycled. A protein's lifespan is generally just a day or two in mammalian cells.

## REVIEW

1. What are proteins?
2. How do two amino acids combine together to make a dipeptide?
3. Outline the four levels of protein structure.
4. Identify four functions of proteins.

5. Explain why proteins can take on so many different functions in living things.
6. What is the role of proteins in the human diet?
7. Can you have a protein with both an alpha helix and a beta-sheet? Why or why not?
8. If there is a mutation in a gene that causes a different amino acid to be encoded than the one that is usually encoded in that position within the protein, would that affect:
   A. The primary structure of the protein? Explain your answer.
   B. The higher structures (secondary, tertiary, quaternary) of the protein? Explain your answer.
   C. The function of the protein? Explain your answer.
9. What is the region of a protein responsible for binding to another molecule called? Which level/s of protein structure create this region?
10. Arrange the following in order from the smallest to the largest level of organization:
11. peptide; protein; amino acid; polypeptide
12. *True or False.* You can tell the function of all proteins from their quaternary structure.
13. Explain what the reading means when it says that amino acids are "recycled."

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# 2.8: NUCLEIC ACIDS

**WHO'S WHO?**

Identical twins show clearly the importance of genes in making us who we are. Genes, in turn, would not be possible without nucleic acids.



Figure **2.8.1**: Twins

**Nucleic acids** are the class of biochemical compounds that includes DNA and RNA. These molecules are built of small monomers called **nucleotides**. Many nucleotides bind together to form a chain called a **polynucleotide**. The nucleic acid **DNA** (deoxyribonucleic acid) consists of two polynucleotide chains. The nucleic acid **RNA** (ribonucleic acid) consists of just one polynucleotide chain.

## STRUCTURE OF NUCLEIC ACIDS

Each nucleotide consists of three smaller molecules:

1. a sugar molecule (the sugar deoxyribose in DNA and the sugar ribose in RNA).
2. a phosphate group.
3. a nitrogenous base.

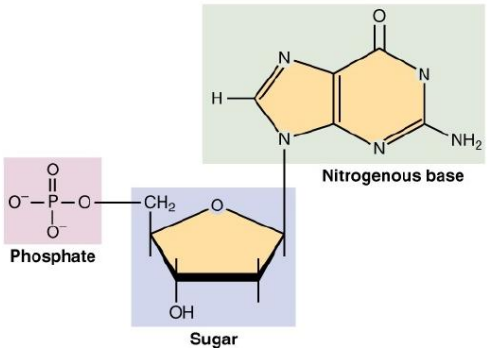



Figure **2.8.2**: Nucleotides consist of a sugar, a nitrogenous base, and a phosphate group

Nucleotides are connected to form DNA as shown in Figure **2.8.3**. The sugar molecule of one nucleotide binds to the phosphate group of the next nucleotide. These two molecules alternate to form the backbone of the nucleotide chain. The nitrogen bases in a nucleic acid stick out from the backbone. There are four different nitrogenous bases: cytosine, adenine, guanine, and either thymine (in DNA) or uracil (in RNA). In DNA, hydrogen bonds form between bases on the two nucleotide chains and hold the chains together. Each type of base binds with just one other type of base: cytosine always bonds with guanine, and adenine always bonds with thymine. These pairs of bases are called **complementary base pairs**.

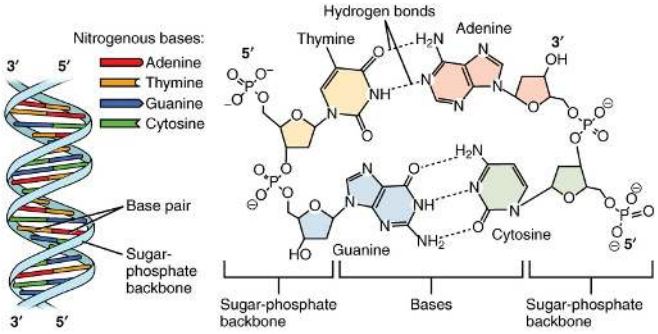



Figure **2.8.3**: Nucleic Acid

The hydrogen bonding of complementary bases causes DNA molecules automatically to take their well-known shape, called a double helix, which is shown in the animation in Figure **2.8.4**. A double helix is like a spiral staircase. The double helix shape forms naturally and is very strong, making the two polynucleotide chains difficult to break apart.

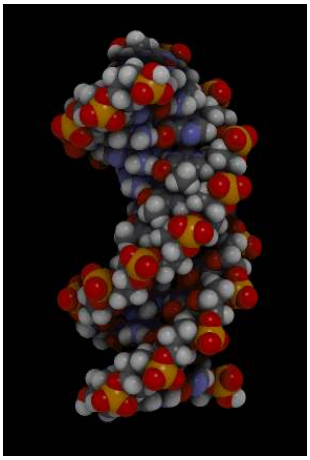


Figure **2.8.4**: DNA molecule

## ROLES OF NUCLEIC ACIDS

The DNA of cells is organized into structures called chromosomes as shown in Figure **2.8.5**. The letters A, T, G, and C stand for the bases adenine, thymine, guanine, and cytosine. The sequence of these four bases in DNA is a code that carries instructions for making proteins. The DNA helix is wrapped around proteins called histones to form nucleosomes. These are then further structured into chromatin and, finally, chromosomes. Human cells have 46 chromosomes; other organisms have different numbers of chromosomes.

DNA makes up genes, and the sequence of bases in DNA makes up the genetic code. Between "starts" and "stops," the code carries instructions for the correct sequence of amino acids in a protein. The information in DNA is passed from parent cells to daughter cells whenever cells divide. The information in DNA is also passed from

parents to offspring when organisms reproduce. This is how inherited characteristics are passed from one generation to the next.

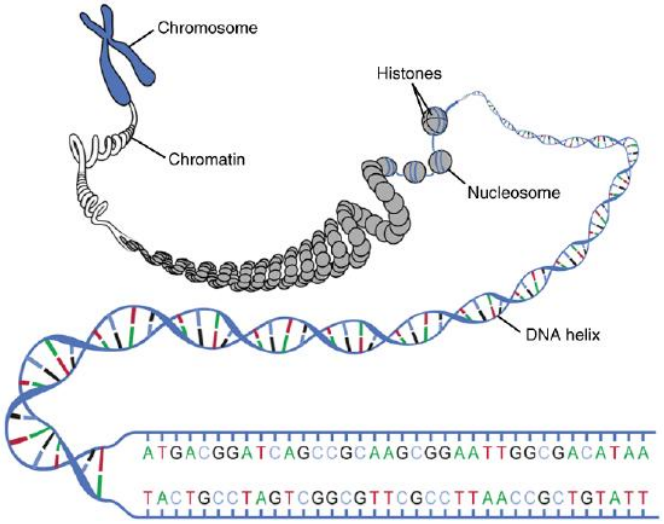



Figure **2.8.5**: The organization of a chromosome

## FEATURE: HUMAN BIOLOGY IN THE NEWS

Look at the Neanderthals in Figure **2.8.6**. The image is an artist's reconstruction of these close human relatives, who seem to have disappeared from Europe some 50,000 years ago. The consensus that Neandertals were brutish and went extinct when overtaken by modern humans is undergoing revision as we learn more about these interesting members of the genus *Homo*.



Figure **2.8.6**: Neanderthals were stocky and barrel-chested, but DNA evidence shows that they mated with modern humans thousands of years ago.

Several years ago, scientists were able to extract DNA from fossilized bones of Neanderthals (see Figure **2.8.7**). When the Neanderthal DNA was compared with modern human DNA, researchers discovered similarities in the DNA of Neanderthals and modern European-derived peoples that suggest modern humans mated with Neanderthals. Some experts now think that Neanderthals didn't go extinct but were simply incorporated into the much larger population of *Homo sapiens*.



Figure **2.8.7**. A scientist works to extract DNA from a fossilized Neanderthal bone

New research published in *Science* early in 2016 shows that our inherited Neanderthal DNA may be more than just an interesting curiosity or useful evidence of our evolutionary past. These bits of DNA may actually be affecting our health today. In the research reported in *Science*, scientists looked for Neanderthal DNA sequences in the DNA from an electronic database compiled from health records of almost 30,000 modern American adults. The scientists found that certain segments of Neanderthal DNA are especially common in people who have particular medical conditions, such as depression and increased amounts of blood clotting. Other bits of Neanderthal DNA seems to boost the immune response to certain parasites and other pathogens.

Most of the Neanderthal DNA segments that have persisted into our modern gene pool were probably beneficial in prehistoric times. Now, however, they may increase the risk of disease because our lifestyles and environments have changed so much since then. For example, an increase in blood clotting would have helped prevent life-threatening bleeding from injuries or childbirth in the past, but today it may increase the risk of blood clots and strokes in older people with sedentary lifestyles. Even immune-boosting bits of Neanderthal DNA may now do more harm than good for Americans who live in environments where there are far fewer parasites. They may make our immune systems overactive and cause allergies and autoimmune disorders.

## REVIEW

1. What are the nucleic acids?
2. How does RNA differ in structure from DNA?
3. Describe a nucleotide. Explain how nucleotides bind together to form a polynucleotide.
4. What role do nitrogen bases in nucleotides play in the structure and function of DNA?
5. What is the role of RNA?
6. Explain why Mark and Scott Kelly look so similar, using what you learned about nucleic acids in this article.
7. *True or False.* A, C, G, and T represent the bases in RNA.
8. *True or False.* The two polynucleotide chains of RNA twist into a double helix shape.
9. *True or False.* Cytosine always binds to guanine in DNA.
10. If part of a chain of DNA has the sequence of bases: ATTG, what is the corresponding sequence of bases that it binds to on the other chain?

11. Arrange the following in order from the smallest to the largest level of organization: DNA; nucleotide; polynucleotide
12. As part of the DNA replication process, the two polynucleotide chains are separated from each other, but each individual chain remains intact. Which bonds are broken in this process?
    A. Bonds between adjacent sugars and phosphate groups
    B. Bonds within nucleotides
    C. Bonds between complementary bases
    D. Bonds between adenine and guanine
13. Adenine, guanine, cytosine, and thymine are:
    A. Nucleotides
    B. Nitrogenous bases
    C. Sugars in DNA and RNA
    D. Phosphate groups
14. Some diseases and disorders are caused by genes. Explain why these genetic disorders can be passed down from parents to their children.

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# 2.9: ENERGY IN CHEMICAL REACTIONS

## SLOW BURN

These old iron chains give off a small amount of heat as they rust. The rusting of iron is a chemical process. It occurs when iron and oxygen undergo a chemical reaction similar to burning or combustion. The chemical reaction that occurs when something burns gives off energy. You can feel the heat, and you may be able to see the light of flames. The rusting of iron is a much slower process, but it still gives off energy. It's just that it releases energy so slowly you can't detect a temperature change.



Figure **2.9.1**: Rusty chain

## WHAT IS A CHEMICAL REACTION?

A **chemical reaction** is a process that changes some chemical substances into others. A substance that starts a chemical reaction is called a **reactant,** and a substance that forms as a result of a chemical reaction is called a **product.** During the reaction, the reactants are used to create the products.

Another example of a chemical reaction is the burning of methane gas, shown in Figure **2.9.2**. In this chemical reaction, the reactants are methane ($CH_4$) and oxygen ($O_2$), and the products are carbon dioxide ($CO_2$) and water ($H_2O$). As this example shows, a chemical reaction involves the breaking and forming of chemical bonds. Chemical bonds are forces that hold together the atoms of a molecule. Bonds occur when atoms share electrons. When methane burns, for example, bonds break within the methane and oxygen molecules, and new bonds form in the molecules of carbon dioxide and water.



Figure **2.9.2**: Flames from methane burning

## CHEMICAL EQUATIONS

Chemical reactions can be represented by chemical equations. A **chemical equation** is a symbolic way of showing what happens during a chemical reaction. For example, the burning of methane can be represented by the chemical equation:

$$CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O \qquad (2.9.1)$$

The arrow in a chemical equation separates the reactants from the products and shows the direction in which the reaction proceeds. If the reaction could occur in the opposite direction as well, two arrows pointing in opposite directions would be used. The number 2 in front of $O_2$ and $H_2O$ shows that two oxygen molecules and two water molecules are involved in the reaction. If just one molecule is involved, no number is placed in front of the chemical symbol.

## ROLE OF ENERGY IN CHEMICAL REACTIONS

Matter rusting or burning are common examples of chemical changes. Chemical changes involve chemical reactions in which some substances, called reactants, change at the molecular level to form new substances, called products. All chemical reactions involve energy. However, not all chemical reactions release energy, as rusting and burning do. In some chemical reactions, energy is absorbed rather than released.

### EXERGONIC REACTIONS

A chemical reaction that releases energy is called an **exergonic reaction**. This type of reaction can be represented by a general chemical equation:

$$\text{Reactants} \rightarrow \text{Products} + \text{Energy} \qquad (2.9.2)$$

Besides rusting and burning, examples of exothermic reactions include chlorine combining with sodium to form table salt. The decomposition of organic matter also releases energy because of exergonic reactions. Sometimes, on a chilly morning, you can see steam rising from a compost pile because of these chemical reactions (see Figure **2.9.3**). Exergonic chemical reactions also take place in the cells of living things. In a chemical process similar to combustion, called cellular respiration, the sugar glucose is "burned" to provide cells with energy.



Figure **2.9.3**: This compost pile is steaming because it is much warmer than the chilly air around it. The heat comes from all the exothermic chemical reactions taking place inside the compost as it decomposes.

## ENDERGONIC REACTIONS

A chemical reaction that absorbs energy is called an **endergonic reaction**. This type of reaction can also be represented by a general chemical equation:

$$\text{Reactants} + \text{Energy} \rightarrow \text{Products} \qquad (2.9.3)$$

Did you ever use a chemical cold pack like the one in the picture below? The pack cools down because of an endergonic reaction. When a tube inside the pack is broken, it releases a chemical that reacts with water inside the pack. This reaction absorbs heat energy and quickly cools down the contents of the pack.




Figure **2.9.4**: This pack gets cold due to an endergonic reaction

Many other chemical processes involve endergonic reactions. For example, most cooking and baking involve the use of energy to produce chemical reactions. You can't bake a cake or cook an egg without adding heat energy. Arguably, the most important endergonic reactions occur during photosynthesis. When plants produce sugar by photosynthesis, they take in light energy to power the necessary endergonic reactions. The sugar they produce provides plants and virtually all other living things with glucose for cellular respiration.

## ACTIVATION ENERGY

All chemical reactions need energy to get started. Even reactions that release energy need a boost of energy in order to begin. The energy needed to start a chemical reaction is called **activation energy**. Activation energy is like the push a child needs to start going down a playground slide. The push gives the child enough energy to start moving, but once she starts, she keeps moving without being pushed again. Activation energy is illustrated in Figure **2.9.5**.

Why do all chemical reactions need energy to get started? In order for reactions to begin, reactant molecules must bump into each other, so they must be moving, and movement requires energy. When reactant molecules bump together, they may repel each other because of intermolecular forces pushing them apart. Overcoming these forces so the molecules can come together and react also takes energy.

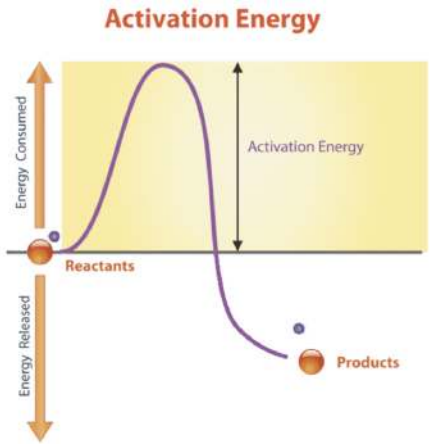



Figure **2.9.5**: This diagram of activation energy shows the reactants on the far left and the products on the right. Notice that the reactants are at a higher energy level than the products, so this reaction releases energy overall. But the reaction consumes energy to get started - this is the activation energy for the reaction.

## REVIEW

1. What is a chemical reaction?
2. Identify reactants and products in a chemical reaction.
3. List three examples of common changes that involve chemical reactions.
4. Define a chemical bond.
5. What is a chemical equation? Give an example.
6. Our cells use glucose ($C_6H_{12}O_6$) to obtain energy in a chemical reaction called cellular respiration. In this reaction, six oxygen molecules ($O_2$) react with one glucose molecule. Answer the following questions about this reaction.
   A. How many oxygen atoms are in one molecule of glucose?
   B. Write out what the reactant side of this equation would look like.
   C. How many oxygen atoms are in the reactants in total? Explain how you calculated your answer.
   D. How many oxygen atoms are in the products in total? Is it possible to answer this question without knowing what the products are? Why or why not?
7. Answer the following questions about the equation you saw above: $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$
   A. Can carbon dioxide ($CO_2$) become transformed into methane ($CH_4$) and oxygen ($O_2$) in this reaction? Why or why not?

B. How many molecules of carbon dioxide ($CO_2$) are produced in this reaction?

8. Is the evaporation of liquid water into water vapor a chemical reaction? Why or why not
9. Why do bonds break in the reactants during a chemical reaction?
10. Contrast endergonic and exergonic chemical reactions. Give an example of each.
11. Define activation energy.
12. Explain why all chemical reactions require activation energy.
13. Heat is a form of _____ .
14. In which type of reaction is heat added to the reactants?
15. In which type of reaction is heat produced?
16. If there was no heat energy added to an endothermic reaction, would that reaction occur? Why or why not?
17. If there was no heat energy added to an exothermic reaction, would that reaction occur? Why or why not?
18. Explain why a chemical cold pack feels cold when activated.
19. Explain why cellular respiration and photosynthesis are “opposites” of each other.
20. Explain how the sun indirectly gives our cells energy.

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# 2.10: CHEMICAL REACTIONS IN LIVING THINGS

## ASSEMBLY LINE

We stay alive because millions of different chemical reactions are taking place inside our bodies all the time. Each of our cells is like the busy auto assembly line pictured here. Raw materials, half-finished products, and waste materials are constantly being used, produced, transported, and excreted. The "workers" on the cellular assembly line are mainly enzymes. These are the proteins that make biochemical reactions happen.



Figure **2.10.1**: Assembly line

## WHAT ARE BIOCHEMICAL REACTIONS?

Chemical reactions that take place inside living things are called **biochemical reactions.** The sum of all the biochemical reactions in an organism is referred to as **metabolism**. Metabolism includes both exothermic (heat-releasing) chemical reactions and endothermic (heat-absorbing) chemical reactions.

### CATABOLIC REACTIONS

Exergonic reactions in organisms are called **catabolic reactions**. These reactions break down molecules into smaller units and release energy. An example of a catabolic reaction is the breakdown of glucose during cellular respiration, which releases energy that cells need to carry out life processes.

### ANABOLIC REACTIONS

Endergonic reactions in organisms are called **anabolic reactions**. These reactions absorb energy and build bigger molecules from smaller ones. An example of an anabolic reaction is the joining of amino acids to form a protein. Which type of reactions — catabolic or anabolic — do you think occur when your body digests food?

## ENZYMES

Most biochemical reactions in organisms need help in order to take place. Why is this the case? For one thing, temperatures are usually too low inside living things for biochemical reactions to occur quickly enough to maintain life. The concentrations of reactants may also be too low for them to come together and react. Where do the biochemical reactions get the help they need to proceed? The help comes from enzymes.

An **enzyme** is a protein that speeds up a biochemical reaction. It is a biological catalyst. An enzyme generally works by reducing the amount of activation energy needed to start the reaction. Figure **2.10.2** shows the activation energy needed for glucose to combine with oxygen to produce carbon dioxide and water. The overall reaction releases energy, but an initial activation energy is needed to start the process. The activation energy without an enzyme is much higher than the activation energy when an enzyme is used.

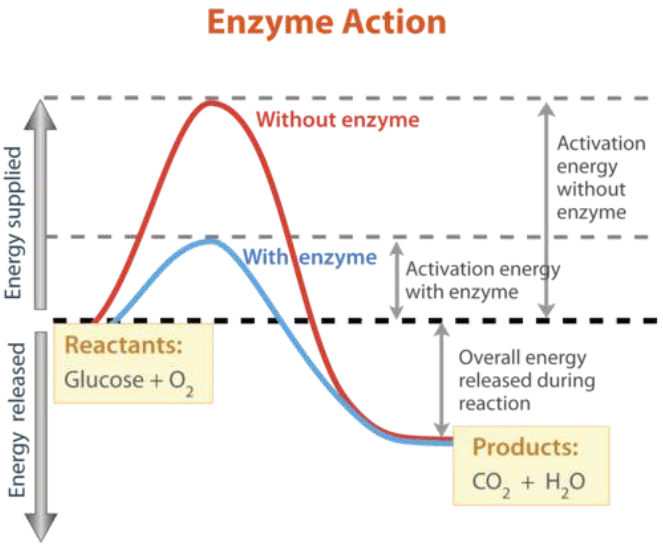



Figure **2.10.2**: Enzyme Action. This graph shows what happens when glucose combines with oxygen. An enzyme speeds up the reaction by lowering the activation energy. Compare the activation energy needed with and without the enzyme.

### HOW WELL ENZYMES WORK

Enzymes are involved in most biochemical reactions, and they do their jobs extremely well. A typical biochemical reaction that would take several days or even several centuries to occur without an enzyme is likely to occur in just a split second with the proper enzyme! Without enzymes to speed up biochemical reactions, most organisms could not survive. Enzymes are substrate-specific. The substrate of an enzyme is the specific substance it affects (Figure **2.10.3**). Each enzyme works only with a particular substrate, which explains why there are so many different enzymes. In addition, for an enzyme to work, it requires specific conditions, such as just the right temperature and pH. Some enzymes work best under acidic conditions, for example, while others work best in neutral environments.

### ENZYME-DEFICIENCY DISORDERS

There are hundreds of known inherited metabolic disorders in humans. In most of them, a single enzyme is either not produced by the body at all or is produced in a form that doesn't work. The missing or defective enzyme is like an absentee worker on the cell's assembly line. The absence of the normal enzyme means that toxic chemicals build-up or an essential product isn't made. Generally, the normal enzyme is missing because the individual with the disorder

inherited two copies of a gene mutation, which may have occurred originally many generations in the past.

Any given inherited metabolic disorder is generally quite rare in the general population. However, there are so many different metabolic disorders that a total of 1 in 1,000 to 2,500 newborns can be expected to have one. In certain ethnic populations, such as Ashkenazi Jews (Jews of central and eastern European ancestry), the rate of certain inherited metabolic disorders is much higher.

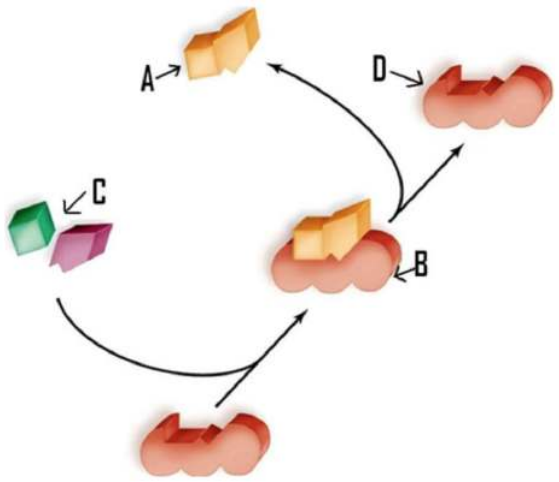



Figure **2.10.3**: The figure shows how enzymes convert substrates into products. the substrate (A) binds at the activation site of the enzyme(D) and makes a substrate-enzyme complex (B). Then, the enzyme converts the substrate into the product (C) by breaking or making bonds between the atoms of the substrate.

### FEATURE: RELIABLE SOURCES

The most common of all known enzyme-deficiency disorders is glucose-6-phosphate-dehydrogenase, or G6PD, deficiency. In the U.S., the disorder occurs most often in African-American males. The enzyme G6PD is needed to prevent the abnormal breakdown of red blood cells. Without the enzyme, red blood cells break down prematurely and anemia results.

Choose one of the following topics about G6PD deficiency:

- genetic basis
- signs and symptoms
- diagnosis and treatment
- worldwide distribution

For the topic, you chose, go online to learn more about it. Find at least three sources of additional information that you think are reliable. Compare the information provided by the different sources, and identify any discrepancies among them. Do additional online research as needed to try to find a reliable consensus view of the discrepant issue.

## REVIEW

1. What are biochemical reactions?
2. Define metabolism.
3. Compare and contrast catabolic and anabolic reactions.
4. Explain the role of enzymes in biochemical reactions.
5. What are enzyme-deficiency disorders?
6. True or False. Metabolism is one specific type of catabolism.
7. True or False. Biochemical reactions include catabolic and anabolic reactions.
8. Explain why the relatively low temperature of living things, as well as the low concentration of reactants, would cause biochemical reactions to occur very slowly in the body without enzymes.
9. Answer the following questions about what happens after you eat a sandwich.
   A. Pieces of the sandwich go into your stomach, where there are digestive enzymes that break down the food. Which type of metabolic reaction is this? Explain your answer.
   B. Through the process of digestion, part of the sandwich is broken down to glucose, which is then further broken down to release energy that your cells can use. Is this an exergonic or endergonic reaction? Explain your answer.
   C. The proteins in the cheese, meat, and bread in the sandwich are broken down into their component amino acids. Then your body uses those amino acids to build new proteins. Which kind of metabolic reaction is represented by the building of these new proteins? Explain your answer.
10. Explain why your body doesn't just use one or two enzymes for all of its biochemical reactions.
11. What is the specific substance that enzyme affects in a biochemical reaction called?
12. An enzyme is a biological
    A. catabolism
    B. form of activation energy
    C. catalyst
    D. reactant

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# 2.11: BIOCHEMICAL PROPERTIES OF WATER

## THE BLUE MARBLE

It's often called the "water planet," and it's been given the nickname "the blue marble." You probably just call it "home." Almost three-quarters of our home planet is covered by water, and without it, life as we know it could not exist on Earth. Water, like carbon, has a special role in living things. It is needed by all known forms of life. Although water consists of simple molecules, each containing just three atoms, its structure gives it unique properties that help explain why it is vital to all living organisms.



Figure **2.11.1**: Planet Earth

## CHEMICAL STRUCTURE AND PROPERTIES OF WATER

You are probably already familiar with many of the water's properties. For example, you no doubt know that water is tasteless, odorless, and transparent. In small quantities, it is also colorless. However, when a large amount of water is observed, as in a lake or the ocean, it is actually light blue in color. The blue hue of the water is an intrinsic property and is caused by selective absorption and scattering of white light. These and other properties of water depend on its chemical structure.

The transparency of water is important for organisms that live in water. Because water is transparent, sunlight can pass through it. Sunlight is needed by water plants and other water organisms for photosynthesis.

### CHEMICAL STRUCTURE OF WATER

Each molecule of water consists of one atom of oxygen and two atoms of hydrogen, so it has the chemical formula $H_2O$. The arrangement of atoms in a water molecule, shown in Figure **2.11.2**, explains many of the water's chemical properties. In each water molecule, the nucleus of the oxygen atom (with 8 positively charged protons) attracts electrons much more strongly than the hydrogen nuclei (with only one positively charged proton). This results in a negative electrical charge near the oxygen atom (due to the "pull" of the negatively charged electrons toward the oxygen nucleus) and a positive electrical charge near the hydrogen atoms. A difference in electrical charge between different parts of a molecule is called **polarity**. A **polar molecule** is a molecule in which part of the molecule is positively charged, and part of the molecule is negatively charged.

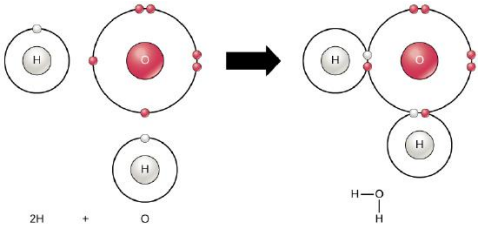



Figure **2.11.2**: This model is an atomic diagram of water, showing the two hydrogen atoms and an oxygen atom in the center.

### WATER IS A GOOD SOLVENT

Water is considered a very good solvent in biochemical reactions. Figure **2.11.3** illustrates how water dissolves salts. Table salt (NaCl) consists of a positively charged sodium ion and a negatively charged chloride ion. The oxygen of water is attracted to the positive Na ion. The hydrogens of water are attracted to the negative Cl ion.

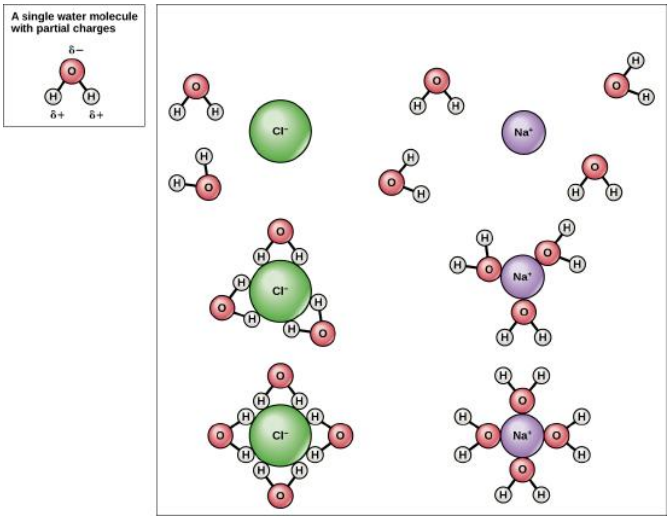



Figure **2.11.3**: This diagram shows the positive and negative parts of a water molecule. It also depicts how a charge, such as on an ion (Na or Cl, for example) can interact with a water molecule.

### HYDROGEN BONDING

Opposite electrical charges attract one another. Therefore, the positive part of one water molecule is attracted to the negative parts of other water molecules. Because of this attraction, bonds form between hydrogen and oxygen atoms of adjacent water molecules, as demonstrated in Figure **2.11.4**. This type of bond always involves a hydrogen atom, so it is called a **hydrogen bond**.

Hydrogen bonds can also form within a single large organic molecule. For example, hydrogen bonds that form between different parts of a protein molecule bend the molecule into a distinctive shape, which is important for the protein's functions. Hydrogen bonds also hold together the two nucleotide chains of a DNA molecule.

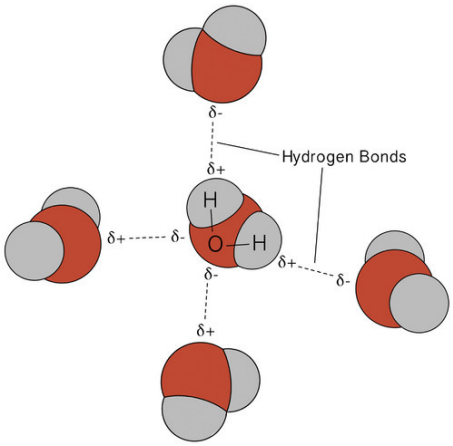



Figure **2.11.4**: Hydrogen bonds form between positively and negatively charged parts of water molecules. The bonds hold the water molecules together. How do you think this might affect water's properties?

## STICKY, WET WATER

Water has some unusual properties due to its hydrogen bonds. One property is **cohesion**, the tendency for water molecules to stick together. The cohesive forces between water molecules are responsible for the phenomenon known as **surface tension**. The molecules at the surface do not have other like molecules on all sides of them, and consequently, they cohere more strongly with those directly associated with them on the surface. For example, if you drop a tiny amount of water onto a very smooth surface, the water molecules will stick together and form a droplet rather than spread out over the surface. The same thing happens when water slowly drips from a leaky faucet. The water doesn't fall from the faucet as individual water molecules but as droplets of water. The tendency of water to stick together in droplets is also illustrated by the dew drops in Figure **2.11.5**.



Figure **2.11.5**: Droplets of dew cling to a spider web, demonstrating cohesion, the tendency of water molecules to stick together because of hydrogen bonds.

Another important physical property of water is **adhesion**. In terms of water, adhesion is the bonding of a water molecule to another substance, such as the sides of a leaf's veins. This process happens because hydrogen bonds are special in that they break and reform with great frequency. This constant rearranging of hydrogen bonds allows a percentage of all the molecules in a given sample to bond to another substance. This grip-like characteristic that water molecules form causes **capillary action**, the ability of a liquid to flow against gravity in a narrow space. An example of capillary action is when you place a straw into a glass of water. The water seems to climb up the straw before you even place your mouth on the straw. The water has created hydrogen bonds with the surface of the straw, causing the water to adhere to the sides of the straw. As the hydrogen bonds keep interchanging with the straw's surface, the water molecules interchange positions, and some begin to ascend the straw.

Adhesion and capillary action are necessary to the survival of most organisms. It is the mechanism that is responsible for water transport in plants through roots and stems, and in animals through small blood vessels.

Hydrogen bonds also explain why water's boiling point (100°C) is higher than the boiling points of similar substances without hydrogen bonds. Because of water's relatively high boiling point, most water exists in a liquid state on Earth. Liquid water is needed by all living organisms. Therefore, the availability of liquid water enables life to survive over much of the planet.

Furthermore, water has a high specific heat because it takes a lot of energy to raise or lower the temperature of the water. As a result, water plays a very important role in temperature regulation. Since cells are made up of water, this property helps to maintain homeostasis.

## THE DENSITY OF ICE AND WATER

The **melting point** of water is 0°C. Below this temperature, water is a solid (ice). Unlike most chemical substances, water in a solid state has a lower density than water in a liquid state. This is because water expands when it freezes. Again, hydrogen bonding is the reason. Hydrogen bonds cause water molecules to line up less efficiently in ice than in liquid water. As a result, water molecules are spaced farther apart in ice, giving ice a lower density than liquid water. A substance with lower density floats on a substance with higher density. This explains why ice floats on liquid water, whereas many other solids sink to the bottom of liquid water.

In a large body of water, such as a lake or the ocean, the water with the greatest density always sinks to the bottom. Water is most dense at about 4°C. As a result, the water at the bottom of a lake or the ocean usually has a temperature of about 4°C. In climates with cold winters, this layer of 4°C water insulates the bottom of a lake from freezing temperatures. Lake organisms such as fish can survive the winter by staying in this cold but unfrozen water at the bottom of the lake.

## REVIEW

1. Describe the structure of a water molecule. What is polarity, and why is water polar?
2. Explain how the internal polarity of the water molecule makes it a good solvent.
3. Explain how hydrogen bonds cause molecules of liquid water to stick together.
4. What is capillary action? Give an example.
5. What property of water helps to maintain homeostasis and how?

## EXPLORE MORE

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# 2.12: ACIDS AND BASES

## DANGER! BATTERY ACID!

You probably know that car batteries like this one contain dangerous chemicals such as strong acids. Strong acids can hurt you if they come into contact with your skin or eyes. Therefore, it may surprise you that your life depends on acids. Many acids are inside your body, and some are as strong as battery acid. Acids are needed for digestion and some forms of energy production. Genes are made of nucleic acids, proteins of amino acids, and lipids of fatty acids.



Figure **2.12.1**: Car battery

## WATER AND SOLUTIONS

Acids such as battery acid are solutions. A **solution** is a mixture of two or more substances with the same composition. Many solutions are a mixture of water and some other substance. Not all solutions are acids. Some are bases, and some are neither acids nor bases. You need to know more about pure water to understand acids and bases.

In pure water (such as distilled water), a tiny fraction of water molecules naturally breaks down to form ions. An ion is an electrically charged atom or molecule. The chemical equation represents the breakdown of water:

$$2H_2O \rightarrow H_3O^+ + OH^- \qquad (2.12.1)$$

The products of this reaction are a hydronium ion ($H_3O^+$) and a hydroxide ion ($OH^-$). The hydroxide ion, which has a negative charge, forms when a water molecule gives up a positively charged hydrogen ion ($H^+$). The hydronium ion, which has a positive charge, forms when another water molecule accepts the hydrogen ion.

## ACIDITY AND PH

The concentration of hydronium ions in a solution is known as **acidity.** The concentration of hydronium ions in pure water is very low; only about 1 in 10 million water molecules naturally breaks down to form a hydronium ion. As a result, pure water is essentially neutral. Acidity is measured on a scale called **pH**. Pure water has a pH of 7, so the point of neutrality on the pH scale is 7.

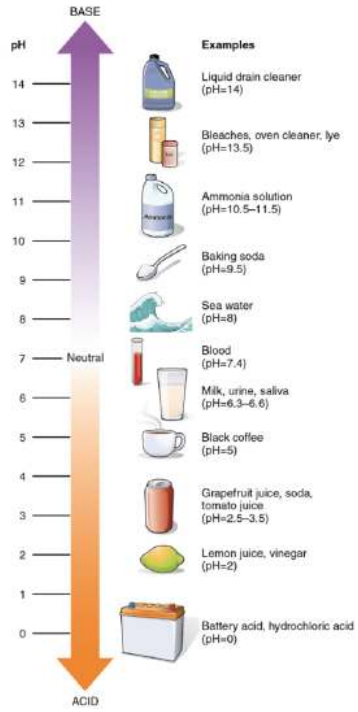



Figure **2.12.2**: This pH scale shows the acidity of many common substances. The lower the pH value, the more acidic a substance is.

**Examples of pH**

- Liquid drain cleaner has a pH = 14
- Bleaches, oven cleaner, lye have a pH = 13.5
- Ammonia solution has a pH = 10.5 - 11.5
- Baking soda has a pH = 9.5
- Sea water has a pH = 8
- Blood has a pH = 7.4
- Milk, urine, saliva have a pH = 6.3 - 6.6
- Black coffee has a pH = 5
- Grapefruit juice, soda, and tomato juice have a pH = 2.5 - 3.5
- Lemon juice, vinegar have a pH = 2
- Battery acid, hydrochloric acid have a pH = 0

### ACIDS

A solution with a higher concentration of hydronium ions than pure water has a pH lower than 7. A solution with a pH lower than 7 is called an **acid**. As the hydronium ion concentration increases, the pH value decreases. Therefore, the more acidic a solution is, the lower its pH value is. Did you ever taste vinegar? Like other acids, it tastes sour. Stronger acids can be harmful to organisms. For example, stomach acid would eat through the stomach if not lined with a layer of mucus. Strong acids can also damage materials, even hard materials such as glass.

### BASES

A solution with a lower concentration of hydronium ions than pure water has a pH higher than 7. This solution is called a **base**. Bases, such as baking soda, have a bitter taste. Like strong acids, strong

bases can harm organisms and damage materials. For example, lye can burn the skin, and bleach can remove the color from clothing.

## ACIDS, BASES, AND ENZYMES

Many acids and bases in living things provide the pH that enzymes need. Enzymes are biological catalysts that must work effectively for biochemical reactions to occur. Most enzymes can do their job only at a certain level of acidity. Cells secrete acids and bases to maintain the proper pH for enzymes to do their work.

Every time you digest food, acids, and bases work in your digestive system. Consider the enzyme pepsin, which helps break down proteins in the stomach. Pepsin needs an acidic environment to do its job. The stomach secretes the hydrochloric acid that allows pepsin to work. When stomach contents enter the small intestine, the acid must be neutralized. This is because enzymes in the small intestine need a basic environment to work. An organ called the pancreas secretes a base named bicarbonate into the small intestine, and this base neutralizes the acid.

### FEATURE: MY HUMAN BODY

Do you ever have heartburn? The answer is probably "yes." More than 60 million Americans have heartburn at least once a month, and more than 15 million suffer from it daily. Knowing more about heartburn may help you prevent it or know when to seek medical treatment.

Heartburn doesn't have anything to do with the heart, but it does cause a burning sensation in the vicinity of that organ. Normally, the acid secreted into the stomach remains in the stomach where it is needed to allow pepsin to do its job of digesting proteins. A long tube called the esophagus carries food from the mouth to the stomach. A sphincter, or valve, between the esophagus and stomach, opens to allow swallowed food to enter the stomach. Then, it closes to prevent stomach contents from flowing back into the esophagus. If this sphincter is weak or relaxes inappropriately, stomach contents flow into the esophagus. Because stomach contents are usually acidic, this causes a burning sensation known as heartburn. People who are prone to heartburn and suffer from it often may be diagnosed with GERD, which stands for gastroesophageal reflux disease.

GERD—as well as occasional heartburn—can often be improved by dietary and other lifestyle changes that decrease the amount and acidity of reflux from the stomach into the esophagus.

- Some foods and beverages seem to contribute to GERD, so these should be avoided. They include chocolate, fatty foods, peppermint, coffee, and alcoholic beverages.
- Decreasing portion size and eating the last meal of the day at least a couple of hours before bedtime may reduce the risk of reflux.
- Smoking weakens the lower esophageal sphincter, so quitting the habit may help control reflux.
- GERD is often associated with being overweight, and losing weight brings improvement.
- Some people are helped by sleeping with the head of the bed elevated. This allows gravity to help control the backflow of acids from the stomach into the esophagus.

## REVIEW

1. What is the solution?
2. Define acidity.
3. Explain how acidity is measured.
4. Compare and contrast acids and bases.
5. The stomach secretes hydrochloric acid to provide an acidic environment for the enzyme pepsin. What is the pH of this acid? How strong of an acid is it compared with other acids?
6. *True or False*. Strong bases are gentle and cannot hurt you, unlike strong acids.
7. *True or False*. The lower the pH, the higher the concentration of hydronium ions.
8. Define an ion.
9. Identify the ions in the following equation and explain why they are ions:

$$2H_2O \rightarrow H_3O^+ + OH^- \qquad (2.12.2)$$

10. Explain why the pancreas secretes bicarbonate into the small intestine.
11. Do you think pepsin would work in the small intestine? Why or why not?
12. How does the pH of the stomach compare to the small intestine? It is
    A. the same as
    B. not as important as the pH of
    C. higher than
    D. lower than
13. You may have mixed vinegar and baking soda and noticed that they bubble and react with each other.
    A. Explain why this happens.
    B. Explain what happens to the pH of this solution after you mix the vinegar and baking soda.
14. Pregnancy hormones can cause the lower esophageal sphincter to relax. What effect do you think this has on pregnant women? Explain your answer.

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# 2.13: CASE STUDY CONCLUSION- DIET AND CHAPTER SUMMARY

## CASE STUDY CONCLUSION: DIET DILEMMA

After reading this chapter, you should be able to see numerous connections between chemistry, human life, and health. In Mohinder's situation, chemistry is involved in the reasons why their father has diabetes, why their personal risk of getting diabetes is high, and the different dietary changes they are considering.



Figure **2.13.1**: Fruits and yogurt

For instance, type 2 diabetes is caused mainly by a lack of response in the body to the hormone insulin, which causes problems in the regulation of blood sugar, or glucose. Insulin is a peptide hormone, and as you have learned, peptides are chains of amino acids. Therefore, insulin is in the class of biochemical compounds called proteins. Mohinder is at increased risk of diabetes partly because there is a genetic component to the disease. DNA, which is a type of chemical compound called a nucleic acid, is passed down from parents to their offspring and carries the instructions for the production of proteins in units called genes. If there is a problem in a gene (or genes) that contributes to the development of a disease, such as type 2 diabetes, this can get passed down to the offspring and may raise that child's risk of getting the disease.

But genetics is only part of the reason why Mohinder is at an increased risk of diabetes. Obesity itself is a risk factor and one that can be shared in families due to shared lifestyle factors such as poor diet and lack of exercise, in addition to genetics. Consumption of too many refined carbohydrates, such as white bread and soda, also may contribute to obesity and the development of diabetes. As you probably now know, these simple carbohydrates are more easily and quickly broken down in the digestive system to glucose than larger complex carbohydrate molecules, such as those found in vegetables and whole grains. This can lead to dramatic spikes in blood sugar levels, which is particularly problematic for people with diabetes because they have trouble maintaining their blood sugar at a safe level. You can understand why Mohinder's father limits the consumption of refined carbohydrates, and in fact, some scientific studies have shown that avoiding refined carbohydrates may actually help reduce the risk of getting diabetes in the first place.

Mohinder's friend recommended eating a low fat and high carbohydrate diet to lose weight, but you can see that which *type* of carbohydrate — simple or complex — is an important consideration. Eating lots of white bread and rice may not help Mohinder reduce their risk of diabetes! But a healthy diet that helps them lose weight may lower their risk of diabetes since obesity itself is a factor. Which specific diet will work best to help them lose weight probably depends on a variety of factors including their biology, lifestyle, and food preferences. Mohinder should consult with their doctor about their diet and exercise plan so that their specific situation can be taken into account and monitored by a medical professional.

Drinking enough water is usually good advice for everyone, especially if it replaces sugary drinks like soda. You now know that water is important for many of the chemical reactions that take place in the body.

Finally, you probably now realize that "chemicals" do not have to be scary, toxic substances. All matter consists of chemicals, including you, water, and healthy fresh fruits and vegetables, like the ones pictured above. When people advocate "clean eating" and avoiding "chemicals" in food, they are usually referring to avoiding synthetic, or man-made, chemical additives such as preservatives. This can be a healthy way to eat because it involves eating a variety of whole, fresh, unprocessed foods. But there is no reason to be scared of chemicals in general – they are simply molecules and how they react depends on what they are, what other molecules are present, and the environmental conditions surrounding them.

## CHAPTER SUMMARY

By now, you should have a good understanding of the basics of the chemistry of life. Specifically, you have learned:

- All matter consists of chemical substances. A chemical substance has a definite and consistent composition and may be either an element or a compound.
- An element is a pure substance that cannot be broken down into other types of substances.
  - An atom is the smallest particle of an element that still has the properties of that element. Atoms, in turn, are composed of subatomic particles, including negative electrons, positive protons, and neutral neutrons. The number of protons in an atom determines the element it represents.
  - Atoms have equal numbers of electrons and protons so they have no charge. Ions are atoms that have lost or gained electrons so they have either a positive or negative charge. Atoms with the same number of protons but different numbers of neutrons are called isotopes.
  - There are almost 120 known elements. The majority of the elements are metals. A smaller number are nonmetals, including carbon, hydrogen, and oxygen.
- A compound is a substance that consists of two or more elements in a unique composition. The smallest particle of a compound is called a molecule. Chemical bonds hold together the atoms of molecules. We discussed four types of bonds, polar covalent bond, hydrogen bond, non-polar covalent bond, and ionic bond.

- In an ionic bond, an atom gives away one or more electrons to another atom.
- In a covalent bond, two atoms share one or more electrons. The equal sharing of electrons gives rise to a non- polar covalent bond, and unequal sharing of electrons gives rise to a polar covalent bond.
- The polar molecules make hydrogen bonds between them and within themselves.
- A chemical bond is a force of attraction between atoms or ions. Bonds form when atoms share or transfer valence electrons.
- Atoms form chemical bonds to achieve a full outer energy level, which is the most stable arrangement of electrons.

- Compounds can form only in chemical reactions, and they can break down only in other chemical reactions.
- Biochemical compounds are carbon-based compounds found in living things. They make up cells and other structures of organisms and carry out life processes. Most biochemical compounds are large molecules called polymers that consist of many repeating units of smaller molecules called monomers.
- There are millions of different biochemical compounds, but all of them fall into four major classes: carbohydrates, lipids, proteins, and nucleic acids.
- Carbohydrates are the most common class of biochemical compounds. They provide cells with energy, store energy, and make up organic structures such as the cell walls of plants. The basic building block of carbohydrates is the monosaccharide.
  - Sugars are short-chain carbohydrates that supply us with energy. Simple sugars, such as glucose, consist of just one monosaccharide. Some sugars, such as sucrose, or table sugar, consist of two monosaccharides and are called disaccharides. Disaccharides are formed with the condensation reaction.
  - Complex carbohydrates, or polysaccharides, consist of hundreds or even thousands of monosaccharides. They include starch, glycogen, cellulose, and chitin.
    - Starch is made by plants to store energy and is readily broken down to its component sugars during digestion.
    - Glycogen is made by animals and fungi to store energy and plays a critical part in the homeostasis of blood glucose levels in humans.
    - Cellulose is the most common biochemical compound in living things. It forms the cell walls of plants and certain algae. Humans cannot digest cellulose, but it makes up most of the crucial dietary fiber in the human diet.
    - Chitin makes up organic structures such as the cell walls of fungi and the exoskeletons of insects and other arthropods.
- Lipids include fats and oils. They store energy, form cell membranes, and carry messages.
  - Lipid molecules consist mainly of repeating units called fatty acids. Fatty acids may be saturated or unsaturated, depending on the proportion of hydrogen atoms they contain. Animals store fat as saturated fatty acids; plants store fat as unsaturated fatty acids.
  - Types of lipids include triglycerides, phospholipids, and steroids.
    - Triglycerides contain glycerol (an alcohol) in addition to fatty acids. Humans and other animals store fat as triglycerides in fat cells.
    - Phospholipids contain phosphate and glycerol in addition to fatty acids. They are the main component of cell membranes in all living things.
    - Steroids are lipids with a four-ring structure. Some steroids, such as cholesterol, are important components of cell membranes. Many other steroids are hormones.
- Proteins include enzymes, antibodies, and numerous other important compounds in living things. They have many functions including helping cells keep their shape, making up muscles, speeding up chemical reactions, and carrying messages and materials.
  - Proteins are made up of small monomer molecules called amino acids.
  - A peptide bond is formed between two amino acids when they come together in a condensation synthesis reaction. Long chains of amino acids form polypeptides. The sequence of amino acids in polypeptides makes up the primary structure of proteins. Secondary structure refers to configurations such as helices and sheets within polypeptide chains. Tertiary structure is a protein's overall three-dimensional shape, which controls the molecule's basic function. A quaternary structure forms if multiple protein molecules join together and function as a complex.
  - The chief characteristic that allows proteins' diverse functions is their ability to bind specifically and tightly with other molecules.
- Nucleic acids include DNA and RNA. They encode instructions for making proteins, helping make proteins, and passing the encoded instructions from parents to offspring.
  - Nucleic acids are built of monomers called nucleotides, which bind together in long chains to form polynucleotides. DNA consists of two polynucleotides, and RNA consists of one polynucleotide.
  - Each nucleotide consists of a sugar molecule, phosphate group, and a nitrogen base. Sugars and phosphate groups of adjacent nucleotides bind together to form the "backbone" of the polynucleotide. Bonds between complementary bases hold together the two polynucleotide chains of DNA and cause it to take on its characteristic double helix shape.
  - DNA makes up genes, and the sequence of nitrogen bases in DNA makes up the genetic code for the synthesis of proteins. RNA helps synthesize proteins in cells. The genetic code in DNA is also passed from parents to offspring during

reproduction, explaining how inherited characteristics are passed from one generation to the next.

- A chemical reaction is a process that changes some chemical substances into others. A substance that starts a chemical reaction is called a reactant, and a substance that forms in a chemical reaction is called a product. During the chemical reaction, bonds break in reactants and new bonds form in products.
- Chemical reactions can be represented by chemical equations. According to the law of conservation of mass, mass is always conserved in a chemical reaction, so a chemical equation must be balanced, with the same number of atoms of each type of element in the products as in the reactants.
- Many chemical reactions occur all around us each day, such as iron rusting and organic matter rotting, but not all changes are chemical processes. Some changes, such as ice melting or paper being torn into smaller pieces, are physical processes that do not involve chemical reactions and the formation of new substances.
- All chemical reactions involve energy and need activation energy to begin. Exergonic reactions release energy. Endergonic reactions absorb energy.
- Biochemical reactions are chemical reactions that take place inside living things. The sum of all the biochemical reactions in an organism is referred to as metabolism. Metabolism includes catabolic reactions, which are exothermic reactions, and anabolic reactions, which are endothermic reactions.
- Most biochemical reactions need a biological catalyst called an enzyme to speed up the reaction by reducing the amount of activation energy needed for the reaction to begin. Most enzymes are proteins that affect just one specific substance, called the enzyme's substrate.
- Water is a polar molecule; therefore, water molecules make hydrogen bonds between them. Due to this property water exists as a liquid over a wide range of temperatures and dissolves many substances. These properties depend on water's polarity, which causes water molecules to "stick" together.
- Organisms need water to dissolve many substances and for most biochemical processes, including photosynthesis and cellular respiration.
- A solution is a mixture of two or more substances that has the same composition throughout. Many solutions consist of water and one or more dissolved substances.
- Acidity is a measure of the hydronium ion concentration in a solution. Pure water has a very low concentration and a pH of 7, which is the point of neutrality on the pH scale. Acids have a higher hydronium ion concentration than pure water and a pH lower than 7. Bases have a lower hydronium ion concentration than pure water and a pH higher than 7.
- Many acids and bases in living things are secreted to provide the proper pH for enzymes to work properly.

Now that you understand the chemistry of the molecules that make up living things, in the next chapter you will learn how these molecules make up the basic unit of structure and function in living organisms — cells — and will be able to understand some of the crucial chemical reactions that occur within cells.

## CHAPTER SUMMARY REVIEW

1. The four major classes of biochemical compounds are carbohydrates, lipids, proteins, and nucleic acids. For each of the substances below, identify which of these classes includes the substance.
   A. Enzymes
   B. Fructose
   C. DNA
   D. RNA
   E. Steroids
2. The chemical formula for the complex carbohydrate glycogen is C24H42O21.
   A. What are the elements in glycogen?
   B. How many atoms are in one molecule of glycogen?
   C. Is glycogen an ion? Why or why not?
   D. Is glycogen a monosaccharide or polysaccharide? Besides memorizing this fact, how would you know this based on the information in the question?
   E. What is the function of glycogen in the human body?
3. What is the difference between an ion and a polar molecule? Give an example of each in your explanation.
4. Define monomer and polymer.
5. For each of the following polymers, identify the name of its monomers.
   A. RNA
   B. Protein
   C. Complex carbohydrate
6. What is the difference between a protein and a polypeptide?
7. People with diabetes have trouble controlling the level of glucose in their bloodstream. Knowing this, why do you think it is often recommended that people with diabetes limit their consumption of carbohydrates?
8. Identify each of the following reactions as endergonic or exergonic.
   A. Cellular respiration
   B. Photosynthesis
   C. Catabolic reactions
   D. Anabolic reactions
9. Pepsin is an enzyme in the stomach that helps us digest protein. Answer the following questions about pepsin.
   A. What is the substrate for pepsin?
   B. How does pepsin work to speed the reaction of protein digestion?
   C. Given what you know about the structure of proteins, what do you think are some of the products of the reaction that pepsin catalyzes?
   D. The stomach is normally acidic. What do you think would happen to the activity of pepsin and the effect on protein

digestion if the pH is raised significantly?

10. What defines a neutral pH? What is the numerical value of a neutral pH?
11. *True or False.* Unsaturated fatty acids have straight chains.
12. *True or False.* The DNA code carries instructions for the correct sequence of nucleic acids in a protein.
13. *True or False.* Phospholipids make up cell membranes.
14. The function of proteins can include
    A. helping cells keep their shape
    B. helping to destroy foreign substances
    C. speeding up biochemical reactions
    D. all of the above
15. Which of the following is not part of a nucleotide?
    A. nitrogen base
    B. cellulose molecule
    C. sugar molecule
    D. phosphate group
16. The "push" needed to start a chemical reaction is the
    A. enzymatic energy
    B. endothermic energy
    C. activation energy
    D. reactant energy

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# CHAPTER OVERVIEW

## 3: CELL STRUCTURE AND FUNCTION

This chapter outlines the discovery of cells and cell theory. It identifies ways in which all cells are alike and ways in which they vary. The chapter describes in detail important cell structures and their functions; and it explains how cells obtain energy, grow, and divide.


3.1: Case Study- The Importance of Cells
3.2: Discovery of Cells and Cell Theory
3.3: Variation in Cells
3.4: Plasma Membrane
3.5: Cytoplasm and Cytoskeleton
3.6: Cell Organelles
3.7: Cell Transport
3.8: Active Transport and Homeostasis
3.9: Cellular Respiration
3.10: Fermentation
3.11: Case Study Conclusion- Tired and Chapter Summary
3.12: DNA and RNA
3.13: Chromosomes and Genes
3.14: Protein Synthesis
3.15: Genetic Code
3.16: Mutations
3.17: Regulation of Gene Expression
3.18: The Human Genome
3.19: Case Study Conclusion- Parmacogenomics and Chapter Summary
3.20: Case Study- Genetic Similarities and Differences
3.21: Cell Cycle and Cell Division
3.22: Mitotic Phase - Mitosis and Cytokinesis
3.23: Mutations and Cancer
3.24: Sexual Reproduction- Meiosis and gametogenesis
3.25: Genetic Variation
3.26: Mitosis vs. Meiosis and Disorders
3.27: Case Study Conclusion- Genes and Chapter Summary



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# 3.1: CASE STUDY- THE IMPORTANCE OF CELLS

## CASE STUDY: MORE THAN JUST TIRED

We all get tired sometimes, especially if we have been doing a lot of physical activity. But for Jasmin, a 34-year-old former high school track star who is now a recreational runner, her tiredness was going far beyond what she thought should be normal for someone who is generally in good physical shape. She was experiencing extreme fatigue after her runs, as well as muscle cramping, spasms, and an unusual sense of heaviness in her legs. At first, she chalked it up to getting older, but her exhaustion and pain worsened to the point where this former athlete could no longer run for more than a few minutes at a time. She also began to experience other unusual symptoms, such as blurry vision and vomiting for no apparent reason.



Figure **3.1.1**: Exhausted

Concerned, she went to her doctor. Her doctor ran many tests and consulted with several specialists. After several months, Jasmin is finally diagnosed with a mitochondrial disease. Jasmin is surprised. She has an 8-year-old niece with a mitochondrial disease, but her niece's symptoms started when she was very young, and included seizures and learning disabilities. How can Jasmin have the same disease but different symptoms? Why did she not have problems until adulthood while her niece had symptoms at an early age? And what are mitochondria anyway?

## CHAPTER OVERVIEW: CELLS

As you will learn in this chapter, mitochondria are important structures within our cells. This chapter will describe cells, which are the basic unit of structure and function in all living organisms. Specifically, you will learn:

- How cells were discovered, their common structures, and the principles of cell theory.
- The importance of size and shape in the functions of cells.
- The differences between eukaryotic cells (such as those in humans and other animals) and prokaryotic cells (such as bacteria).
- The structures and functions of parts of cells including mitochondria, the plasma membrane, cytoplasm, cytoskeleton, nucleus, ribosomes, Golgi apparatus, endoplasmic reticulum, vesicles, and vacuoles.
- How the processes of passive and active transport move substances into and out of cells and help maintain homeostasis.
- How organisms obtain the energy needed for life, including how the sugar glucose is broken down to produce ATP through the processes of aerobic cellular respiration and anaerobic respiration.

As you read this chapter, think about the following questions related to Jasmin's disease:

1. What are mitochondria? What is their structure, function, and where did they come from during evolution?
2. Why are fatigue and "exercise intolerance," such as Jasmin's extreme exhaustion after running, common symptoms of mitochondrial diseases?
3. Why do you think Jasmin has symptoms that affect so many different parts of her body including her legs, eyes, and digestive system?

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# 3.2: DISCOVERY OF CELLS AND CELL THEORY

## A BIG BLUE CELL

What is this incredible object? Would it surprise you to learn that it is a human cell? The cell is actually too small to see with the unaided eye. It is visible here in such detail because it is being viewed with a very powerful microscope. Cells may be small in size, but they are extremely important for life. Like all other living things, you are made of cells. Cells are the basis of life, and without cells, life as we know it would not exist. You will learn more about these amazing building blocks of life when you read this section.

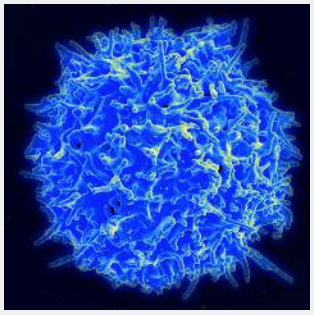


Figure **3.2.1**: Healthy human T-cell

If you look at a living matter with a microscope — even a simple light microscope — you will see that it consists of cells. **Cells** are the basic units of the structure and function of living things. They are the smallest units that can carry out the processes of life. All organisms are made up of one or more cells, and all cells have many of the same structures and carry out the same basic life processes. Knowing the structure of cells and the processes they carry out is necessary to understanding life itself.

## DISCOVERY OF CELLS

The first time the word *cell* was used to refer to these tiny units of life was in 1665 by a British scientist named Robert Hooke. Hooke was one of the earliest scientists to study living things under a microscope. The microscopes of his day were not very strong, but Hooke was still able to make an important discovery. When he looked at a thin slice of cork under his microscope, he was surprised to see what looked like a honeycomb. Hooke made the drawing in the figure below to show what he saw. As you can see, the cork was made up of many tiny units, which Hooke called cells.

Soon after Robert Hooke discovered cells in cork, Anton van Leeuwenhoek in Holland made other important discoveries using a microscope. Leeuwenhoek made his own microscope lenses, and he was so good at it that his microscope was more powerful than other microscopes of his day. In fact, Leeuwenhoek's microscope was almost as strong as modern light microscopes. Using his microscope, Leeuwenhoek was the first person to observe human cells and bacteria.

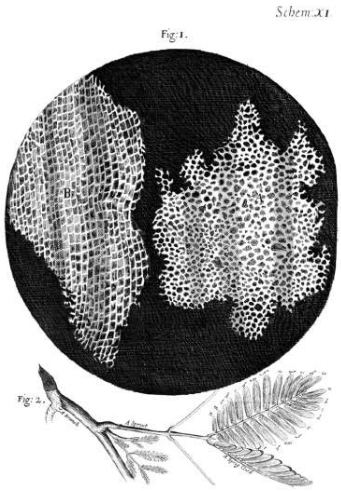



Figure **3.2.2**: Robert Hooke sketched these cork cells as they appeared under a simple light microscope.

## CELL THEORY

By the early 1800s, scientists had observed the cells of many different organisms. These observations led two German scientists, named Theodor Schwann and Matthias Jakob Schleiden, to propose that cells are the basic building blocks of all living things. Around 1850, a German doctor named Rudolf Virchow was studying cells under a microscope when he happened to see them dividing and forming new cells. He realized that living cells produce new cells through division. Based on this realization, Virchow proposed that living cells arise only from other living cells.

The ideas of all three scientists — Schwann, Schleiden, and Virchow — led to **cell theory**, which is one of the fundamental theories unifying all of biology. Cell theory states that:

- All organisms are made of one or more cells.
- All the life functions of organisms occur within cells.
- All cells come from already existing cells.

## SEEING INSIDE CELLS

Starting with Robert Hooke in the 1600s, the **microscope** opened up an amazing new world — the world of life at the level of the cell. As microscopes continued to improve, more discoveries were made about the cells of living things. However, by the late 1800s, light microscopes had reached their limit. Objects much smaller than cells, including the structures inside cells, were too small to be seen with even the strongest light microscope.

Then, in the 1950s, a new type of the microscope was invented. Called the electron microscope, it used a beam of electrons instead of light to observe extremely small objects. With an electron microscope, scientists could finally see the tiny structures inside cells. In fact, they could even see individual molecules and atoms. The electron microscope had a huge impact on biology. It allowed scientists to study organisms at the level of their molecules and led

to the emergence of the field of cell biology. With the electron microscope, many more cell discoveries were made. Figure **3.2.3** shows how the cell structures called **organelles** appear when scanned by an electron microscope.

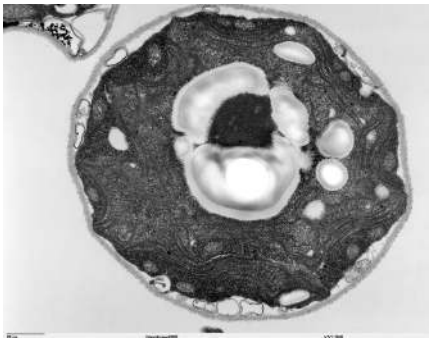


Figure **3.2.3**: An electron microscope produced this image of the structures inside a cell.

## STRUCTURES SHARED BY ALL CELLS

Although cells are diverse, all cells have certain parts in common. These parts include a plasma membrane, cytoplasm, ribosomes, and DNA.

1. The **plasma membrane** (also called the cell membrane) is a thin coat of phospholipids that surrounds a cell. It forms the physical boundary between the cell and its environment, so you can think of it as the "skin" of the cell.
2. **Cytoplasm** refers to all of the cellular material inside the plasma membrane. The Cytoplasm is made up of a watery substance called cytosol and contains other cell structures such as ribosomes.
3. **Ribosomes** are structures in the cytoplasm where proteins are made.
4. **DNA** is a nucleic acid found in cells. It contains the genetic instructions that cells need to make proteins.

These parts are common to all cells, from organisms as different as bacteria and human beings. How did all known organisms come to have such similar cells? The similarities show that all life on Earth has a common evolutionary history.

## REVIEW

1. Describe cells.
2. Explain how cells were discovered.
3. Outline how cell theory developed.
4. Identify structures shared by all cells.
5. *True or False.* Cork is not a living organism.
6. *True or False.* Some organisms are made of only one cell.
7. *True or False.* Ribosomes are found outside of the cytoplasm of a cell.
8. Proteins are made on _____ .
9. What are the differences between a light microscope and an electron microscope?
10. The first microscopes were made around
    A. 1965
    B. 1665
    C. 1950
    D. 1776
11. Which of these scientists made each of the following discoveries? (Anton van Leeuwenhoek; Robert Hooke; Rudolf Virchow)
    A. Observed some of the first cells and first used the term "cell"
    B. Observed the first human cells
    C. Observed cells dividing
12. Robert Hooke sketched what looked like honeycombs, or repeated circular or square units when he observed plant cells under a microscope.
    A. What is each unit?
    B. Of the shared parts of all cells, what makes up the outer surface of each unit?
    C. Of the shared parts of all cells, what makes up the inside of each unit?

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# 3.3: VARIATION IN CELLS

## BACTERIA ATTACK!

Figure **3.3.1** shows a bacterial cell (colored green) attacking human red blood cells. The bacterium causes a disease called relapsing fever. The bacterial and human cells look very different in size and shape. Although all living cells have certain things in common — such as a plasma membrane and cytoplasm — different types of cells, even within the same organism, may have their own unique structures and functions. Cells with different functions generally have different shapes that suit them for their particular job. Cells vary not only in shape but also in size, as this example shows. In most organisms, however, even the largest cells are no bigger than the period at the end of this sentence. Why are cells so small?



Figure **3.3.1**: Bacterial cell attacking a human red blood cell

## EXPLAINING CELL SIZE

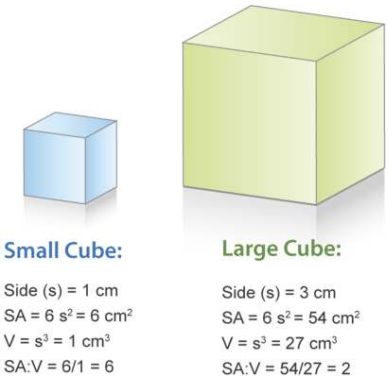



Figure **3.3.2**: Surface Area to Volume Comparison. A larger cube has a smaller surface area (SA) to volume (V) ratio than a smaller cube. This also holds true for cells and limits how large they can be.

Table **3.3.1**: Characteristics of small and large cubes

| Characteristic | Small Cube | Large Cube |
|---|---|---|
| sides (S) | $1cm$ | $3cm$ |
| Surface Area (SA) | $6S^2 = 6 \times 1^2 = 6cm^2$ | $6S^2 = 6 \times 3^2 = 54cm^2$ |
| Volume (V) | $S^3 = 1^3 = 1cm^3$ | $S^3 = 3^3 = 27cm^3$ |
| SA:V | $SA/V = 6/1 = 6$ | $SA/V = 54/27 = 2$ |

Most organisms, even very large ones, have microscopic cells. Why don't cells get bigger instead of remaining tiny and multiplying? What limits cell size?

The answers to these questions are clear once you know how a cell functions. To carry out life processes, a cell must be able to quickly pass substances into and out of the cell. For example, it must be able to pass nutrients and oxygen into the cell and waste products out of the cell. Anything that enters or leaves a cell must cross its outer surface. It is this need to pass substances across the surface that limits how large a cell can be.

Look at the two cubes in Figure **3.3.2**. As this figure and table show, a larger cube has less surface area relative to its volume than a smaller cube. This relationship also applies to cells; a larger cell has less surface area relative to its volume than a smaller cell. A cell with a larger volume also needs more nutrients and oxygen and produces more wastes. Because all of these substances must pass through the surface of the cell, a cell with a large volume will not have enough surface area to allow it to meet its needs. The larger the cell is, the smaller its ratio of surface area to volume, and the harder it will be for the cell to get rid of its wastes and take in necessary substances. This is what limits the size of the cell.

## CELL FORM AND FUNCTION

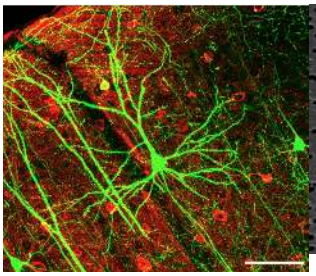


Figure **3.3.3**: Human nerve cell

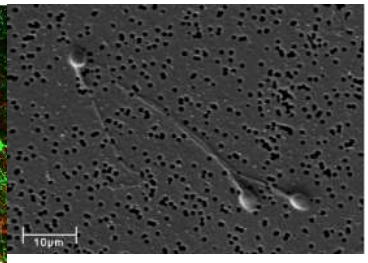



Figure **3.3.4**: Human sperm cells

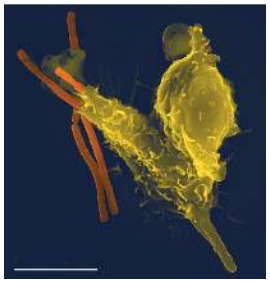


Figure **3.3.5**: Human white blood cell

Cells with different functions often have different shapes. The cells in Figure **3.3.3** - Figure **3.3.5** are just a few examples of the many different shapes that human cells may have. Each type of cell in the figure has characteristics that help it do its job. For example, the job of the nerve cell is to carry messages to other cells. The nerve cell has many long extensions that reach out in all directions, allowing it to pass messages to many other cells at once. Do you see the tail of each tiny sperm cell? Its tail helps a sperm cell "swim" through fluids in the female reproductive tract in order to reach an egg cell. The white blood cell has the job of destroying bacteria and other pathogens. Figure **3.3.5** shows the large white blood cell (in yellow) engulfing and destroying bacteria (in orange).

## CELLS WITH AND WITHOUT A NUCLEUS

There is a basic cell structure that is present in many but not all living cells: the nucleus. The nucleus of a cell is a structure in the cytoplasm that is surrounded by a membrane (the nuclear membrane) and contains DNA. Based on whether or not they have a nucleus, there are two basic types of cells: prokaryotic cells and eukaryotic cells.

### PROKARYOTIC CELLS

**Prokaryotic cells** are cells without a nucleus. The DNA in prokaryotic cells is in the cytoplasm rather than enclosed within a nuclear membrane. Prokaryotic cells are found in single-celled organisms, such as the bacterium represented by the model below. Organisms with prokaryotic cells are called **prokaryotes**. They were the first type of organisms to evolve and are still the most common organisms today.

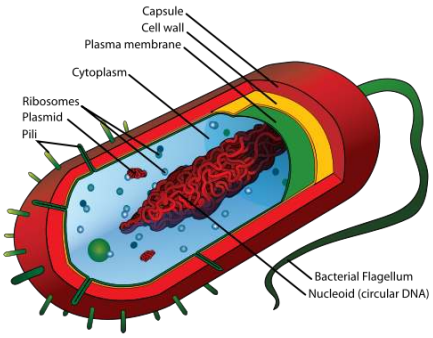



Figure **3.3.6**: Prokaryotic Cell. This diagram shows the structure of a typical prokaryotic cell, a bacterium. Like other prokaryotic cells, this bacterial cell lacks a nucleus but has other cell parts, including a plasma membrane, cytoplasm, ribosomes, and DNA.

Table **3.3.2**: Prokaryotic cell structures

| Cell Structure | Description |
|---|---|
| Flagellum | Long projection(s) outside of the cell in some bacteria; aids in the motility |
| Pili | Small projections outside of the cell; aid in attachment |
| Capsule | A thick protective layer outside the cell wall of some bacteria |
| Cell wall | Outer layer of bacterial cells; more chemically complex than eukaryotic cell walls |
| Plasma Membrane | Phospholipid bilayer marking the outside of the cytoplasm |
| Cytoplasm | The fluid portion of the cell |
| Ribosome | Involved in protein synthesis |
| Nucleoid | Circular DNA found in the cytoplasm |
| Plasmid | Small loops of DNA found in some bacteria |

### EUKARYOTIC CELLS

**Eukaryotic cells** are cells that contain a nucleus. A typical eukaryotic cell is represented by the model below. Eukaryotic cells are usually larger than prokaryotic cells. They are found in some single-celled and all multicellular organisms. Organisms with eukaryotic cells are called **eukaryotes**, and they range from fungi to people.

Besides a nucleus, eukaryotic cells also contain other organelles. An **organelle** is a structure within the cytoplasm that performs a specific job in the cell. Organelles called mitochondria, for example, provide energy to the cell, and organelles called vacuoles store substances in the cell. Organelles allow eukaryotic cells to carry out more functions than prokaryotic cells can.

Table **3.3.3**: Eukaryotic cell structures

| Structure | Location | Description |
|---|---|---|
| Flagellum | Outside the cell | A projection used for locomotion in some eukaryotic cells |
| Plasma Membrane | Outer layer of cell | Phospholipid bilayer enclosing the cytoplasm |
| Cytoplasm | Bound by the plasma membrane | Entire region between the plasma membrane and the nuclear envelope, consisting of organelles suspended in the gel-like cytosol, the cytoskeleton, and various chemicals |
| Golgi Vesicles (Golgi Apparatus) | Cytoplasm | A series of stacked membranes that sorts, tags, and packages lipids and proteins for distribution |
| Ribosomes | free-floating or on rough ER | Involved in protein synthesis |
| Rough Endoplasmic Reticulum | Cytoplasm | Interconnected membranous structures that are studded with ribosomes and engage in protein modification and phospholipid synthesis |
| Smooth Endoplasmic Reticulum | Cytoplasm | Interconnected membranous structures that have few or no ribosomes on its cytoplasmic surface and synthesize carbohydrates, lipids, and steroid hormones; detoxifies certain chemicals (like pesticides, preservatives, medications, and environmental pollutants), and stores calcium ions |
| Mitochondria | Cytoplasm | (singular = mitochondrion) cellular organelles responsible for carrying out cellular respiration, resulting in producing ATP, the cell's main energy-carrying molecule |
| Peroxisome | Cytoplasm | The small, round organelle that contains hydrogen peroxide, and detoxifies many poisons |
| Lysosome | Cytoplasm | Organelle in an animal cell that functions as the cell's digestive component; it breaks down proteins, polysaccharides, lipids, nucleic acids, and even worn-out organelles |
| Secretory Vesicle | Cytoplasm | Small, membrane-bound sac that functions in cellular storage and transport; its membrane is capable of fusing with the plasma membrane and the membranes of the endoplasmic reticulum and Golgi apparatus |
| Centrosome (with 2 centrioles) | Cytoplasm | Region in animal cells made of two centrioles that serve as an organizing center for microtubules |
| Actin Filaments | Cytoskeleton | The cytoskeleton's narrowest element; it provides rigidity and shape to the cell and enables cellular movements |
| Intermediate Filaments | Cytoskeleton | Cytoskeletal component, comprised of several fibrous protein intertwined strands, that bears tension, supports cell-cell junctions, and anchors cells to extracellular structures |
| Microtubules | Cytoskeleton | The cytoskeleton's widest element; provides a track along which vesicles move through the cell, pulls replicated chromosomes to opposite ends of a dividing cell, and is the structural element of centrioles |
| Cytoskeleton | Throughout cell | Protein fiber network that collectively maintains the cell's shape, secures some organelles in specific positions and allows cytoplasm and vesicles to move within the cell |
| Nucleus | Cytoplasm | Cell organelle that houses the cell's DNA and directs ribosome and protein synthesis |
| Nuclear Pore | Nucleus | Pores in the nuclear envelope allow substances to enter and exit the nucleus. |
| Nuclear Envelope | Nucleus | Double-membrane structure that constitutes the nucleus' outermost portion |
| Chromatin | Nucleus | Protein-DNA complex that serves as the chromosomes' building material |
| Nucleolus | Nucleus | Darkly staining body within the nucleus that is responsible for assembling ribosome subunits |

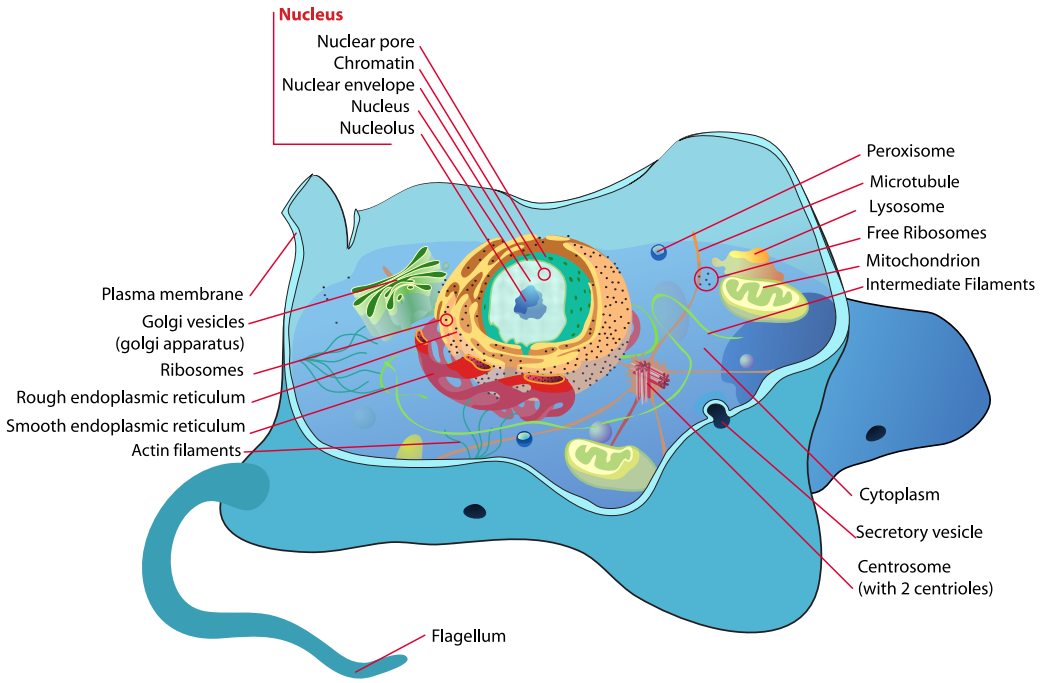



Figure **3.3.7**: Eukaryotic Cell. Compare and contrast the eukaryotic cell shown here with the prokaryotic cell. What similarities and differences can you identify?

## REVIEW

1. Explain why most cells are very small.
2. Discuss variations in the form and function of cells.
3. Compare and contrast prokaryotic and eukaryotic cells.
4. *True or False.* Prokaryotic cells do not have mitochondria.
5. *True or False.* Prokaryotic cells do not have DNA.
6. *True or False.* All single-celled organisms are prokaryotes.
7. Which was the first type of organism to evolve – eukaryotes or prokaryotes? Based on their structures, does this make sense to you? Explain your answer.
8. Do human cells have organelles? Explain your answer.
9. Which are usually larger – prokaryotic or eukaryotic cells? What do you think this means for their relative ability to take in needed substances and release wastes? Discuss your answer.
10. DNA in eukaryotes is enclosed within the _____ _____.
11. Name three different types of cells in humans.
12. Which organelle provides energy in eukaryotic cells?
13. What is the function of a vacuole in a cell?

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# 3.4: PLASMA MEMBRANE

## A BAG FULL OF JELL-O

This simple, cut-away model of an animal cell (Figure **3.4.1**) shows that a cell resembles a plastic bag full of Jell-O. Its basic structure is a plasma membrane filled with cytoplasm. Like Jell-O containing mixed fruit, the cytoplasm of the cell also contains various structures, such as a nucleus and other organelles. Your body is made up of trillions of cells, but all of them perform the same basic life functions. They all obtain and use energy, respond to the environment, and reproduce. How do your cells carry out these basic functions and keep themselves — and you — alive? To answer these questions, you need to know more about the structures that make up cells, starting with the plasma membrane.



Figure **3.4.1**: Animal cell model

The plasma membrane is a structure that forms a barrier between the cytoplasm inside the cell and the environment outside the cell. Without the plasma membrane, there would be no cell. The membrane also protects and supports the cell and controls everything that enters and leaves it. It allows only certain substances to pass through while keeping others in or out. To understand how the plasma membrane controls what passes into or out of the cell, you need to know its basic structure.

## PHOSPHOLIPID BILAYER

The **plasma membrane** is composed mainly of **phospholipids**, which consist of fatty acids and alcohol. The phospholipids in the plasma membrane are arranged in two layers, called a **phospholipid bilayer**, with a hydrophobic, or water-hating, interior and a hydrophilic, or water-loving, exterior. Each phospholipid molecule has a head and two tails. The head “loves” water (hydrophilic) and the tails “fear” water (hydrophobic). The water-fearing tails are on the interior of the membrane, whereas the water-loving heads point outwards, toward either the cytoplasm or the fluid that surrounds the cell. The polar head group and fatty acid chains are attached by a 3-carbon glycerol unit. Figure **3.4.2** shows a single phospholipid next to a phospholipid bilayer.

Molecules that are hydrophobic can easily pass through the plasma membrane if they are small enough because they are water-hating like the interior of the membrane. Molecules that are hydrophilic, on the other hand, cannot pass through the plasma membrane — at least not without help — because they are water-loving like the exterior of the membrane.

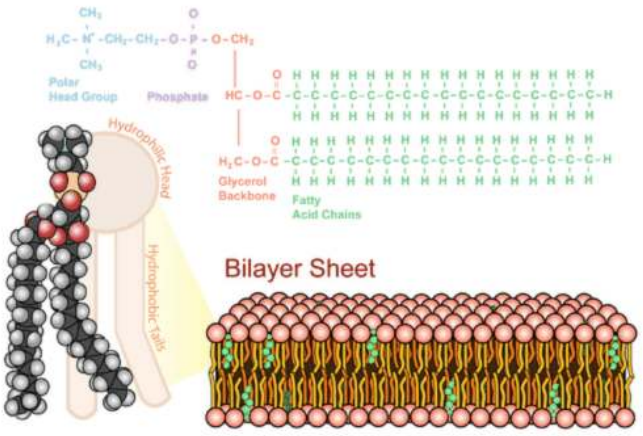



Figure **3.4.2**: Phospholipid and a phospholipid Bilayer.

## OTHER MOLECULES IN THE PLASMA MEMBRANE

The plasma membrane also contains other molecules, primarily other lipids and proteins. The green molecules in Figure **3.4.2**, for example, are the lipid cholesterol. Molecules of the steroid lipid cholesterol help the plasma membrane keep its shape. (Figure **3.4.3**) shows the cholesterol molecules as yellow structures within the center of the phospholipid bilayer. Other structures shown in (Figure **3.4.3**):

- Protein channels. These span the full membrane and have a space within them because they are used to transport materials into or out of the cell.
- Transmembrane proteins. The root "trans" explains that these span (go "across") the membrane. Transmembrane proteins can have a variety of functions.
- Peripheral proteins. These are found only on one side of the membrane. They can be found on either the cytoplasmic side or the outside of the membrane.
- Glycoproteins. These consist of a protein in the plasma membrane with chains of carbohydrates projecting out of the cell.
- Glycolipids. These are chains of carbohydrates attached directly to a lipid in the membrane. Both glycoproteins and glycolipids act as labels to identify the cell.
- Filaments of cytoskeleton are found along the cytoplasmic side of the membrane and provide a scaffolding for the membrane.

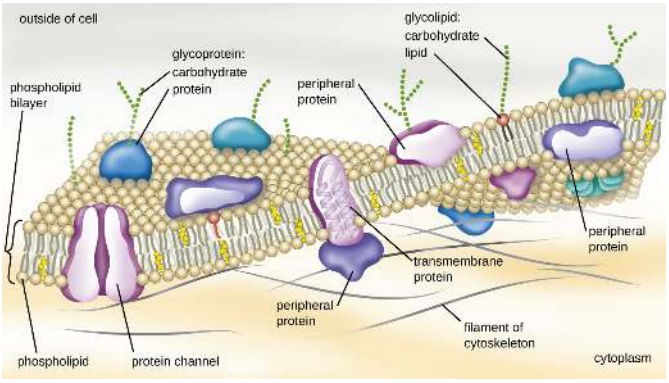



Figure **3.4.3**: The figure illustrates the major components of the phospholipid bilayer.

## ADDITIONAL FUNCTIONS OF THE PLASMA MEMBRANE

The plasma membrane may have extensions, such as whip-like **flagella** or brush-like **cilia**, that give it other functions. In single-celled organisms, like those shown below, these membrane extensions may help the organisms move. In multicellular organisms, the extensions have different functions. For example, the cilia on human lung cells sweep foreign particles and mucus toward the mouth and nose.

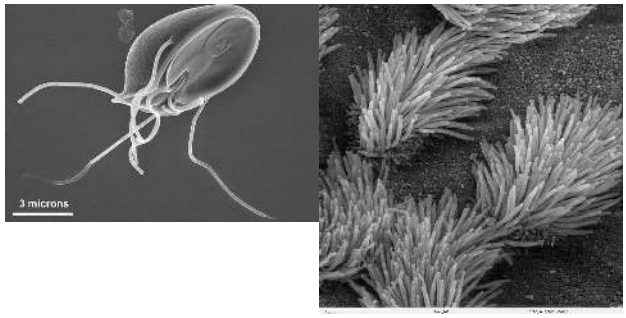



Figure **3.4.4**: Flagella of Giardia (left) and cilia of human respiratory mucosa (right). Flagella and cilia are extensions of the plasma membrane of many cells.

### FEATURE: MY HUMAN BODY

If you smoke and need another reason to quit, here's a good one. We usually think of lung cancer as a major disease caused by smoking. But smoking can have devastating effects on the body's ability to protect itself from repeated, serious respiratory infections, such as bronchitis and pneumonia.

Cilia are microscopic, hair-like projects on cells that line the respiratory, reproductive, and digestive systems. Cilia in the respiratory system line most of your airways where they have the job of trapping and removing dust, germs, and other foreign particles before they can make you sick. Cilia secrete mucus that traps particles, and they move in a continuous wave-like motion that sweeps the mucus and particles upward toward the throat, where they can be expelled from the body. When you are sick and cough up phlegm, that's what you are doing.

Smoking prevents cilia from performing these important functions. Chemicals in tobacco smoke paralyze the cilia so they can't sweep mucus out of the airways and they also inhibit the cilia from producing mucus. Fortunately, these effects start to wear off soon after the last exposure to tobacco smoke. If you stop smoking, your cilia will return to normal. Even if prolonged smoking has destroyed cilia, they will regrow and resume functioning in a matter of months after you stop smoking.

## REVIEW

1. What are the general functions of the plasma membrane?
2. Describe the phospholipid bilayer of the plasma membrane.
3. Identify other molecules in the plasma membrane, and state their functions.
4. Why do some cells have plasma membrane extensions such as flagella and cilia?
5. Explain why hydrophilic molecules cannot easily pass through the cell membrane. What type of molecule in the cell membrane might help hydrophilic molecules pass through it?
6. Which part of a phospholipid molecule in the plasma membrane is made of fatty acid chains? Is this part hydrophobic or hydrophilic?
7. The two layers of phospholipids in the plasma membrane are called a phospholipid _____.
8. *True or False.* The flagella on your lung cells sweep foreign particles and mucus toward your mouth and nose.
9. *True or False.* Small hydrophobic molecules can easily pass through the plasma membrane.
10. *True or False.* The side of the cell membrane that faces the cytoplasm is hydrophilic.
11. Steroid hormones can pass directly through cell membranes. Why do you think this is the case?
12. Some antibiotics work by making holes in the plasma membrane of bacterial cells. How do you think this kills the cells?
13. What is the name of the long, whip-like extensions of the plasma membrane that helps some single-celled organisms move?

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# 3.5: CYTOPLASM AND CYTOSKELETON

## A PEEK INSIDE THE CELL

Figure **3.5.1** may look like a colorful work of abstract art or maybe an ultra-modern carpet design, but it's neither. It is actually a model of the interior of a cell. It's an artist's representation of what you might see if you could take a peek inside one of these basic building blocks of living things. A cell's interior is obviously a crowded and busy space. It contains cytoplasm, dissolved substances, and many structures; and it's a hive of countless biochemical activities all going on at once.

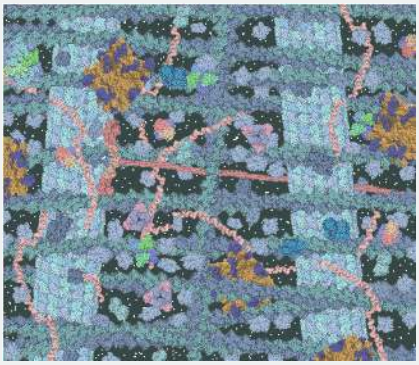


Figure **3.5.1**: Picture of cytosol, showing microtubules (light blue), actin filaments (dark blue), ribosomes (yellow and purple), soluble proteins (light blue), kinesin (red), small molecules (white) and RNA (pink).

## CYTOPLASM

The **cytoplasm** is a thick, usually colorless solution that fills each cell and is enclosed by the cell membrane. Cytoplasm presses against the cell membrane, filling out the cell and giving it its shape. Sometimes cytoplasm acts like a watery solution and sometimes it takes on a more gel-like consistency. In eukaryotic cells, the cytoplasm includes all of the material inside the cell but outside the nucleus, which contains its own watery substance called **nucleoplasm**. All of the organelles in eukaryotic cells, such as the endoplasmic reticulum and mitochondria, are located in the cytoplasm. The cytoplasm helps to keep them in place. It is also the site of most metabolic activities in the cell, and it allows materials to pass easily throughout the cell.

The portion of the cytoplasm surrounding organelles is called cytosol, which is the liquid part of the cytoplasm. It is composed of about 80 percent water and also contains dissolved salts, fatty acids, sugars, amino acids, and proteins such as enzymes. These dissolved substances are needed to keep the cell alive and carry out metabolic processes. For example, enzymes dissolved in cytosol break down larger molecules into smaller products that can then be used by organelles of the cell. Waste products are also dissolved in the cytosol before they are taken in by vacuoles or expelled from the cell.

Though prokaryotic cells do not have organelles (they do have ribosomes), they still have cytoplasm. It is within the cytoplasm that most cellular activities occur, including the many metabolic pathways that occur within organelles, such as photosynthesis and aerobic respiration.

## CYTOSKELETON

Although cytoplasm may appear to have no form or structure, it is actually highly organized. A framework of protein scaffolds called the **cytoskeleton** provides the cytoplasm and the cell with structure. The cytoskeleton consists of thread-like filaments and tubules that criss-cross the cytoplasm. You can see these filaments and tubules in the cells in Figure **3.5.2**. As its name suggests, the cytoskeleton is like a cellular “skeleton.” It helps the cell maintain its shape and also helps to hold cell structures such as organelles in place within the cytoplasm.

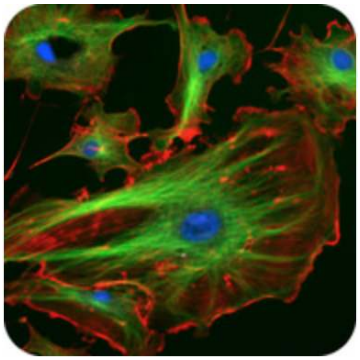


Figure **3.5.2**: Cytoskeleton. The cytoskeleton gives the cell an internal structure, like the frame of a house. In this photograph, actin filaments and tubules of the cytoskeleton are green and red, respectively. The blue dots are cell nuclei.

The eukaryotic cytoskeleton is made up of a network of long, thin protein fibers. These threadlike proteins continually rebuild to adapt to the cell's constantly changing needs. Three main kinds of cytoskeleton fibers are microtubules, intermediate filaments, and microfilaments (Table **3.5.1**).

- **Microtubules** are the thickest of the cytoskeleton structures. They are most commonly made of filaments which are polymers of alpha and beta-tubulin and radiate outwards from an area near the nucleus called the centrosome. Two forms of tubulin form dimers (pairs) which come together to form the hollow cylinders. The cylinders are twisted around each other to form the microtubules. Microtubules help the cell keep its shape. They hold organelles in place and allow them to move around the cell, and they form the mitotic spindle during cell division. Microtubules also make up parts of cilia and flagella, the organelles that help a cell move.
- **Microfilaments** are made of two thin **actin** chains that are twisted around one another. Microfilaments are mostly concentrated just beneath the cell membrane, where they support the cell and help the cell keep its shape. Microfilaments form cytoplasmatic extensions, such as **microvilli** and pseudopodia, which allow certain cells to move. The actin and myosin protein interact to cause a contraction in muscle cells. Microfilaments

are found in almost every cell and are numerous in muscle cells and in cells that move by changing shape, such as phagocytes (white blood cells that search the body for bacteria and other invaders).

- **Intermediate filaments (IF)** differ in make-up from one cell type to another. The IF may be composed of **vimentin**, **keratin**, **desmin**, or **lamin**. Each cell type can have a unique combination of IFs. For example, intermediate filaments made of keratin are found in skin, hair, and nail cells. IFs organize the inside structure of the cell by holding organelles and providing strength. They are also structural components of the nuclear envelope. Intermediate filaments made of the protein keratin are found in skin, hair, and nail cells.

Table **3.5.1**: Cytoskeleton Structure

| Characteristic | Microtubules | Intermediate Filaments | Microfilaments |
|---|---|---|---|
| Fiber Diameter | About 25 nm | 8 to 11 nm | Around 7 nm |
| Protein Composition | Tubulin with two subunits, alpha, and beta-tubulin | One of the different types of proteins such as lamin, vimentin, desmin, and keratin | Actin |
| Shape | Hollow cylinders made of two protein chains twisted around each other | Protein fiber coils twisted into each other | Two actin chains twisted around one another |
| Main Functions | Organelle and vesicle movement; form mitotic spindles during cell reproduction; cell motility (in cilia and flagella) | Organize cell shape; positions organelles in cytoplasm structural support of the nuclear envelope and sarcomeres; involved in cell-to-cell and cell-to-matrix junctions | Keep cellular shape; allows movement of certain cells by forming cytoplasmatic extensions or contraction of actin fibers; involved in some cell-to-cell or cell-to-matrix junctions |

## FEATURE: HUMAN BIOLOGY IN THE NEWS

News about an important study of the cytoplasm of eukaryotic cells appeared early in 2016. Researchers in Dresden, Germany discovered that when cells are deprived of adequate nutrients, they may essentially shut down and become dormant. Specifically, when cells do not get enough nutrients, they shut down their metabolism, their energy level drops, and the pH of their cytoplasm decreases. Their normally liquid cytoplasm also assumes a solid state. The cells appear dead and as though a kind of rigor mortis has set in. The researchers think that these changes protect the sensitive structures inside the cells and allow the cells to survive difficult conditions. If nutrients are returned to the cells, they can emerge from their dormant state unharmed. They will continue to grow and multiply when conditions improve.

This important basic science research was carried out on a nonhuman organism: one-celled fungi called yeasts. Nonetheless, it may have important implications for humans because yeasts have eukaryotic cells with many of the same structures as human cells. Yeast cells appear to be able to "trick" death by shutting down all life processes in a controlled way. Researchers hope to learn with the continued research on whether human cells can be taught this "trick" as well.

## REVIEW

1. Describe the composition of cytoplasm.
2. What are some of the functions of cytoplasm?
3. Outline the structure and functions of the cytoskeleton.
4. Is the cytoplasm made of cells? Why or why not?
5. Name two types of cytoskeletal structures.
6. *True or False.* The cytoplasm is usually green.
7. *True or False.* The nucleus of a cell is filled with cytoplasm.
8. In Figure **3.5.2** of the different cytoskeletal structures above (shown in red and green), what do you notice about these different structures?
9. Describe one example of a metabolic process that occurs in the cytosol.
10. In eukaryotic cells, all of the material inside of the cell but outside of the nucleus is called the _____.
11. What is the liquid part of the cytoplasm called?
12. What chemical substance makes up most of the cytosol?
13. When yeast cells deprived of nutrients go dormant, their cytoplasm assumes a solid-state. What effect do you think a solid cytoplasm would have on normal cellular processes? Explain your answer.
14. What is the difference between cytoplasm and cytosol?
15. Name the three main parts of the cytoskeleton.
16. List two functions of the eukaryotic cytoskeleton

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# 3.6: CELL ORGANELLES

## RIBOSOME REVIEW

Figure **3.6.1** represents an important structure in living cells. It is a component of a ribosome, the cell structure where proteins are synthesized. Large ribosomal subunit (50S) of *Haloarcula marismortui*, facing the 30S subunit. The ribosomal proteins are shown in blue, the rRNA in ochre (a shade of brown and yellow), the active site in red. All living cells contain ribosomes, whether they are prokaryotic or eukaryotic cells. However, only eukaryotic cells also contain a nucleus and several other types of organelles.

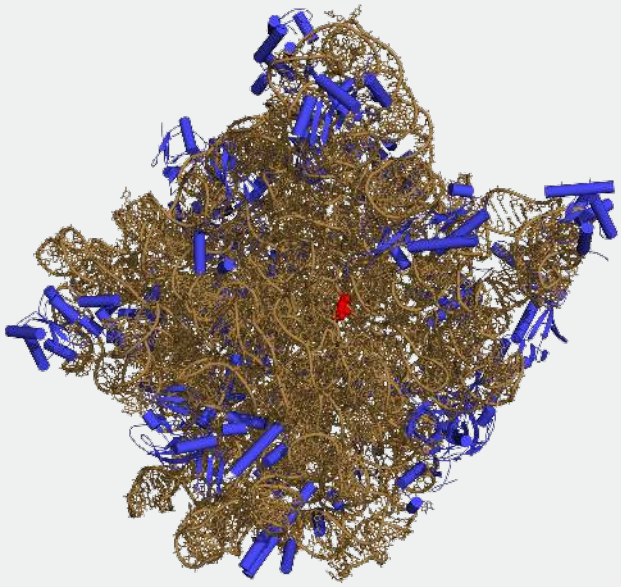


Figure **3.6.1**: Ribosomal subunit

An organelle is a structure within the cytoplasm of a eukaryotic cell that is enclosed within a membrane and performs a specific job. Organelles are involved in many vital cell functions. Organelles in animal cells include the nucleus, mitochondria, endoplasmic reticulum, Golgi apparatus, vesicles, and vacuoles. Ribosomes are not enclosed within a membrane but are still commonly referred to as organelles in eukaryotic cells.

## THE NUCLEUS

The nucleus is the largest organelle in a eukaryotic cell and is considered to be the cell's control center. It contains most of the cell's DNA, which makes up chromosomes and is encoded with the genetic instructions for making proteins. The function of the nucleus is to regulate gene expression, including controlling which proteins the cell makes. In addition to DNA, the nucleus contains a thick liquid called nucleoplasm that is similar in composition to the cytosol found in the cytoplasm outside the nucleus (Figure **3.6.2**). Most eukaryotic cells contain just a single nucleus, but some types of cells, such as red blood cells, contain no nucleus. A few other types of cells, such as muscle cells, contain multiple nuclei.

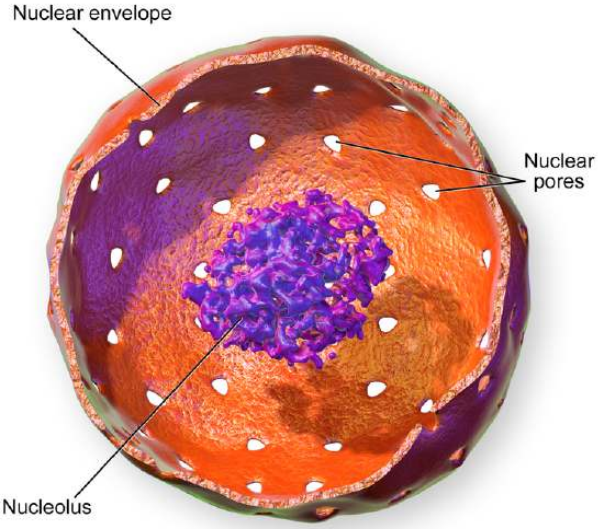



Figure **3.6.2**: This closeup of a cell nucleus shows that it is surrounded by a structure called the nuclear envelope, which contains tiny perforations, or pores. The nucleus also contains a dense center called the nucleolus.

As you can see from the model in Figure **3.6.2**, the membrane enclosing the nucleus is called the **nuclear envelope**. This is actually a double membrane that encloses the entire organelle and isolates its contents from the cellular cytoplasm. Tiny holes, called **nuclear pores**, allow large molecules to pass through the nuclear envelope with the help of special proteins. Large proteins and RNA molecules must be able to pass through the nuclear envelope so proteins can be synthesized in the cytoplasm and the genetic material can be maintained inside the nucleus. The **nucleolus** shown in the model below is mainly involved in the assembly of ribosomes. After being produced in the nucleolus, ribosomes are exported to the cytoplasm where they are involved in the synthesis of proteins.

## MITOCHONDRIA

The **mitochondrion** (plural, **mitochondria)** is an organelle that makes energy available to the cell (Figure **3.6.3**). This is why mitochondria are sometimes referred to as the power plants of the cell. They use energy from organic compounds such as glucose to make molecules of **ATP (adenosine triphosphate)**, an energy-carrying molecule that is used almost universally inside cells for energy.

Scientists think that mitochondria were once free-living organisms because they contain their own DNA. They theorize that ancient prokaryotes infected (or were engulfed by) larger prokaryotic cells, and the two organisms evolved a symbiotic relationship that benefited both of them. The larger cells provided the smaller prokaryotes with a place to live. In return, the larger cells got extra energy from the smaller prokaryotes. Eventually, the smaller prokaryotes became permanent guests of the larger cells, as organelles inside them. This theory is called the **endosymbiotic theory**, and it is widely accepted by biologists today

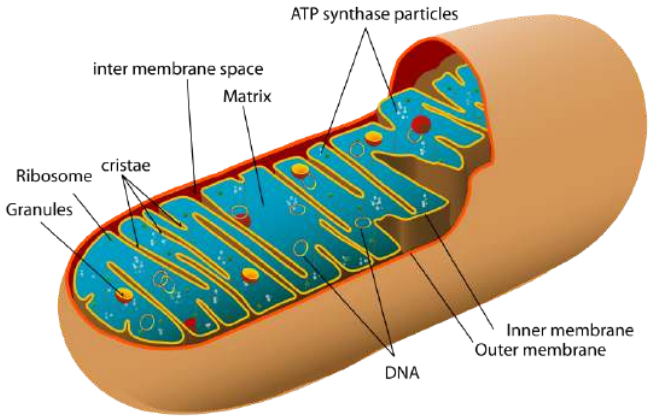



Figure **3.6.3**: Mitochondria, organelles specialized to carry out aerobic respiration, contain an inner membrane folded into cristae, which form two separate compartments: the inner membrane space and the matrix. The Krebs Cycle takes place in the matrix. The electron transport chain is embedded in the inner membrane and uses both compartments to make ATP by chemiosmosis. Mitochondria have their own DNA and ribosomes, resembling those of prokaryotic organisms.

### MITOCHONDRIAL COMPARTMENTS

The double membrane nature of the mitochondria results in five distinct compartments, each with an important role in cellular respiration. These compartments are:

1. the outer mitochondrial membrane,
2. the intermembrane space (the space between the outer and inner membranes),
3. the inner mitochondrial membrane,
4. the cristae (formed by infoldings of the inner membrane), and
5. the matrix (space within the inner membrane).

## ENDOPLASMIC RETICULUM

The *endoplasmic reticulum* **(ER)** (plural, reticuli) is a network of phospholipid membranes that form hollow tubes, flattened sheets, and round sacs. These flattened, hollow folds and sacs are called *cisternae*. The ER has two major functions:

- Transport: Molecules, such as proteins, can move from place to place inside the ER, much like on an intracellular highway.
- Synthesis: Ribosomes that are attached to the ER, similar to unattached ribosomes, make proteins. Lipids are also produced in the ER.

There are two types of endoplasmic reticulum, rough endoplasmic reticulum (RER) and smooth endoplasmic reticulum (SER):

- **Rough endoplasmic reticulum** is studded with ribosomes, which gives it a “rough” appearance. These ribosomes make proteins that are then transported from the ER in small sacs called transport vesicles. The transport vesicles pinch off the ends of the ER. The rough endoplasmic reticulum works with the Golgi apparatus to move new proteins to their proper destinations in the cell. The membrane of the RER is continuous with the outer layer of the nuclear envelope.
- **Smooth endoplasmic reticulum** does not have any ribosomes attached to it, and so it has a smooth appearance. SER has many different functions, some of which include lipid synthesis, calcium ion storage, and drug detoxification. The smooth endoplasmic reticulum is found in both animal and plant cells and it serves different functions in each. The SER is made up of tubules and vesicles that branch out to form a network. In some cells, there are dilated areas like the sacs of RER. Smooth endoplasmic reticulum and RER form an interconnected network.

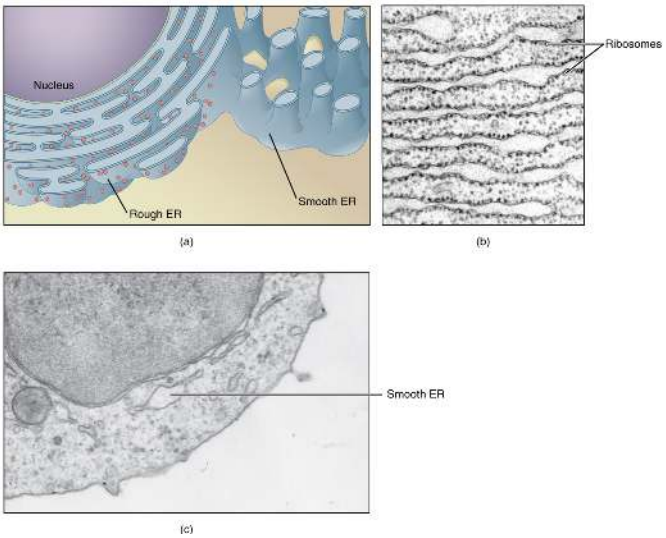



Figure **3.6.4**: The ER is a winding network of thin membranous sacs found in close association with the cell nucleus. The smooth and rough endoplasmic reticula are very different in appearance and function (source: mouse tissue). (b) Rough ER is studded with numerous ribosomes, which are sites of protein synthesis (source: mouse tissue). EM × 110,000. (c) Smooth ER synthesizes phospholipids, steroid hormones, regulates the concentration of cellular $Ca^{2+}$, metabolizes some carbohydrates, and breaks down certain toxins.

## GOLGI APPARATUS

The **Golgi apparatus** (Figure **3.6.5**) is a large organelle that processes proteins and prepares them for use both inside and outside the cell. It was identified in 1898 by the Italian physician Camillo Golgi. The Golgi apparatus modifies, sorts, and packages different substances for secretion out of the cell, or for use within the cell. The Golgi apparatus is found close to the nucleus of the cell where it modifies proteins that have been delivered in transport vesicles from the Rough Endoplasmic Reticulum. It is also involved in the transport of lipids around the cell. Pieces of the Golgi membrane pinch off to form vesicles that transport molecules around the cell. The Golgi apparatus can be thought of as similar to a post office; it packages and labels "items" and then sends them to different parts of the cell. The Golgi apparatus tends to be larger and more numerous in cells that synthesize and secrete large quantities of materials; for example, the plasma B cells and the antibody-secreting cells of the immune system have prominent Golgi complexes.

The Golgi apparatus manipulates products from the Rough Endoplasmic Reticulum (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.

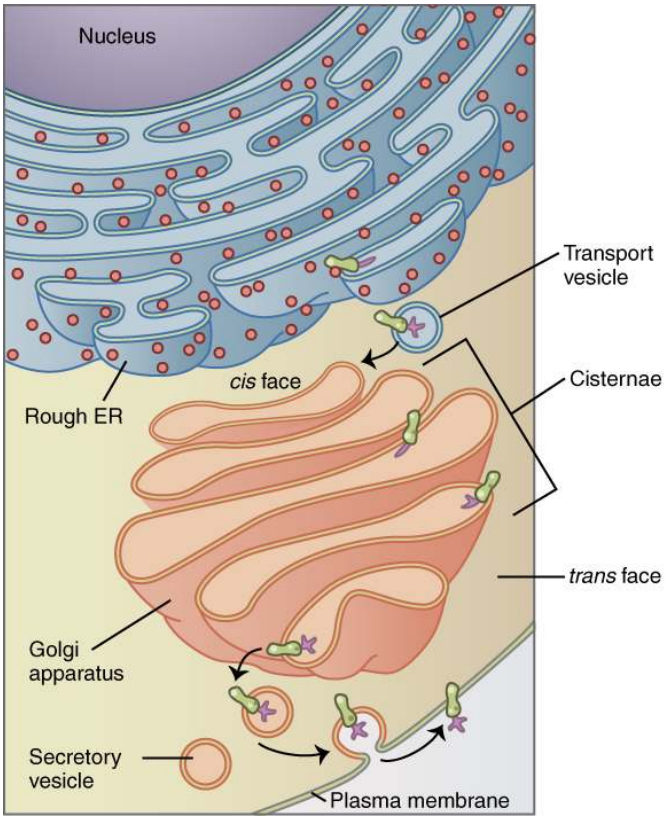



Figure **3.6.5**: The rough ER is continuous with the nuclear envelope and has ribosomes on it's surface. The ribosomes produce proteins such as the one shown which remains bound to the membrane of the rough ER. The membrane of the rough ER pinches off to form a transport vesicle containing the protein. The vesicle fuses with the cis face of the Golgi apparatus. The protein is now found on the membrane of the Golgi apparatus and travels along the cisternae. Once it reaches the trans face of the Golgi apparatus, it gets packaged into a secretory vesicle that sends the protein to the plasma membrane.

The stack of **cisternae** has four functional regions: the **cis-Golgi network**, medial-Golgi, endo-Golgi, and trans-Golgi network. Vesicles from the ER fuse with the network and subsequently progress through the stack from the cis- to the **trans-Golgi network**, where they are packaged and sent to their destination. Each cisterna includes special Golgi enzymes which modify or help to modify proteins that travel through it. Proteins may be modified by the addition of a carbohydrate group (glycosylation) or phosphate group (phosphorylation). These modifications may form a signal sequence on the protein, which determines the final destination of the protein. For example, the addition of mannose-6-phosphate signals the protein for lysosomes.

## VESICLES AND VACUOLES

Both **vesicles** and **vacuoles** are sac-like organelles that store and transport materials in the cell. Vesicles are much smaller than vacuoles and have a variety of functions. The vesicles that pinch off from the membranes of the ER and Golgi apparatus store and transport protein and lipid molecules. You can see an example of this type of transport vesicle in the figure above. Some vesicles are used as chambers for biochemical reactions. Other vesicles include:

- Lysosomes, which use enzymes to break down foreign matter and dead cells.
- Peroxisomes, which use oxygen to break down poisons.
- Transport vesicles, transport contents between organelle as well as between cell exterior and interior.

## CENTRIOLES

**Centrioles** are organelles involved in cell division. The function of centrioles is to help organize the chromosomes before cell division occurs so that each daughter cell has the correct number of chromosomes after the cell divides. Centrioles are found only in animal cells and are located near the nucleus. Each centriole is made mainly of a protein named **tubulin**. The centriole is cylindrical in shape and consists of many microtubules, as shown in the model pictured below.

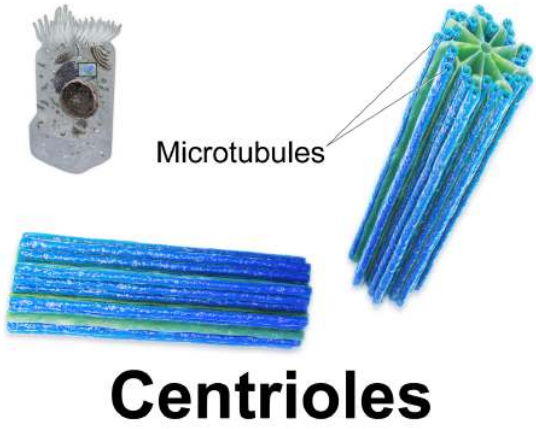



Figure **3.6.6**: Centrioles are tiny cylinders near the nucleus, enlarged here to show their tubular structure.

## RIBOSOMES

Ribosomes are small structures where proteins are made. Although they are not enclosed within a membrane, they are frequently considered organelles. Each ribosome is formed of two subunits, like the one pictured at the top of this section. Both subunits consist of proteins and RNA. RNA from the nucleus carries the genetic code, copied from DNA, which remains in the nucleus. At the ribosome, the genetic code in RNA is used to assemble and join together amino acids to make proteins. Ribosomes can be found alone or in groups within the cytoplasm as well as on the RER.

## REVIEW

1. Define organelle.
2. Describe the structure and function of the nucleus.
3. Explain how the nucleus, ribosomes, rough endoplasmic reticulum, and Golgi apparatus work together to make and transport proteins.
4. Why are mitochondria referred to as the power plants of the cell?
5. What roles are played by vesicles and vacuoles?
6. Why do all cells need ribosomes, even prokaryotic cells that lack a nucleus and other cell organelles?
7. Explain endosymbiotic theory as it relates to mitochondria. What is one piece of evidence that supports this theory?
8. Lysosomes and peroxisomes are types of:
   A. A. Organelles
   B. B. Vesicles
   C. C. Vacuoles
   D. D. Both A and B
9. Which of the following organelles fits best with each description of function? Choose only one organelle for each answer: Golgi apparatus, centrioles, nucleolus, nucleus, rough endoplasmic reticulum
   A. a. Contains the genetic instructions for the production of proteins
   B. b. Organizes chromosomes before cell division
   C. c. Provides a framework for ribosomes
   D. d. Packages and labels proteins
   E. e. Assembles ribosomes
10. *True or False.* All eukaryotic cells have a nucleus.
11. *True or False.* The outer surface of the nucleus of a eukaryotic cell is not completely solid.

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## ATTRIBUTIONS


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# 3.7: CELL TRANSPORT

## LETTING IN THE LIGHT

Look at the big windows and glass doors in this house. Imagine all the light they must let in on a sunny day. Now imagine living in a house that has walls without any windows or doors. Nothing could enter or leave. Or imagine living in a house with holes in the walls instead of windows and doors. Things could enter or leave, but you couldn't control what came in or went out. Only if a house has walls with windows and doors that can be opened or closed you can control what enters or leaves. For example, windows and doors allow you to let in light and the family dog and keep out rain and bugs.



Figure **3.7.1**: A house with windows

## TRANSPORT ACROSS MEMBRANES

If a cell were a house, the plasma membrane would be walls with windows and doors. Moving things in and out of the cell is an important role of the plasma membrane. It controls everything that enters and leaves the cell. There are two basic ways that substances can cross the plasma membrane: passive transport, which requires no energy; and active transport, which requires energy. Passive transport is explained in this section and Active transport is explained in the next section, Active Transport and Homeostasis. Various types of cell transport are summarized in the concept map in Figure **3.7.2**.

## TRANSPORT WITHOUT ENERGY

**Passive transport** occurs when substances cross the plasma membrane without any input of energy from the cell. No energy is needed because the substances are moving from an area where they have a higher concentration to an area where they have a lower concentration. Water solutions are very important in biology. When water is mixed with other molecules this mixture is called a **solution**. Water is the **solvent** and the dissolved substance is the **solute**. A solution is characterized by the solute. For example, water and sugar would be characterized as a sugar solution. More the particles of a solute in a given volume, the higher the concentration. The particles of solute always move from an area where it is more concentrated to an area where it is less concentrated. It's a little like a ball rolling down a hill. It goes by itself without any input of extra energy.

The different categories of cell transport are outlined in Figure **3.7.2**. Cell transport can be classified as follows:

- Passive Transport which includes
  - Simple Diffusion
  - Osmosis
  - Facilitated Diffusion
- Active Transport can involve either a pump or a vesicle
  - Pump Transport can be
    - primary
    - secondary
  - Vesicle Transport can involve
    - Exocytosis
    - Endocytosis which includes
      - Pinocytosis
      - Phagocytosis
      - Receptor-Mediated Endocytosis

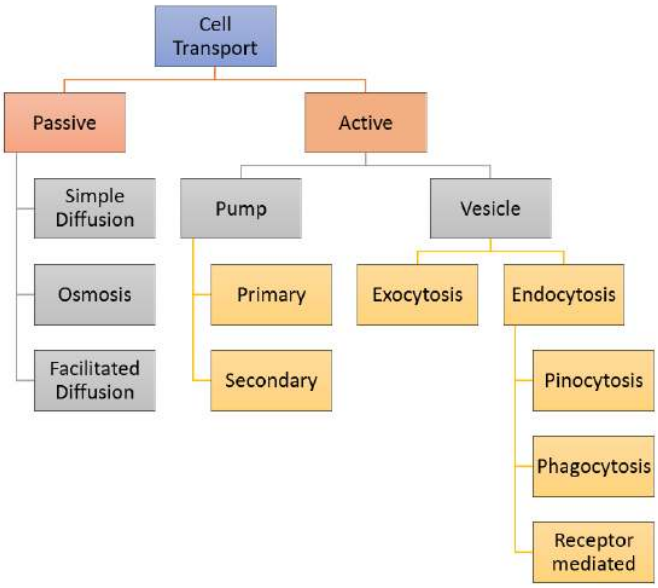



Figure **3.7.2**: The Cell Transport Concept Map illustrates various types of cell transports that happen at the plasma membrane

### SIMPLE DIFFUSION

Diffusion Although you may not know what diffusion is, you have experienced the process. Can you remember walking into the front door of your home and smelling a pleasant aroma coming from the kitchen? It was the diffusion of particles from the kitchen to the front door of the house that allowed you to detect the odors. **Diffusion** is defined as the net movement of particles from an area of greater concentration to an area of lesser concentration.

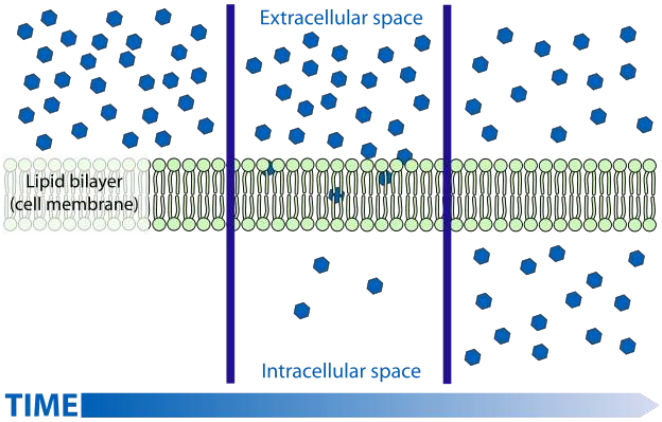



Figure **3.7.3**. Simple diffusion shows as a timeline with the outside of the cell (extracellular space) separated from the inside of the cell (intracellular space) by the cell membrane. In the beginning of the timeline there are many molecules outside of the cell and none inside. Over time, they diffuse into the cell until there is an equal amount outside and inside.

The molecules in a gas, a liquid, or a solid are in constant motion due to their kinetic energy. Molecules are in constant movement and collide with each other. These collisions cause the molecules to move in random directions. Over time, however, more molecules will be propelled into the less concentrated area. Thus, the net movement of molecules is always from more tightly packed areas to less tightly packed areas. Many things can diffuse. Odors diffuse through the air, salt diffuses through water and nutrients diffuse from the blood to the body tissues. This spread of particles through the random motion from an area of high concentration to an area of lower concentration is known as diffusion. This unequal distribution of molecules is called a concentration gradient. Once the molecules become uniformly distributed, a dynamic equilibrium exists. The equilibrium is said to be dynamic because molecules continue to move, but despite this change, there is no net change in concentration over time. Both living and nonliving systems experience the process of diffusion. In living systems, diffusion is responsible for the movement of a large number of substances, such as gases and small uncharged molecules, into and out of cells.

## OSMOSIS

**Osmosis** is a specific type of diffusion; it is the passage of water from a region of high water concentration through a semi-permeable membrane to a region of low water concentration. Water moves in or out of a cell until its concentration is the same on both sides of the plasma membrane.

**Semi-permeable membranes** are very thin layers of material that allow some things to pass through them but prevent other things from passing through. Cell membranes are an example of semi-permeable membranes. Cell membranes allow small molecules such as oxygen, water carbon dioxide, and oxygen to pass through but do not allow larger molecules like glucose, sucrose, proteins, and starch to enter the cell directly.

The classic example used to demonstrate osmosis and osmotic pressure is to immerse cells into sugar solutions of various concentrations. There are three possible relationships that cells can encounter when placed into a sugar solution. Figure **3.7.4** shows what happens in osmosis through the semi-permeable membrane of the cells.

A. The concentration of solute in the solution can be **greater than** the concentration of solute in the cells. This cell is described as being in a **hypertonic solution** (hyper = greater than normal). The net flow or water will be out of the cell.
B. The concentration of solute in the solution can be **equal to** the concentration of solute in cells. In this situation, the cell is in an **isotonic solution** (iso = equal or the same as normal). The amount of water entering the cell is the same as the amount leaving the cell.
C. The concentration of solute in the solution can be **less than** the concentration of solute in the cells. This cell is in a **hypotonic solution** (hypo = less than normal). The net flow of water will be into the cell.

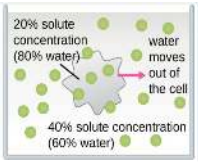



Figure **3.7.4.*A***: **Hypertonic solution.** A solution that has a higher solute concentration than another solution. Water particles will move out of the cell, causing crenation.

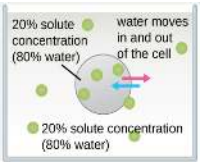



Figure **3.7.4.*B***: **Isotonic solution.** A solution that has the same solute concentration as another solution. There is no net movement of water particles, and the overall concentration on both sides of the cell membrane remains constant.

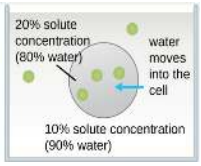



Figure **3.7.4.*C***: **Hypotonic solution.** A solution that has a lower solute concentration than another solution. Water particles will move into the cell, causing the cell to expand and eventually lyse.

Figure **3.7.5** demonstrates the specific outcomes of osmosis in red blood cells.

A. **Hypertonic solution.** The red blood cell will appear to shrink as the water flows out of the cell and into the surrounding environment.
B. **Isotonic solution.** The red blood cell will retain its normal shape in this environment as the amount of water entering the cell is the same as the amount leaving the cell.
C. **Hypotonic solution**. The red blood cell in this environment will become visibly swollen and potentially rupture as water rushes into the cell.

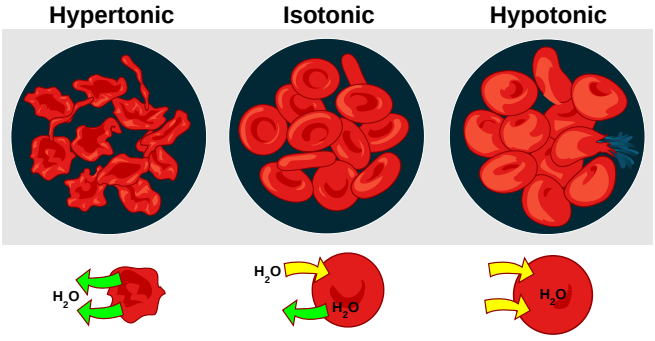



Figure **3.7.5**: Osmosis demonstration with Red Blood cells places in a hypertonic, isotonic, and hypotonic solution.

## FACILITATED DIFFUSION

Water and many other substances cannot simply diffuse across a membrane. Hydrophilic molecules, charged ions, and relatively large molecules such as glucose all need help with diffusion. The help comes from special proteins in the membrane known as **transport proteins**. Diffusion with the help of transport proteins is called **facilitated diffusion**. There are several types of transport proteins, including channel proteins and carrier proteins (Figure **3.7.6**)

- Channel proteins form pores, or tiny holes, in the membrane. This allows water molecules and small ions to pass through the membrane without coming into contact with the hydrophobic tails of the lipid molecules in the interior of the membrane.
- Carrier proteins bind with specific ions or molecules, and in doing so, they change shape. As carrier proteins change shape, they carry the ions or molecules across the membrane.

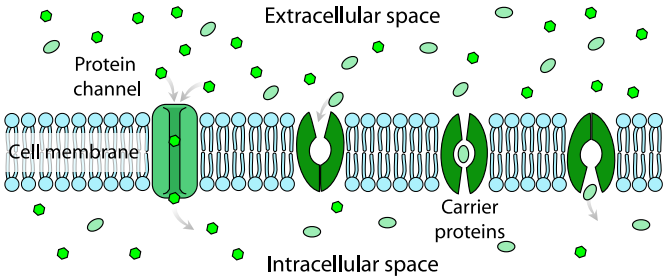



Figure **3.7.6**: Facilitated Diffusion Across a Cell Membrane. Channel proteins and carrier proteins help substances diffuse across a cell membrane. In this diagram, the channel and carrier proteins are helping substances move into the cell (from the extracellular space to the intracellular space). The channel protein has an opening that allows the substances to cross. In a carrier protein, the substance binds to the protein, which then causes the protein to changes shape, thereby releasing the substance into the cell.

## REVIEW

1. What is the main difference between passive and active transport?
2. Summarize three different ways that passive transport can occur, and give an example of a substance that is transported in each way.
3. Explain how transport across the plasma membrane is related to the homeostasis of the cell.
4. Why can generally only very small, hydrophobic molecules across the cell membrane by simple diffusion?
5. Explain how facilitated diffusion assists in osmosis in cells. Be sure to define osmosis and facilitated diffusion in your answer.
6. Imagine a hypothetical cell with a higher concentration of glucose inside the cell than outside. Answer the following questions about this cell, assuming all transport across the membrane is passive, not active.
   A. Can the glucose simply diffuse across the cell membrane? Why or why not?
   B. Assuming that there are glucose transport proteins in the cell membrane, which way would glucose flow – into or out of the cell? Explain your answer.
   C. If the concentration of glucose was equal inside and outside of the cell, do you think there would be a net flow of glucose across the cell membrane in one direction or the other? Explain your answer.
7. What are the similarities and differences between channel proteins and carrier proteins?
8. *True or False.* Only active transport, not passive transport, involves transport proteins.
9. *True or False.* Oxygen and carbon dioxide can squeeze between the lipid molecules in the plasma membrane.
10. *True or False.* Ions easily diffuse across the cell membrane by simple diffusion.
11. Controlling what enters and leaves the cell is an important function of the:
    A. nucleus
    B. vesicle
    C. plasma membrane
    D. Golgi apparatus

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# 3.8: ACTIVE TRANSPORT AND HOMEOSTASIS

## LIKE PUSHING A HUMVEE UPHILL

You can tell by their faces that these airmen are expending a lot of energy trying to push this Humvee up a slope. The men are participating in a competition that tests their brute strength against that of other teams. The Humvee weighs about 13,000 pounds, so it takes every ounce of energy they can muster to move it uphill against the force of gravity. Transport of some substances across a plasma membrane is a little like pushing a Humvee uphill — it can't be done without adding energy.



Figure **3.8.1**: Pushing a machine up a hill.

## WHAT IS ACTIVE TRANSPORT?

Some substances can pass into or out of a cell across the plasma membrane without any energy required because they are moving from an area of higher concentration to an area of lower concentration. This type of transport is called passive transport as you learned in the last section. Other substances require energy to cross a plasma membrane often because they are moving from an area of lower concentration to an area of higher concentration. This type of transport is called **active transport**. The energy for active transport comes from the energy-carrying molecule called ATP (adenosine triphosphate). Active transport may also require transport proteins, such as carrier proteins, which are embedded in the plasma membrane. Two types of active transport are pump and vesicle transport.

### PUMP

Two pump mechanisms (primary and secondary active transports) exist for the transport of small-molecular weight material and macromolecules. The **primary active transport** moves ions across a membrane and creates a difference in charge across that membrane. The primary active transport system uses ATP to move a substance, such as an ion, into the cell, and often at the same time, a second substance is moved out of the cell. The **sodium-potassium pump** is a mechanism of active transport that moves sodium ions out of the cell and potassium ions into the cells — in all the trillions of cells in the body! Both ions are moved from areas of lower to higher concentration, so energy is needed for this "uphill" process. The energy is provided by ATP. The sodium-potassium pump also requires carrier proteins. Carrier proteins bind with specific ions or molecules, and in doing so, they change shape. As carrier proteins change shape, they carry the ions or molecules across the membrane. Figure **3.8.2** shows in greater detail how the sodium-potassium pump works and the specific roles played by carrier proteins in this process.

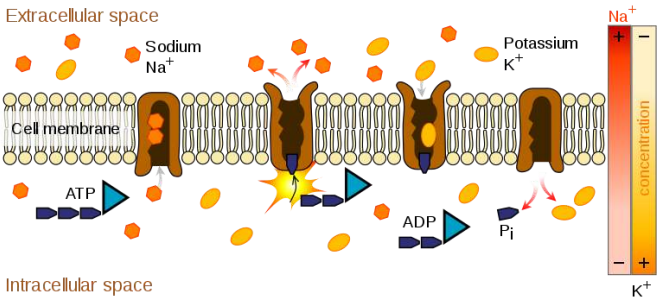



Figure **3.8.2**: The sodium-potassium pump. The sodium-potassium pump moves sodium ions ($Na^+$) out of the cell and potassium ions ($K^+$) into the cell. First, three sodium ions bind with a carrier protein in the cell membrane. Then, the carrier protein receives a phosphate group from ATP. When ATP loses a phosphate group, energy is released. The carrier protein changes shape, and as it does, it pumps the three sodium ions out of the cell. At that point, two potassium ions bind to the carrier protein. The process is reversed, and the potassium ions are pumped into the cell.

To appreciate the importance of the sodium-potassium pump, you need to know more about the roles of sodium and potassium in the body. Both are essential dietary minerals, meaning you have to obtain them in the foods you eat. Both sodium and potassium are also electrolytes, meaning that they dissociate into ions (charged particles) in solution, which allows them to conduct electricity. Normal body functions require a very narrow range of concentrations of sodium and potassium ions in body fluids, both inside and outside of cells.

- Sodium is the principal ion in the fluid outside of cells. Normal sodium concentrations are about 10 times higher outside than inside of cells.
- Potassium is the principal ion in the fluid inside of cells. Normal potassium concentrations are about 30 times higher inside than outside of cells.

These differences in concentration create an electrical gradient across the cell membrane, called the membrane potential. the **secondary active transport** describes the movement of material using the energy of the electrochemical gradient established by the primary active transport. Using the energy of the electrochemical gradient created by the primary active transport system, other substances such as amino acids and glucose can be brought into the cell through membrane channels. ATP itself is formed through secondary active transport using a hydrogen ion gradient in the mitochondrion. Tightly controlling the membrane potential is critical for vital body functions, including the transmission of nerve impulses and the contraction of muscles. A large percentage of the

body's energy goes to maintaining this potential across the membranes of its trillions of cells with the sodium-potassium pump.

## VESICLE TRANSPORT

Some molecules, such as proteins, are too large to pass through the plasma membrane, regardless of their concentration inside and outside the cell. Very large molecules cross the plasma membrane with a different sort of help, called **vesicle transport**. Vesicle transport requires energy, so it is also a form of active transport. There are two types of vesicle transport: endocytosis and exocytosis.

### *ENDOCYTOSIS*

**Endocytosis** is a type of vesicle transport that moves a substance into the cell. The plasma membrane completely engulfs the substance, a vesicle pinches off from the membrane, and the vesicle carries the substance into the cell. It is used by all cells of the body because most substances important to them are polar and consist of big molecules, and thus cannot pass through the hydrophobic plasma membrane. When an entire cell or other solid particle is engulfed, the process is called **phagocytosis**. When fluid is engulfed, the process is called **pinocytosis**. When the content is taken in specifically with the help of receptors on the plasma membrane, it is called **receptor-mediated endocytosis**.

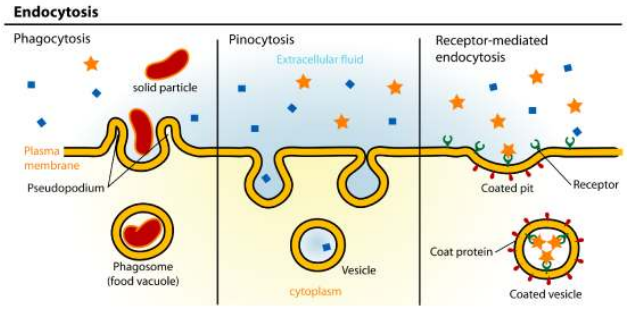



Figure **3.8.3**: (On the right) Phagocytosis is when the plasma membrane wraps around a solid particle outside the cell using projections called pseudopodia. The membrane then pinches off to form a phagosome (food vacuole). (Middle)Pinocytosis is when the membrane folds to form a vesicle that carries substances dissolved in the extracellular fluid. (On the left) Receptor-mediated endocytosis occurs when the receptors on the plasma membrane bind to specific particles. The coated pit region of the membrane forms a coated vesicle containing the receptors with their bound particles.

A targeted variation of endocytosis employs binding proteins in the plasma membrane that are specific for certain substances. The particles bind to the proteins and the plasma membrane invaginates, bringing the substance and the proteins into the cell. If passage across the membrane of the target of **receptor-mediated endocytosis** is ineffective, it will not be removed from the tissue fluids or blood. Instead, it will stay in those fluids and increase in concentration. Some human diseases are caused by a failure of receptor-mediated endocytosis. For example, the form of cholesterol termed low-density lipoprotein or LDL (also referred to as “bad” cholesterol) is removed from the blood by receptor-mediated endocytosis. In the human genetic disease familial hypercholesterolemia, the LDL receptors are defective or missing entirely. People with this condition have life-threatening levels of cholesterol in their blood because their cells cannot clear the chemical from their blood.

### *EXOCYTOSIS*

**Exocytosis** is a type of vesicle transport that moves a substance out of the cell. A vesicle containing the substance moves through the cytoplasm to the cell membrane. Then, the vesicle membrane fuses with the cell membrane, and the substance is released outside the cell.

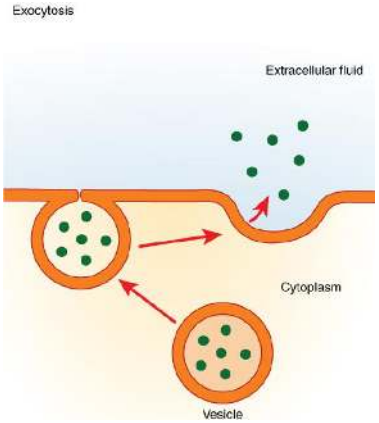



Figure **3.8.4**: Exocytosis is much like endocytosis in reverse. Material destined for export is packaged into a vesicle inside the cell. The membrane of the vesicle fuses with the cell membrane, and the contents are released into the extracellular space.

## HOMEOSTASIS AND CELL FUNCTION

For a cell to function normally, a stable state must be maintained inside the cell. For example, the concentration of salts, nutrients, and other substances must be kept within a certain range. The process of maintaining stable conditions inside a cell (or an entire organism) is homeostasis. Homeostasis requires constant adjustments because conditions are always changing both inside and outside the cell. The processes described in this and previous lessons play important roles in homeostasis. By moving substances into and out of cells, they keep conditions within normal ranges inside the cells and the organism as a whole.

### FEATURE:FEATURE: MY HUMAN BODY

Maintaining the proper balance of sodium and potassium in body fluids by active transport is necessary for life itself, so it's no surprise that getting the right balance of sodium and potassium in the diet is important for good health. Imbalances may increase the risk of high blood pressure, heart disease, diabetes, and other disorders.

If you are like the majority of Americans, sodium and potassium are out of balance in your diet. You are likely to consume too much sodium and too little potassium. Follow these guidelines to help ensure that these minerals are in balance in the foods you eat:

- Total sodium intake should be less than 2300 mg/day. Most salt in the diet is found in processed foods or added with a salt shaker. Stop adding salt and start checking food labels for sodium content. Foods considered low in sodium have less than 140 mg/serving (or 5% daily value).
- Total potassium intake should be 4700 mg/day. It's easy to add potassium to the diet by choosing the right foods, and there are plenty of choices. Most fruits and vegetables are high in potassium, but especially potatoes, bananas, oranges, apricots, plums, leafy greens, tomatoes, lima beans, and avocado. Other foods with substantial amounts of potassium are fish, meat, poultry, and whole grains.

## REVIEW

1. Define active transport.
2. What is the sodium-potassium pump? Why is it so important?
3. Name two types of vesicle transport. Which type moves substances out of the cell?
4. What are the similarities and differences between phagocytosis and pinocytosis?
5. The sodium-potassium pump is a:
   A. Phospholipid
   B. Protein
   C. Carbohydrate
   D. Ion
6. What is the functional significance of the shape change of the carrier protein in the sodium-potassium pump after the sodium ions bind?
7. A potentially deadly poison derived from plants called ouabain blocks the sodium-potassium pump and prevents it from working. What do you think this does to the sodium and potassium balance in cells? Explain your answer.
8. True or False. The sodium-potassium pump uses one protein to pump both sodium and potassium.
9. True or False. Vesicles are made of the nuclear membrane.
10. What is an electrical gradient across the cell membrane called?
11. Chemical signaling molecules called neurotransmitters are released from nerve cells (neurons) through vesicles. This is an example of:
    A. Pinocytosis
    B. Phagocytosis
    C. Endocytosis
    D. Exocytosis
12. The energy for active transport comes from
    A. ATP
    B. RNA
    C. Carrier proteins
    D. Sodium ions
13. Transport proteins that move substances into and out of a cell are located in which structure?

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# 3.9: CELLULAR RESPIRATION

## BRING ON THE S'MORES!

This inviting campfire can be used for both heat and light. Heat and light are two forms of energy that are released when a fuel like wood is burned. The cells of living things also get energy by "burning." They "burn" glucose in the process called cellular respiration.



Figure **3.9.1**: Burning logs that convert carbon in wood into carbon dioxide and a significant amount of thermal energy.

Inside every cell of all living things, energy is needed to carry out life processes. Energy is required to break down and build up molecules and to transport many molecules across plasma membranes. All of life's work needs energy. A lot of energy is also simply lost to the environment as heat. The story of life is a story of energy flow — its capture, its change of form, its use for work, and its loss as heat. Energy, unlike matter, cannot be recycled, so organisms require a constant input of energy. Life runs on chemical energy. Where do living organisms get this chemical energy?

## WHERE DO ORGANISMS GET ENERGY FROM?

The chemical energy that organisms need comes from food. Food consists of organic molecules that store energy in their chemical bonds. Glucose is a simple carbohydrate with the chemical formula $C_6H_{12}O_6$. It stores chemical energy in a concentrated, stable form. In your body, glucose is the form of energy that is carried in your blood and taken up by each of your trillions of cells. Cells do cellular respiration to extract energy from the bonds of glucose and other food molecules. Cells can store the extracted energy in the form of ATP (adenosine triphosphate).

## WHAT IS ATP?

Let's take a closer look at a molecule of ATP, shown in the figure **3.9.2**. Although it carries less energy than glucose, its structure is more complex. "A" in ATP refers to the majority of the molecule – adenosine – a combination of a nitrogenous base and a five-carbon sugar. "T" and "P" indicate the three phosphates, linked by bonds that hold the energy actually used by cells. Usually, only the outermost bond breaks to release or spend energy for cellular work.

An ATP molecule is like a rechargeable battery: its energy can be used by the cell when it breaks apart into ADP (adenosine diphosphate) and phosphate, and then the "worn-out battery" ADP can be recharged using new energy to attach a new phosphate and rebuild ATP. The materials are recyclable, but recall that energy is not! ADP can be further reduced to AMP (adenosine monophosphate and phosphate, releasing additional energy. As with ADP "recharged" to ATP, AMP can be recharged to ADP.

How much energy does it cost to do your body's work? A single cell uses about 10 million ATP molecules per second and recycles all of its ATP molecules about every 20-30 seconds.

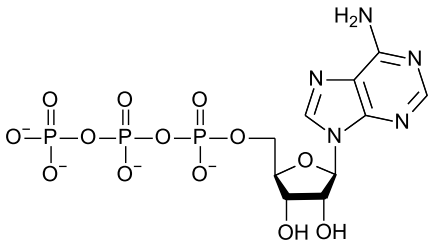



Figure **3.9.2**: Chemical structure of ATP consists of a 5-carbon sugar (ribose) attached to a nitrogenous base (adenine) and three phosphates. When the covalent bond between the terminal phosphate group and the middle phosphate group breaks, energy is released which is used by the cells to do work.

## WHAT IS CELLULAR RESPIRATION?

Some organisms can make their own food, whereas others cannot. An **autotroph** is an organism that can produce its own food. The Greek roots of the word *autotroph* mean "self" (*auto*) "feeder" (*troph*). Plants are the best-known autotrophs, but others exist, including certain types of bacteria and algae. Oceanic algae contribute enormous quantities of food and oxygen to global food chains. Plants are also **photoautotrophs**, a type of autotroph that uses sunlight and carbon from carbon dioxide to synthesize chemical energy in the form of carbohydrates. **Heterotrophs** are organisms incapable of photosynthesis that must therefore obtain energy and carbon from food by consuming other organisms. The Greek roots of the word *heterotroph* mean "other" (*hetero*) "feeder" (*troph*), meaning that their food comes from other organisms. Even if the food organism is another animal, this food traces its origins back to autotrophs and the process of photosynthesis. Humans are heterotrophs, as are all animals. Heterotrophs depend on autotrophs, either directly or indirectly.

**Cellular respiration** is the process by which individual cells break down food molecules, such as glucose and release energy. The process is similar to burning, although it doesn't produce light or intense heat as a campfire does. This is because cellular respiration releases the energy in glucose slowly, in many small steps. It uses the energy that is released to form molecules of ATP, the energy-carrying molecules that cells use to power biochemical processes. Cellular respiration involves many chemical reactions, but they can all be summed up with this chemical equation:

$$C_6H_{12}O_6 + 6\,O_2 \longrightarrow 6\,CO_2 + 6\,H_2O + \text{Energy}$$

where the energy that is released is in chemical energy in ATP (vs. thermal energy as heat). The equation above shows that glucose ( $C_6H_{12}O_6$) and oxygen ($O_2$) react to form carbon dioxide ($CO_2$) and water $H_2O$, releasing energy in the process. Because oxygen is required for cellular respiration, it is an **aerobic** process.

Cellular respiration occurs in the cells of all living things, both autotrophs and heterotrophs. All of them catabolize glucose to form ATP. The reactions of cellular respiration can be grouped into three main stages and an intermediate stage: **glycolysis**, **Transformation of pyruvate**, the **Krebs cycle** (also called the citric acid cycle), and **Oxidative Phosphorylation**. Figure 3.9.3 gives an overview of these three stages, which are also described in detail below.

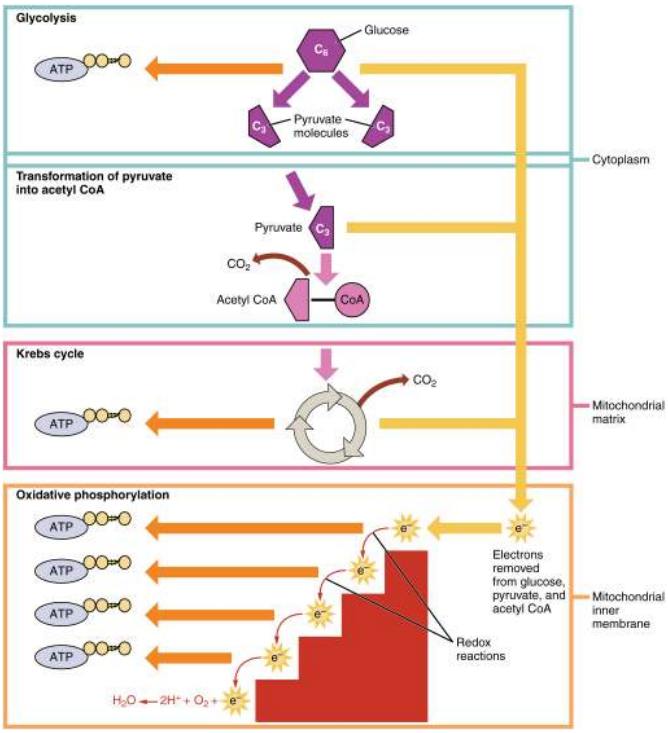



Figure 3.9.3: Cellular respiration takes place in the stages shown here. The process begins with Glycolysis. In this first step, a molecule of glucose, which has six carbon atoms, is split into two three-carbon molecules. The three-carbon molecule is called pyruvate. Pyruvate is oxidized and converted into Acetyl CoA. These two steps occur in the cytoplasm of the cell. Acetyl CoA enters into the matrix of mitochondria, where it is fully oxidized into Carbon Dioxide via the Krebs cycle. Finally, During the process of oxidative phosphorylation, the electrons extracted from food move down the electron transport chain in the inner membrane of the mitochondrion. As the electrons move down the ETC and finally to oxygen, they lose energy. This energy is used to phosphorylate AMP to make ATP.

## GLYCOLYSIS

The first stage of cellular respiration is **glycolysis**. This process is shown in the top box in Figure 3.9.3 showing a 6-carbon molecule being broken down into two 3-carbon pyruvate molecules. ATP is produced in this process which takes place in the cytosol of the cytoplasm.

### SPLITTING GLUCOSE

The word *glycolysis* means "glucose splitting," which is exactly what happens in this stage. Enzymes split a molecule of glucose into two molecules of pyruvate (also known as pyruvic acid). This occurs in several steps, as shown in figure 3.9.4. Glucose is first split into glyceraldehyde 3-phosphate (a molecule containing 3 carbons and a phosphate group). This process uses 2 ATP. Next, each glyceraldehyde 3-phosphate is converted into pyruvate (a 3-carbon molecule). this produces two 4 ATP and 2 NADH.

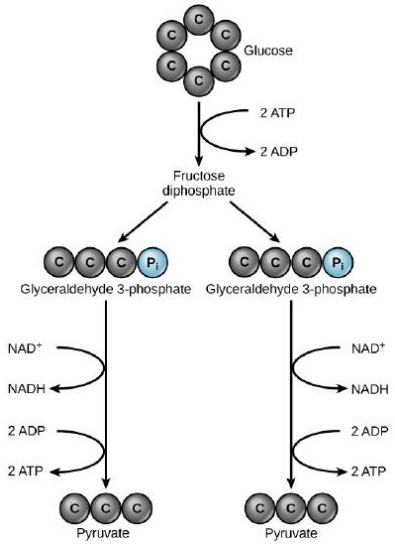



Figure 3.9.4: In glycolysis, a glucose molecule is converted into two pyruvate molecules.

### RESULTS OF GLYCOLYSIS

Energy is needed at the start of glycolysis to split the glucose molecule into two pyruvate molecules. These two molecules go on to stage II of cellular respiration. The energy to split glucose is provided by two molecules of ATP. As glycolysis proceeds, energy is released, and the energy is used to make four molecules of ATP. As a result, there is a **net gain of two ATP molecules** during glycolysis. high-energy electrons are also transferred to energy-carrying molecules called electron carriers through the process
known as reduction. The electron carrier of glycolysis is **NAD+ (nicotinamide adenine diphosphate)**. Electrons are transferred to 2 NAD+ to produce two molecules of NADH. The energy stored in NADH is used in stage III of cellular respiration to make more ATP. At the end of glycolysis, the following has been produced:

- 2 molecules of NADH
- 2 net molecules of ATP

## TRANSFORMATION OF PYRUVATE INTO ACETYL-COA

In eukaryotic cells, the pyruvate molecules produced at the end of glycolysis are transported into mitochondria, which are sites of cellular respiration. If oxygen is available, aerobic respiration will go forward. In mitochondria, pyruvate will be transformed into a two-carbon acetyl group (by removing a molecule of carbon dioxide) that will be picked up by a carrier compound called

coenzyme A (CoA), which is made from vitamin $B_5$. The resulting compound is called acetyl CoA and its production is frequently called the oxidation or the Transformation of Pyruvate (see Figure **3.9.5**. Acetyl CoA can be used in a variety of ways by the cell, but its major function is to deliver the acetyl group derived from pyruvate to the next pathway step, the Citric Acid Cycle.

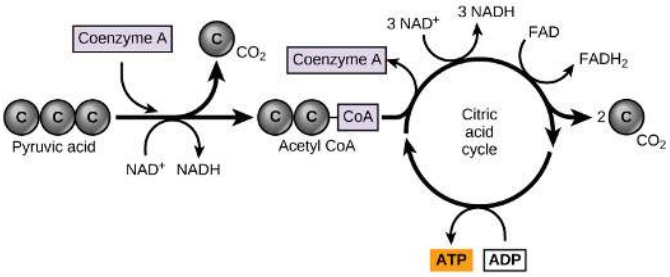



Figure **3.9.5**: Pyruvate is converted into acetyl-CoA before entering the Citric Acid Cycle (Krebs cycle)

## CITRIC ACID CYCLE

Before you read about the last two stages of cellular respiration, you need to review the structure of the mitochondrion, where these two stages take place. As you can see from Figure **3.9.6**, a mitochondrion has an inner and outer membrane. The space between the inner and outer membrane is called the intermembrane space. The space enclosed by the inner membrane is called the matrix. The second stage of cellular respiration, the Krebs cycle, takes place in the matrix. The third stage, electron transport, takes place on the inner membrane.

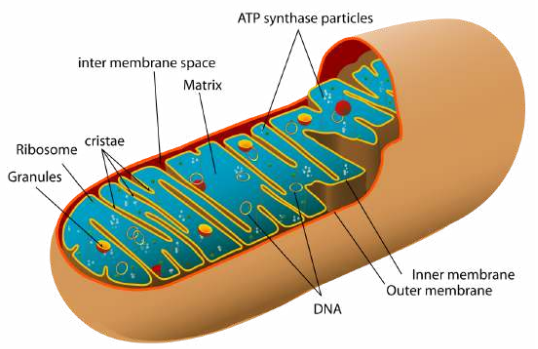



Figure **3.9.6**: The structure of a mitochondrion is defined by an inner and outer membrane. The space inside the inner membrane is full of fluid, enzymes, ribosomes, and mitochondrial DNA. This space is called a matrix. The inner membrane has a larger surface area as compared to the outer membrane. Therefore, it creases. The extensions of the creases are called cristae. The space between the outer and inner membrane is called intermembrane space.

Recall that glycolysis produces two molecules of pyruvate (pyruvic acid). Pyruvate, which has three carbon atoms, is split apart and combined with CoA, which stands for coenzyme A. The product of this reaction is acetyl-CoA. These molecules enter the matrix of a mitochondrion, where they start the Citric Acid Cycle. The third carbon from pyruvate combines with oxygen to form carbon dioxide, which is released as a waste product. High-energy electrons are also released and captured in NADH. The reactions that occur next are shown in Figure **3.9.7**.

## STEPS OF THE CITRIC ACID (KREBS) CYCLE

The Citric Acid Cycle begins when acetyl-CoA combines with a four-carbon molecule called OAA (oxaloacetate; see the lower panel of Figure **3.9.7**). This produces citric acid, which has six carbon atoms. This is why the Krebs cycle is also called the citric acid cycle. After citric acid forms, it goes through a series of reactions that release energy. This energy is captured in molecules of ATP and electron carriers. The Krebs cycle has two types of energy-carrying electron carriers: NAD+ and FAD. The transfer of electrons to FAD during the Kreb's Cycle produces a molecule of $FADH_2$. Carbon dioxide is also released as a waste product of these reactions. The final step of the Krebs cycle regenerates OAA, the molecule that began the Krebs cycle. This molecule is needed for the next turn through the cycle. Two turns are needed because glycolysis produces two pyruvate molecules when it splits glucose.

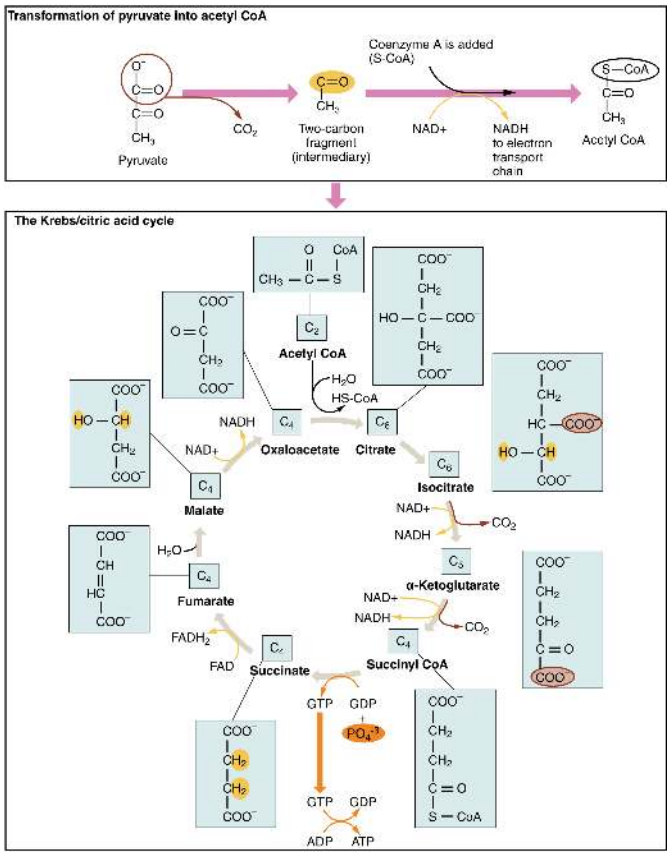



Figure **3.9.7**: In the Citric Acid Cycle, the acetyl group from acetyl CoA is attached to a four-carbon oxaloacetate molecule to form a six-carbon citrate molecule. Through a series of steps, citrate is oxidized, releasing two carbon dioxide molecules for each acetyl group fed into the cycle. In the process, three $NAD^+$ molecules are reduced to NADH, one FAD molecule is reduced to $FADH_2$, and one ATP or GTP (depending on the cell type) is produced (by substrate-level phosphorylation). Because the final product of the citric acid cycle is also the first reactant, the cycle runs continuously in the presence of sufficient reactants.

### RESULTS OF THE CITRIC ACID CYCLE

After the second turn through the Citric Acid Cycle, the original glucose molecule has been broken down completely. All six of its carbon atoms have combined with oxygen to form carbon dioxide. The energy from its chemical bonds has been stored in a total of 16 energy-carrier molecules. These molecules are:

- 2 ATP
- 8 NADH
- 2 $FADH_2$
- 6 $CO_2$: 2 $CO_2$ from Transformation of Acetyl CoA and 4 $CO_2$ from Citric Acid Cycle.

## OXIDATIVE PHOSPHORYLATION

Oxidative phosphorylation is the final stage of aerobic cellular respiration. There are two substages of oxidative phosphorylation, Electron transport chain and Chemiosmosis. In these stages, energy from NADH and $FADH_2$, which result from the previous stages of cellular respiration, is used to create ATP.

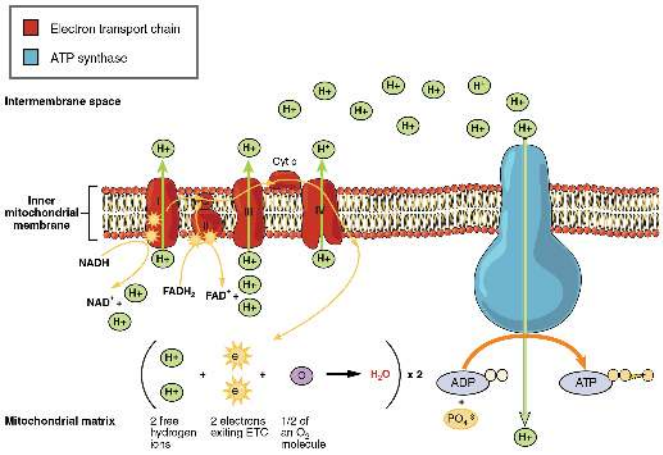



Figure **3.9.8**: Oxidative Phosphorylation: Electron Transport chain and Chemiosmosis.

### ELECTRON TRANSPORT CHAIN (ETC)

During this stage, high-energy electrons are released from NADH and $FADH_2$, and they move along electron-transport chains found in the inner membrane of the mitochondrion. An electron-transport chain is a series of molecules that transfer electrons from molecule to molecule by chemical reactions. These molecules are found making up the three complexes of the electron transport chain (red structures in the inner membrane in Figure **3.9.8**). As electrons flow through these molecules, some of the energy from the electrons is used to pump hydrogen ions (H+) across the inner membrane, from the matrix into the intermembrane space. This ion transfer creates an electrochemical gradient that drives the synthesis of ATP. The electrons from the final protein of the ETC are gained by the oxygen molecule, and it is reduced to water in the matrix of the mitochondrion.

### CHEMIOSMOSIS

The pumping of hydrogen ions across the inner membrane creates a greater concentration of these ions in the intermembrane space than in the matrix – producing an electrochemical gradient. This gradient causes the ions to flow back across the membrane into the matrix, where their concentration is lower. The flow of these ions occurs through a protein complex, known as the ATP synthase complex (see blue structure in the inner membrane in Figure **3.9.8**. The ATP synthase acts as a channel protein, helping the hydrogen ions across the membrane. The flow of protons through ATP synthase is considered chemiosmosis. ATP synthase also acts as an enzyme, forming ATP from ADP and inorganic phosphate. It is the flow of hydrogen ions through ATP synthase that gives the energy for ATP synthesis. After passing through the electron-transport chain, the low-energy electrons combine with oxygen to form water.

## HOW MUCH ATP?

You have seen how the three stages of aerobic respiration use the energy in glucose to make ATP. How much ATP is produced in all three stages combined? Glycolysis produces 2 ATP molecules, and the Krebs cycle produces 2 more. Electron transport from the molecules of NADH and $FADH_2$ made from glycolysis, the transformation of pyruvate, and the Krebs cycle creates as many as 32 more ATP molecules. Therefore, a total of up to 36 molecules of ATP can be made from just one molecule of glucose in the process of cellular respiration.

## REVIEW

1. What is the purpose of cellular respiration? Provide a concise summary of the process.
2. Draw and explain the structure of ATP (Adenosine Tri-Phosphate).
3. State what happens during glycolysis.
4. Describe the structure of a mitochondrion.
5. Outline the steps of the Krebs cycle.
6. What happens during the electron transport stage of cellular respiration?
7. How many molecules of ATP can be produced from one molecule of glucose during all three stages of cellular respiration combined?
8. Do plants undergo cellular respiration? Why or why not?
9. Explain why the process of cellular respiration described in this section is considered aerobic.
10. Name three energy-carrying molecules involved in cellular respiration.
11. Energy is stored within chemical _____ within a glucose molecule.
12. *True or False*. During cellular respiration, NADH and ATP are used to make glucose.
13. *True or False*. ATP synthase acts as both an enzyme and a channel protein.
14. *True or False*. The carbons from glucose end up in ATP molecules at the end of cellular respiration.
15. Which stage of aerobic cellular respiration produces the most ATP?

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# 3.10: FERMENTATION

## FAST AND FURIOUS

The muscles of this sprinter will need a lot of energy to complete their short race because they will be running at top speed. The action won't last long, but it will be very intense. The energy the sprinter needs can't be provided quickly enough by aerobic cellular respiration. Instead, a different process must be used by their muscle cells to power their activity.



Figure **3.10.1**: Sprinter on the field

## MAKING ATP WITHOUT OXYGEN

The cells of living things power their activities with the energy-carrying molecule ATP (adenosine triphosphate). The cells of most living things make ATP from glucose in the process of cellular respiration. This process occurs in three major stages, and one intermediate stage: glycolysis, oxidation of pyruvate, the Krebs cycle, and electron transport. The latter two stages require oxygen, making cellular respiration an aerobic process. There are also other ways of making ATP from glucose without oxygen, such as **anaerobic respiration** and **fermentation,** of making ATP from glucose without oxygen. Our cells do not perform anaerobic respiration. Therefore, we will only focus on fermentation in this section.

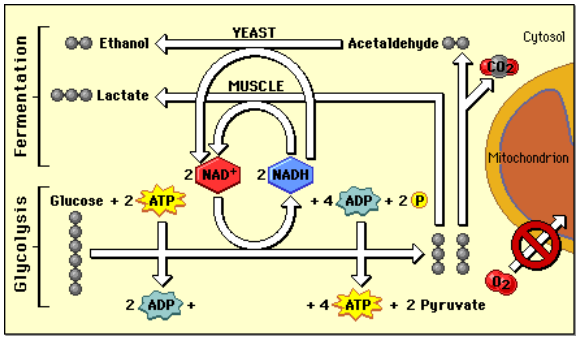



Figure **3.10.2**. The picture shows glycolysis and fermentation. There are two types of fermentation, alcoholic and lactic acid. Fermentation follows glycolysis in the absence of oxygen. Alcoholic fermentation produces ethanol, carbon dioxide, and $NAD^+$. Lactic acid fermentation produces lactic acid (lactate) and $NAD^+$. The $NAD^+$ cycles back to allow glycolysis to continue so more ATP is made. Each black ball in the image represents a carbon atom, and the red balls represent oxygen.

## FERMENTATION

Fermentation starts with glycolysis, but it does not involve the latter two stages of aerobic cellular respiration (the Krebs cycle and oxidative phosphorylation). During glycolysis, two NAD+ electron carriers are reduced to two NADH molecules and 2 net ATPs are produced. The NADH must be oxidized back so that glycolysis can continue and cells can continue making 2 ATPs. The cells cannot make more than 2 ATP in fermentation because oxidative phosphorylation does not happen due to a lack of oxygen. There are two types of fermentation, alcoholic fermentation and lactic acid fermentation. Our cells can only perform lactic acid fermentation; however, we make use of both types of fermentation using other organisms.

### ALCOHOLIC FERMENTATION

**Alcoholic fermentation** The process by which this happens is summarized in Figure **3.10.2**. The two pyruvate molecules are shown in this diagram come from the splitting of glucose through glycolysis. This process also produces 2 molecules of ATP. Continued breakdown of pyruvate produces acetaldehyde, carbon dioxide, and eventually ethanol. Alcoholic fermentation requires the electrons from NADH and results in the generation of NAD+.

Yeast in bread dough also uses alcoholic fermentation for energy and produces carbon dioxide gas as a waste product. The carbon dioxide that is released causes bubbles in the dough and explains why the dough rises. Do you see the small holes in the bread in Figure **3.10.3**? The holes were formed by bubbles of carbon dioxide gas.



Figure **3.10.3**: Holes from carbon dioxide gas in bread dough are left behind after the bread bakes.

### LACTIC ACID FERMENTATION

**Lactic acid fermentation** is carried out by certain bacteria, including the bacteria in yogurt. It is also carried out by your muscle cells when you work them hard and fast. This is how the muscles of the sprinter in Figure **3.10.1**get energy for their short-duration but intense activity. The process by which this happens is summarized in Figure **3.10.2**. Again, two pyruvate and two ATP molecules result from glycolysis. Reduction of pyruvate using the electrons carried by NADH produces lactate (i.e. lactic acid). While this is similar to alcoholic fermentation, there is no carbon dioxide produced in this process.

Did you ever run a race, lift heavy weights, or participate in some other intense activity and notice that your muscles start to feel a burning sensation? This may occur when your muscle cells use lactic acid fermentation to provide ATP for energy. The buildup of lactic acid in the muscles causes the feeling of burning. The painful sensation is useful if it gets you to stop overworking your muscles and allow them a recovery period during which cells can eliminate the lactic acid.

## PROS AND CONS OF FERMENTATION

With oxygen, organisms can use aerobic cellular respiration to produce up to 36 molecules of ATP from just one molecule of glucose. Without oxygen, some human cells must use fermentation to produce ATP, and this process produces only two molecules of ATP per molecule of glucose. Although fermentation produces less ATP, it has the advantage of doing so very quickly. It allows your muscles, for example, to get the energy they need for short bursts of intense activity. Aerobic cellular respiration, in contrast, produces ATP more slowly.

### FEATURE: MYTH VS. REALITY

**Myth:** lactic acid build-up can cause muscle fatigue and a burning sensation in muscles. The soreness is thought to be due to microscopic damage to the muscle fibers.

**Reality:** The statement about lactic acid causing the burn in the muscle has no solid experimental proof. Alternate hypotheses suggest that through the production of lactic acid, the internal pH of the muscle decreases, triggering contraction in muscle due to the activation of motor neurons.

## REVIEW

1. State the main difference between aerobic cellular respiration and fermentation.
2. What is fermentation?
3. Compare and contrast alcoholic and lactic acid fermentation.
4. Identify the major pro and the major con of fermentation relative to aerobic cellular respiration.
   A. What process is shared between aerobic cellular respiration and fermentation? Describe the process briefly.
   B. Why is this process able to occur in fermentation as well as aerobic respiration?
5. Which type of metabolic process occurs in the human body?
   A. Aerobic cellular respiration
   B. Alcoholic fermentation
   C. Lactic acid fermentation
   D. Both A and C
6. *True or False.* Lactic acid fermentation produces carbon dioxide.
7. *True or False.* Types of bacteria can carry out alcoholic fermentation and lactic acid fermentation.
8. *True or False.* No ATP is produced by fermentation.
9. Both lactic acid fermentation and alcoholic fermentation use which acid molecules to make their final products?
10. Which type of process is used in the making of bread and wine?
    A. Alcoholic fermentation
    B. Lactic acid fermentation
    C. Aerobic cellular respiration
    D. Prokaryotic respiration
11. Is fermentation an aerobic or anaerobic process?
12. What is the reactant, or starting material, shared by aerobic respiration and both types of fermentation?

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# 3.11: CASE STUDY CONCLUSION- TIRED AND CHAPTER SUMMARY

## CASE STUDY CONCLUSION: MORE THAN JUST TIRED

Jasmin discovered that her extreme fatigue, muscle pain, vision problems, and vomiting were due to problems in her mitochondria. Mitochondria are small membrane-bound organelles found in eukaryotic cells that provide energy for the cells of the body. They do this by carrying out the final two steps of aerobic cellular respiration, the Krebs cycle, and electron transport, which is the major way that the human body breaks down the sugar glucose from food into a form of energy cells can use, namely the molecule ATP.

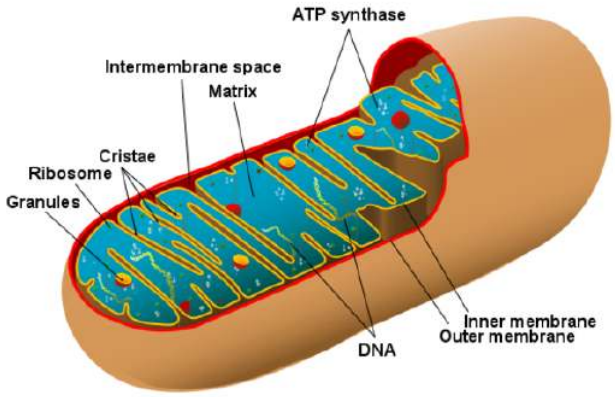



Figure **3.11.1**: Mitochondrial structures. You can see the outer membrane, the inner membrane with cristae, intermembrane space, and matrix with granules, ribosomes, and mitochondrial DNA. ATP synthase is located in the inner membrane.

Because mitochondria provide energy for cells, you can probably easily see why Jasmin was experiencing extreme fatigue, particularly after running. Her damaged mitochondria could not keep up with her need for energy, particularly after intense exercise which requires a lot of additional energy. What is perhaps not so obvious are the reasons for her other symptoms, such as blurry vision, muscle spasms, and vomiting. But all the cells in the body require energy in order to function properly. Mitochondrial diseases can cause problems in mitochondria in any cell of the body, including muscle cells and cells of the nervous system, which includes the brain and nerves. The nervous system and muscles work together to control vision and digestive system functions, such as vomiting, so when they are not functioning properly, a variety of symptoms can emerge. This also explains why Jasmin's niece, who also has mitochondrial disease, has symptoms related to brain function, such as seizures and learning disabilities. Our cells are microscopic and mitochondria are even tinier, but they are essential for the proper functioning of our bodies and when they are damaged, serious health effects can occur.

A seemingly confusing aspect of mitochondrial diseases is that the type of symptoms, severity of symptoms, and age of onset can vary wildly between people — even within the same family! In Jasmin's case, she did not notice symptoms until adulthood, while her niece had more severe symptoms starting at a much younger age. However, this makes sense when you know more about how mitochondrial diseases work.

Inherited mitochondrial diseases can be due to damage in either the DNA in the nucleus of cells or the DNA in the mitochondria themselves. Recall that mitochondria are thought to have evolved from prokaryotic organisms that were once free-living, but then infected or were engulfed by larger cells. One of the pieces of evidence that supports this endosymbiotic theory is that mitochondria have their own, separate DNA. When the mitochondrial DNA is damaged or mutated, it can result in some types of mitochondrial diseases. However, these mutations do not typically affect *all of* the mitochondria in a cell. During cell division, organelles such as mitochondria are replicated and passed down to the new daughter cells. If some of the mitochondria are damaged, and others are not, the daughter cells can have different amounts of damaged mitochondria. This helps explain the wide range of symptoms in people with mitochondrial diseases, even ones in the same family because different cells in their bodies are affected to different extents. Jasmin's niece was affected strongly and her symptoms were noticed early, while Jasmin's symptoms were milder and did not become apparent until adulthood.

There is still much more that needs to be discovered about the different types of mitochondrial diseases. But by learning about cells, their organelles, how they obtain energy, and how they divide, you should now have a better understanding of the biology behind these diseases. Apply your understanding of cells to your own life — can you think of other diseases that affect cellular structures or functions, maybe that even affect people you know? Since your entire body is made of cells, when they are damaged or not functioning properly it can cause a wide variety of health problems.

## CHAPTER SUMMARY

In this chapter, you learned many facts about cells. Specifically, you learned that:

- Cells are the basic units of structure and function of living things.
- The first cells, from cork, were observed by Hooke in the 1600s. Soon after, van Leeuwenhoek observed other living cells.
- In the early 1800s, Schwann and Schleiden theorized that cells are the basic building blocks of all living things. Around 1850, Virchow saw cells dividing and added that living cells arise only from other living cells. These ideas led to cell theory, which states that all organisms are made of cells, all life functions occur in cells, and all cells come from other cells.
- The invention of the electron microscope in the 1950s allowed scientists to see organelles and other structures inside cells for the first time.

- There is variation in cells, but all cells have a plasma membrane, cytoplasm, ribosomes, and DNA.
  - The plasma membrane is composed mainly of a bilayer of phospholipid molecules and forms a barrier between the cytoplasm inside the cell and the environment outside the cell. It allows only certain substances to pass in or out of the cell. Some cells have extensions of their plasma membrane with other functions, such as flagella or cilia.
  - The cytoplasm is a thick solution that fills a cell and is enclosed by the cell membrane. It helps give the cell shape, holds organelles, and provides a site for many of the biochemical reactions inside the cell. The liquid part of the cytoplasm is called cytosol.
  - Ribosomes are small structures where proteins are made.
- Cells are usually very small so they have a large enough surface-area-to-volume ratio to maintain normal cell processes. Cells with different functions often have different shapes.
- Prokaryotic cells do not have a nucleus. Eukaryotic cells have a nucleus as well as other organelles. An organelle is a structure within the cytoplasm of a cell that is enclosed within a membrane and performs a specific job.
- The cytoskeleton is a highly organized framework of protein filaments and tubules that criss-cross the cytoplasm of a cell. It gives the cell structure and helps to hold cell structures such as organelles in place.
- The nucleus is the largest organelle in a eukaryotic cell and is considered to be the cell's control center. It contains DNA and controls gene expression, including which proteins the cell makes.
- The mitochondrion is an organelle that makes energy available to cells. According to the widely accepted endosymbiotic theory, mitochondria evolved from prokaryotic cells that were once free-living organisms that infected or were engulfed by larger prokaryotic cells.
- The endoplasmic reticulum (ER) is an organelle that helps make and transport proteins and lipids. Rough endoplasmic reticulum (RER) is studded with ribosomes. Smooth endoplasmic reticulum (SER) has no ribosomes.
- The Golgi apparatus is a large organelle that processes proteins and prepares them for use both inside and outside the cell. It is also involved in the transport of lipids around the cell.
- Vesicles and vacuoles are sac-like organelles that may be used to store and transport materials in the cell or as chambers for biochemical reactions. Lysosomes and peroxisomes are vesicles that break down foreign matter, dead cells, or poisons.
- Centrioles are organelles located near the nucleus that help organize the chromosomes before cell division so each daughter cell receives the correct number of chromosomes.
- There are two basic ways that substances can cross the cell's plasma membrane: passive transport, which requires no energy; and active transport, which requires energy.
- No energy is needed for passive transport because it occurs when substances move naturally from an area of higher concentration to an area of lower concentration. Types of passive transport in cells include:
  - Simple diffusion, which is the movement of a substance due to differences in concentration without any help from other molecules. This is how very small, hydrophobic molecules, such as oxygen and carbon dioxide, enter and leave the cell.
  - Osmosis, which is the diffusion of water molecules across the membrane.
  - Facilitated diffusion, which is the movement of a substance across a membrane due to differences in concentration but only with the help of transport proteins in the membrane, such as channel proteins or carrier proteins. This is how large or hydrophilic molecules and charged ions enter and leave the cell.
- Active transport requires energy to move substances across the plasma membrane, often because the substances are moving from an area of lower concentration to an area of higher concentration or because of their large size. Two examples of active transport are the sodium-potassium pump and vesicle transport.
  - The sodium-potassium pump moves sodium ions out of the cell and potassium ions into the cell, both against a concentration gradient, in order to maintain the proper concentrations of both ions inside and outside the cell and to thereby control membrane potential.
  - Vesicle transport uses vesicles to move large molecules into or out of cells.
- Energy is the ability to do work and is needed by every living cell to carry out life processes.
- The form of energy that living things need is chemical energy, and it comes from food. Food consists of organic molecules that store energy in their chemical bonds.
- Organisms mainly use glucose and ATP for energy. Glucose is the compact, stable form of energy that is carried in the blood and taken up by cells. ATP contains less energy and is used to power cellular processes.
- Cellular respiration is the aerobic process by which living cells break down glucose molecules, release energy, and form molecules of ATP. This process involves Glycolysis, Transformation of Pyruvate, Krebs Cycle, and Oxidative phosphorylation. Overall, in this process, glucose and oxygen react to form carbon dioxide and water.
  - The first stage of cellular respiration, called glycolysis, takes place in the cytoplasm. In this step, enzymes split a molecule of glucose into two molecules of pyruvate, which releases energy that is transferred to ATP.
  - Pyruvate is transformed to Acetyl CoA in the intermediate stage
  - The second major stage of cellular respiration, called the Krebs cycle, takes place in the matrix of a mitochondrion. During this stage, two turns through the cycle result in all of the carbon atoms from the two pyruvate molecules forming

carbon dioxide and the energy from their chemical bonds being stored in a total of 16 energy-carrying molecules (including 4 from glycolysis).
    - The third stage of cellular respiration, Oxidative Phosphorylation, takes place on the inner membrane of the mitochondrion. Electrons are transported from molecule to molecule down an electron-transport chain. Some of the energy from the electrons is used to pump hydrogen ions across the membrane, creating an electrochemical gradient that drives the synthesis of many more molecules of ATP.
    - In all three stages of aerobic cellular respiration combined, as many as 36 molecules of ATP are produced from just one molecule of glucose.
- Some organisms can produce ATP from glucose by anaerobic respiration, which does not require oxygen. Many human cells perform fermentation that also does not require oxygen. It is performed to recycle NADH back into NAD+. There are two types: alcoholic fermentation and lactic acid fermentation. Both start with glycolysis.
    - Alcoholic fermentation is carried out by single-celled organisms including yeasts and some bacteria. We use alcoholic fermentation in these organisms to make biofuels, bread, and wine.
    - Lactic acid fermentation is undertaken by certain bacteria, including the bacteria in yogurt, and also by our muscle cells when they are worked hard and fast.
    - Anaerobic respiration produces far less ATP than does aerobic cellular respiration, but it has the advantage of being much faster.

## CHAPTER SUMMARY REVIEW

1. For the following questions, choose whether the description applies to eukaryotic cells, prokaryotic cells, or both.
    A. Has a nuclear membrane
    B. Has a plasma membrane made of a phospholipid bilayer
    C. Can be in a multicellular organism
    D. Has ribosomes
    E. Has an endoplasmic reticulum
    F. Its DNA replicates before cell division
    G. Has a single circular chromosome
    H. Has cytoplasm that splits into two daughter cells during cell division
    I. Has a cell cycle that includes interphase and mitosis
    J. The type of cell that most likely evolved to become mitochondria
2. Name one example of a prokaryotic organism and one example of a eukaryotic organism.
3. Neurons are cells in the nervous system that transmit messages. They use energy to maintain the balance of sodium and potassium ions inside and outside of them, which is critical for their ability to send messages.
    A. What kind of transport is this maintenance of sodium and potassium ion concentrations – active or passive? Explain your reasoning.
    B. What creates the barrier between the inside and the outside of these cells?
    C. What molecule uses energy to maintain the balance of sodium and potassium ions inside and outside of neurons? Describe two reasons why such a molecule is required.
    D. What form of energy is used in this process?
    E. Briefly explain how the energy in the food you eat gets there and provides energy for your neurons in the form necessary to power this process.
4. Explain why the inside of the plasma membrane, the side that faces the cytoplasm of the cell, must be hydrophilic.
5. *True or False*. Anaerobic and aerobic cellular respiration both produce ATP.
6. *True or False*. The cell membrane can also be called the plasma membrane.
7. *True or False*. Each phospholipid molecule in the cell membrane has two heads and a tail.
8. *True or False*. For cells, a smaller size is generally more efficient.
9. *True or False*. DNA is located in the nucleus of prokaryotic cells.
10. *True or False*. Cilia and flagella stick out of the cell membrane but are not made of cell membrane themselves.
11. Which statement about the cell membrane is false?
    A. It encloses the cytoplasm
    B. It protects and supports the cell
    C. It keeps all external substances out of the cell
    D. None of the above
12. During diffusion, substances move from an area of **X?** concentration to an area of **Y?** concentration.
    A. higher, lower
    B. lower, higher
    C. higher, equal
    D. lower, equal
13. Which type of respiration involves electron transport?
    A. Where does this electron transport occur within the cell?
    B. Energy from electron transport is used to pump hydrogen ions across a membrane. Is this active or passive transport of hydrogen ions? Explain your answer.
    C. After the process described in part B, hydrogen ions then flow from a region of higher concentration to a region of lower concentration. Is this active or passive transport of hydrogen ions? Explain your answer.

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# 3.12: DNA AND RNA

## WHAT MAKES YOU...YOU?

This person has naturally red hair. Why is this hair red instead of some other color? And, in general, what causes specific traits to occur? There is a molecule in human beings and most other living things that is largely responsible for their traits. The molecule is large and has a spiral structure in eukaryotes. What molecule is it? With these hints, you probably know that the molecule is DNA.



Figure **3.12.1**: Red hair

## INTRODUCING DNA

Today, it is commonly known that DNA is the genetic material that is passed from parents to offspring and determines our traits. For a long time, scientists knew such molecules existed, that is, they were aware that genetic information is contained within biochemical molecules. However, they didn't know which molecules play this role. In fact, for many decades, scientists thought that proteins were the molecules that contain genetic information.

## DISCOVERY THAT DNA IS THE GENETIC MATERIAL

Determining that DNA is the genetic material was an important milestone in biology. It took many scientists undertaking creative experiments over several decades to show with certainty that DNA is the molecule that determines the traits of organisms. This research began in the early part of the 20th century.

### GRIFFITH'S EXPERIMENTS WITH MICE

The first important discovery was made in the 1920s. An American scientist named Frederick Griffith was studying mice and two different strains of a bacterium called R (rough) strain and S (smooth) strain. He injected the two bacterial strains into mice. The S strain was virulent and killed the mice, whereas the R strain was not virulent and did not kill the mice. You can see these details in Figure **3.12.2**. Griffith also injected mice with S-strain bacteria that had been killed by heat. As expected, the dead bacteria did not harm the mice. However, when the dead S-strain bacteria were mixed with live R-strain bacteria and injected, the mice died.

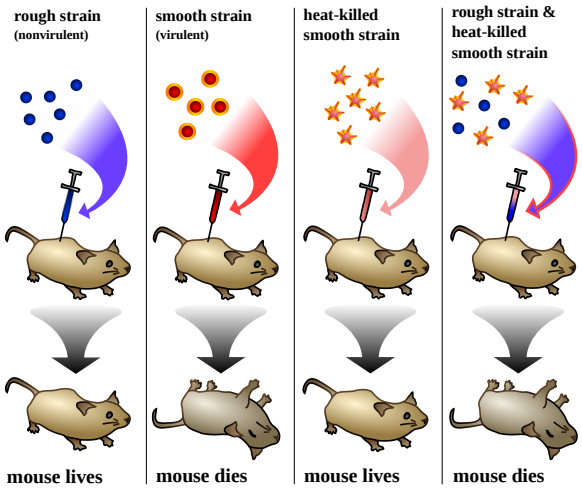



Figure **3.12.2**: Griffith's experiment discovering a "transforming principle" in heat-killed virulent smooth *pneumococcus* that enables the transformation of rough non-virulent rough pneumococcal bacteria.

Based on his observations, Griffith deduced that something in the dead S-strain was transferred to the previously harmless R-strain, making the R-strain deadly. What was this "something?" What type of substance could change the characteristics of the organism that received it?

### AVERY AND HIS COLLEAGUES MAKE A MAJOR CONTRIBUTION

In the early 1940s, a team of scientists led by Oswald Avery tried to answer the question raised by Griffith's research results. First, they inactivated various substances in the S-strain bacteria. Then they killed the S-strain bacteria and mixed the remains with live R-strain bacteria. (Keep in mind that the R-strain bacteria normally did not harm the mice.) When they inactivated proteins, the R-strain was deadly to the injected mice. This ruled out proteins as genetic material. Why? Even without the S-strain proteins, the R-strain was changed or transformed into a deadly strain. However, when the researchers inactivated DNA in the S-strain, the R-strain remained harmless. This led to the conclusion that DNA — and not protein — is the substance that controls the characteristics of organisms. In other words, DNA is the genetic material.

### HERSHEY AND CHASE CONFIRM THE RESULTS

The conclusion that DNA is the genetic material was not widely accepted until it was confirmed by additional research. In the 1950s, Alfred Hershey and Martha Chase did experiments with viruses and bacteria. Viruses are not cells. Instead, they are basically DNA (or RNA) inside a protein coat. To reproduce, a virus must insert its own genetic material into a cell (such as a bacterium). Then it uses the cell's machinery to make more viruses. The researchers used different radioactive elements to label the DNA and proteins in DNA viruses. This allowed them to identify which molecule the viruses inserted into bacterial cells. DNA was the molecule they identified. This confirmed that DNA is the genetic material.

## CHARGAFF FOCUSES ON DNA BASES

Erwin Chargaff (1905-2002), an Austrian-American biochemist from Columbia University, analyzed the base composition of the DNA of various species. This led him to propose two main rules that have been appropriately named **Chargaff's rules**.

### RULE 1

Chargaff determined that in DNA, the amount of one base, a purine, always approximately equals the amount of a particular second base, a pyrimidine. Specifically, in any double-stranded DNA, the number of guanine units equals approximately the number of cytosine units and the number of adenine units equals approximately the number of thymine units.

Human DNA is 30.9% A and 29.4% T, 19.9% G and 19.8% C. The rule constitutes the basis of **base pairs** in the DNA double helix: A always pairs with T, and G always pairs with C. He also demonstrated that the number of purines (A+G) always approximates the number of pyrimidines (T+C), an obvious consequence of the base-pairing nature of the DNA double helix.

### RULE 2

In 1947 Chargaff showed that the composition of DNA, in terms of the relative amounts of the A, C, G, and T bases, varied from one species to another. This molecular diversity added to the evidence that DNA could be the genetic material.

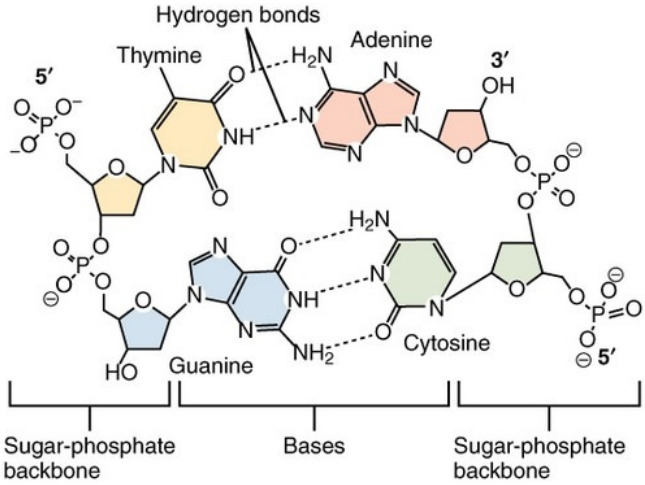



Figure **3.12.3**: Chemical structure of the four nitrogenous bases in the two strands of DNA. Notice how the purines (A and G) are composed of two ring structures, whereas the pyrimidines (T and C) are composed of one ring structure. The DNA of all species has the same four nitrogen bases. The figure also illustrates that Adenine pairs with Thymine and Guanine pairs with cytosine.

## DISCOVERY OF THE DOUBLE HELIX

After DNA was shown to be the genetic material, scientists wanted to learn more about it, including its structure. James Watson and Francis Crick are usually given credit for discovering that DNA has a double-helix shape like a spiral staircase, as shown in Figure **3.12.4**. In fact, Watson and Crick's discovery of the double helix depended heavily on the prior work of Rosalind Franklin and other scientists, who had used X-rays to learn more about DNA's structure. Unfortunately, Franklin and these other scientists have not usually been given credit for their important contributions to the discovery of the double helix.

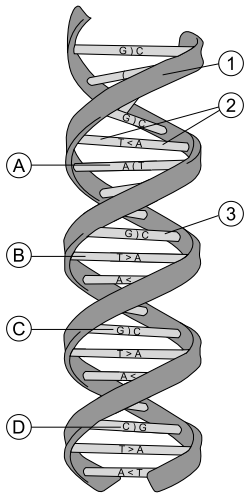



Figure **3.12.4**: Double helix structure of DNA resembles a twisted staircase. In this image A. Adenine B. Thymine C. Guanine D. Cytosine 1. Sugar, Phosphate, Backbone 2. Base pair 3. Nitrogenous base. This image also shows the application of 2 rules of Chargaff.

The double-helix shape of DNA, together with Chargaff's rules, led to a better understanding of DNA. As a nucleic acid, DNA is made from nucleotide monomers. Long chains of nucleotides form polynucleotides, and the DNA double helix consists of two polynucleotide chains. Each nucleotide consists of a sugar (deoxyribose), a phosphate group, and one of the four bases (adenine, cytosine, guanine, or thymine). The sugar and phosphate molecules in adjacent nucleotides bond together and form the "backbone" of each polynucleotide chain.

Scientists concluded that bonds between the bases hold together the two polynucleotide chains of DNA. Moreover, adenine always bonds with thymine, and cytosine always bonds with guanine. That's why these pairs of bases are called **complementary base pairs.** If you look at the nitrogen bases in Figure **3.12.3**, you will see why the bases bond together only in these pairings. Adenine and guanine have a two-ring structure, whereas cytosine and thymine have just one ring. If adenine were to bond with guanine as well as thymine, for example, the distance between the two DNA chains would be variable. However, when a one-ring molecule (such as thymine) always bonds with a two-ring molecule (such as adenine), the distance between the two chains remains constant. This maintains the uniform shape of the DNA double helix. The bonded base pairs (A-T and G-C) stick into the middle of the double helix, forming, in essence, the steps of the spiral staircase.

## DNA REPLICATION

Knowledge of DNA's structure helped scientists understand how DNA replicates. **DNA replication** is the process in which DNA is copied. It occurs during the synthesis (S) phase of the eukaryotic cell cycle. DNA must be copied so that, after cell division occurs, each daughter cell will have a complete set of chromosomes.

DNA replication begins when an enzyme breaks the bonds between complementary bases in the molecule. This exposes the bases inside the molecule so they can be "read" by another enzyme and used to build two new DNA strands with complementary bases. The two daughter molecules that result each contain one strand from the parent molecule and one new strand that is complementary to it. As a result, the two daughter molecules are both identical to the parent molecule. This is a semi-conservative process (see Figure **3.12.5**.)

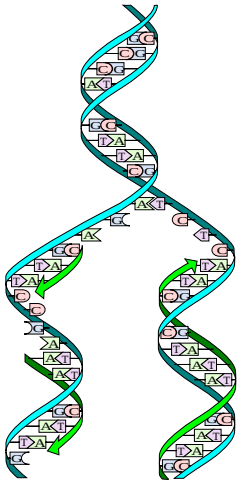


Figure 3.12.5: DNA Replication. DNA replication is a semi-conservative process. Half of the parent DNA molecule is conserved in each of the two daughter DNA molecules. The blue strand belongs to the parent cell, and the green DNA strand represents a brand new DNA strand.

## HELICASE AND POLYMERASE

DNA replication begins as an enzyme, **DNA helicase**, breaks the hydrogen bonds holding the two strands together and forms a **replication fork** (see Figure 3.12.6. The resulting structure has two branching strands of DNA backbone with exposed bases. These exposed bases allow the DNA to be "read" by another enzyme, **DNA polymerase**, which then builds the complementary DNA strand. As DNA helicase continues to open the double helix, the replication fork grows.

### LEADING AND LAGGING STRANDS

Two DNA polymerase enzymes work at a Replication fork. This enzyme can only build new DNA in the 5' → 3' direction. It also needs a **primer** built by **primase** to start building DNA. Therefore, the two new strands, the l**eading strand** and the **lagging strand**, of DNA are "built" in opposite directions. The leading strand is the DNA strand that DNA polymerase constructs in the 5' → 3' direction. This strand of DNA is made in a continuous manner, moving as the replication fork grows. The "lagging" strand is synthesized in short segments known as **Okazaki fragments**. On the lagging strand, **primase** builds a short RNA primer. DNA polymerase is then able to use the free 3'-OH group on the RNA primer to make DNA in the 5' → 3' direction till it reaches to end of the template strand. DNA polymerase of the lagging strand then jumps to go further into the replication fork to make another Okazaki fragment. The RNA fragments are then degraded and new DNA nucleotides are added to fill the gaps where the RNA was present. Another enzyme, **DNA ligase**, is then able to attach (ligate) the DNA nucleotides together, completing the synthesis of the lagging strand (Figure 3.12.6).

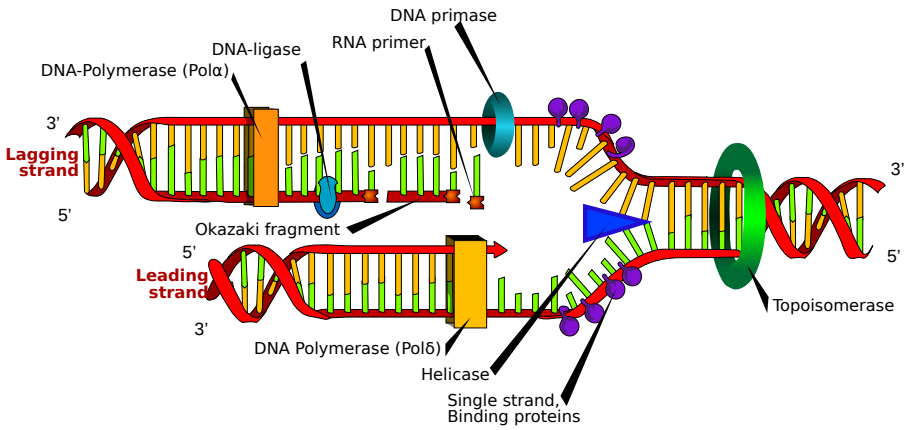



Figure 3.12.6: DNA replication. The two DNA strands are opened by helicase. The strands are held open by a single strand of binding proteins, preventing premature reannealing. Topoisomerase solves the problem caused by the tension generated by the winding/unwinding of DNA. This enzyme wraps around DNA and makes a cut permitting the helix to spin and relax. Once DNA is relaxed, topoisomerase reconnects broken strands. DNA primase synthesizes a short RNA primer that initiates the Okazaki fragment and leading strand. DNA polymerase synthesizes the leading strand and Okazaki fragments. Okazaki fragments are attached by DNA ligase after the primers are removed.

## WHAT IS RNA?

RNA structure differs from the DNA structure in three specific ways. Both are nucleic acids and made out of **nucleotides**; however, RNA is single-stranded while DNA is double-stranded. RNA nucleotides, like those from DNA, have three parts: a 5-carbon sugar, a phosphate group, and a base. RNA contains the 5-carbon sugar **ribose**, whereas, in DNA, the sugar is **deoxyribose**. The difference between ribose and deoxyribose is the lack of a hydroxyl group attached to the pentose ring in the 2' position of deoxyribose (see figure Figure **3.12.7**.

Table **3.12.1**: comparison of RNA and DNA

| | RNA | DNA |
|---|---|---|
| Strands | single stranded | double stranded |
| Specific Base | contains uracil | contains thymine |
| Sugar | ribose | deoxyribose |
| Size | relatively small | big (chromosomes) |
| Location | moves to cytoplasm | stays in nucleus |
| Types | 3 types: mRNA, tRNA, rRNA | generally 1 type |

Though both RNA and DNA contain the nitrogenous bases adenine, guanine, and cytosine, RNA contains the nitrogenous base **uracil** instead of thymine. Uracil pairs with adenine in RNA, just as thymine pairs with adenine in DNA. Uracil and thymine have very similar structures; uracil is an unmethylated form of thymine.

The nucleotide sequence of RNA, which is complementary to the DNA sequence, allows RNA to encode genetic information. RNA though carries the genetic information of just one gene. Hence, compared to DNA, RNA molecules are relatively small.

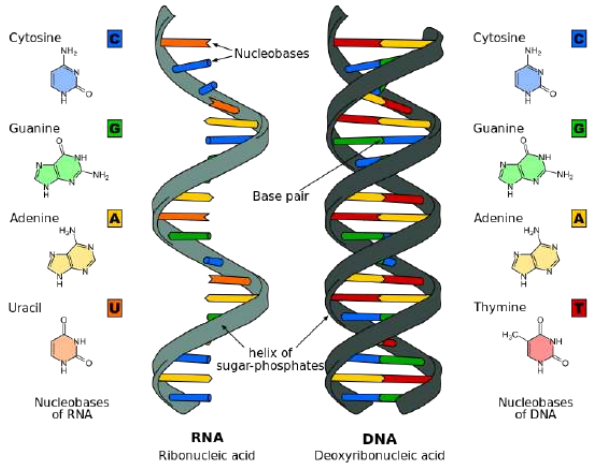



Figure **3.12.7**. Comparison of a single-stranded RNA and a double-stranded DNA with their corresponding nucleobases. Also, refer to Table **3.12.1** as your read this image.

## REVIEW

1. Outline the discoveries that led to the determination that DNA, and not protein, is the biochemical molecule that contains genetic information.
2. State Chargaff's rules. Explain how the rules are related to the structure of the DNA molecule.
3. Explain how the structure of a DNA molecule is like a spiral staircase. Which parts of the staircase represent the various parts of the molecule?
4. Describe the process of DNA replication.
5. When does DNA replication occur, and why is the process said to be semi-conservative?
6. Why do you think dead S strain bacteria injected into mice does not harm the mice but kills them when mixed with living (and normally harmless) R strain bacteria?
7. In Griffith's experiment, do you think the heat treatment that killed the bacteria also inactivated the bacterial DNA? Why or why not?
8. Give one example of a specific piece of evidence that helped rule out proteins as the genetic material.
9. *True or False.* Two-ring bases always bind to each other.
10. *True or False.* DNA replication involves the breaking of one of the polynucleotide chains into individual nucleotides.
11. *True or False.* In DNA, each nucleotide has a sugar.
12. What would the complementary strand of this stretch of DNA bases be? GTTAC

13. Which scientists detected labeled DNA that was transferred from one organism to another?
    A. Hershey and Chase
    B. Chargaff
    C. Avery
    D. Griffith
14. Which enzyme break the bonds between complementary bases and add new complementary nucleotides to the parental strands during DNA replication?
    A. Phosphates
    B. Enzymes
    C. Viruses
    D. RNA molecules
15. Describe the differences between DNA and RNA.
16. How is DNA replicated? Why is DNA replication called a "semi-conservative" process?
17. What are the roles of the following enzymes?
    A. DNA polymerase
    B. DNA helicase
    C. DNA ligase
    D. primase

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# 3.13: CHROMOSOMES AND GENES

## IDENTICAL TWINS, IDENTICAL GENES

You probably can tell by their close resemblance that these two individuals are identical twins. Identical twins develop from the same fertilized egg, so they inherited copies of the same chromosomes and have all the same genes. Unless you have an identical twin, no one else in the world has exactly the same genes as you. What are genes? How are they related to chromosomes? And how do genes make you the person you are?



Figure **3.13.1**: Identical twins

Chromosomes are coiled structures made of DNA and proteins. Chromosomes are encoded with genetic instructions for making proteins. These instructions are organized into units called **genes**. Most genes contain the instructions for a single protein. There may be hundreds or even thousands of genes on a single chromosome.

## HUMAN CHROMOSOMES

Each species is characterized by a set number of chromosomes. The human number is 23. Human cells normally have two sets of chromosomes in each of their cells, one set inherited from each parent. There are 23 chromosomes in each set, for a total of 46 chromosomes per cell. Each chromosome in one set is matched by a chromosome of the same type in the other set, so there are actually 23 pairs of chromosomes per cell. Each pair consists of chromosomes of the same size and shape, and they also contain the same genes. The chromosomes in a pair are known as **homologous chromosomes**. As see in Figure **3.13.2**, there are two types of chromosomes, autosomal and sex chromosomes. Read more about this in the genetics chapter.

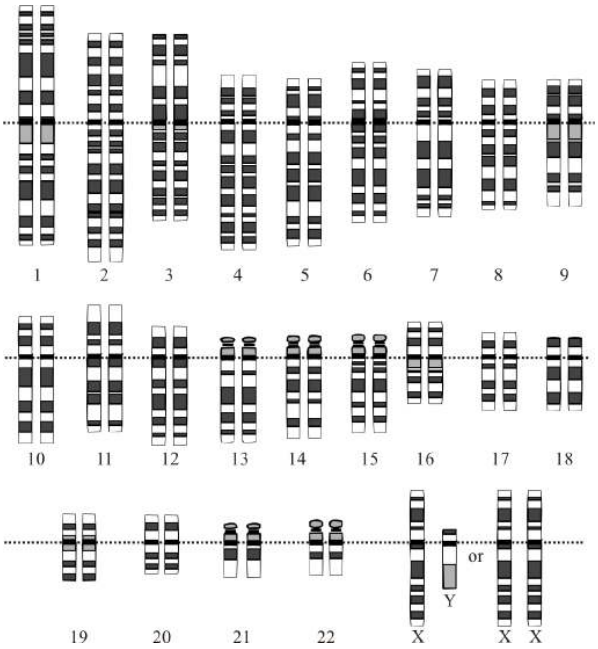



Figure **3.13.2**: All human cells (except gametes, which are sperm and egg cells) have the 23 pairs of chromosomes shown here. There are two types of chromosomes, autosomal (pairs 1-22) and sex (23rd pair). The chromosomes are numbered according to their size, the first chromosome pair being the longest and the twenty-second chromosome pair being the shortest. The 23rd pair is not always homologous. It can be XY or XX. The X chromosome is significantly longer than the Y chromosome. The stripes on the chromosomes represent genes.

## HUMAN GENES

Humans have an estimated 25,000 genes. This may sound like a lot, but it really isn't. Far simpler species have almost as many genes as humans. However, human cells use splicing and other processes to make multiple proteins from the instructions encoded in a single gene. Only about 25 percent of the nitrogen base pairs of DNA in human chromosomes make up genes and their regulatory elements. Out of this 25 percent, only two percent code for genes. The functions of many of the other base pairs are still unclear.

The majority of human genes have two or more possible versions, called alleles. Differences in alleles account for the considerable genetic variation among people. In fact, most human genetic variation is the result of differences in individual DNA base pairs within alleles.

## LINKAGE

Genes that are located on the same chromosome are called **linked genes**. Linkage explains why certain characteristics are frequently inherited together. For example, genes for hair color and eye color are linked, so certain hair and eye colors tend to be inherited together, such as blonde hair with blue eyes and brown hair with brown eyes. Can you think of other human traits that seem to occur together? Do you think they might be controlled by linked genes?

Genes located on the sex chromosomes are called **sex-linked genes**. Most sex-linked genes are on the X chromosome because the Y chromosome has relatively few genes. Strictly speaking, genes on the X chromosome are **X-linked genes**, but the term sex-linked is often used to refer to them. Figure **3.13.3** is called a linkage map. A linkage map shows the locations of specific genes on a chromosome. It shows the locations of a few of the genes on the human X chromosome, such as a blood group protein gene, Lethyosis (a skin disease gene), ocular albinism gene, and many more.

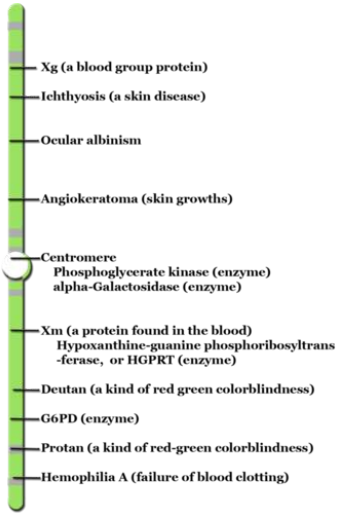



Figure 3.13.3: Linkage Map for the Human X Chromosome. This linkage map shows the locations of several genes on the X chromosome. Some of the genes code for normal proteins. Others code for abnormal proteins that lead to genetic disorders.

## CHROMOSOMES AND GENES

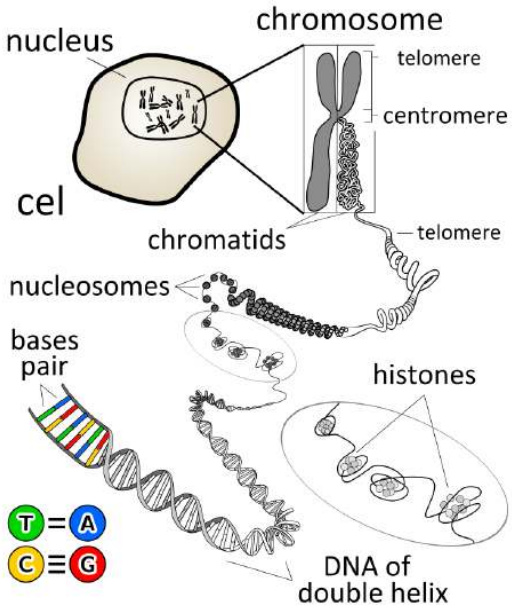



Figure 3.13.4: Graphic decomposition of a chromosome (found in the cell nucleus), to the bases pair of the DNA. Chromosomes are located in the nucleus of the cell. A duplicated chromosome has two chromatids, double-helix DNA is wrapped in histone proteins to form nucleosomes. This allows DNA to organize into chromosomes.

## REVIEW

1. What are chromosomes and genes, and how are the two related?
2. Describe human chromosomes and genes.
3. Explain the difference between autosomes and sex chromosomes.
4. What are linked genes, and what does a linkage map show?
5. Explain why females are considered the default sex in humans.
6. *True or False.* Humans have 46 pairs of chromosomes.
7. *True or False.* Autosomes refer to any chromosome other than sex chromosomes.
8. *True or False.* The majority of human DNA does not encode for proteins.
9. Explain the relationship between genes and alleles.
10. Put the following in order of size, from smallest to largest: chromosome; gene; base pair
11. Sex-linked genes are usually found on which chromosome? Explain why these genes are called sex-linked.

12. Which of the following are considered homologous chromosomes?
    A. Chromosome 22 and the X chromosome
    B. The two copies of chromosome 22 that make up a pair
    C. All of the chromosomes in a skin cell and all of the chromosomes in a muscle cell
    D. Chromosomes 21 and 22
13. What is the one chromosome that is different between genetic males and females? Explain your answer.
14. Most males and females have two sex chromosomes. Explain why then, do only females have Barr bodies.

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# 3.14: PROTEIN SYNTHESIS

## THE CENTRAL DOGMA OF BIOLOGY

Your **DNA**, or deoxyribonucleic acid, contains the genes that determine who you are. How can this organic molecule control your characteristics? DNA contains instructions for all the proteins your body makes. **Proteins**, in turn, determine the structure and function of all your cells. What determines a **protein**'s structure? It begins with the sequence of **amino acids** that make up the protein. Instructions for making proteins with the correct sequence of amino acids are encoded in DNA.



Figure **3.14.1**: Transcription and translation (Protein synthesis) in a cell.

DNA is found in chromosomes. In eukaryotic cells, chromosomes always remain in the nucleus, but proteins are made at ribosomes in the cytoplasm or on the rough endoplasmic reticulum (RER). How do the instructions in DNA get to the site of protein synthesis outside the nucleus? Another type of nucleic acid is responsible. This nucleic acid is **RNA** or ribonucleic acid. RNA is a small molecule that can squeeze through pores in the nuclear membrane. It carries the information from DNA in the nucleus to a ribosome in the cytoplasm and then helps assemble the protein. In short:

**DNA → RNA → Protein**

Discovering this sequence of events was a major milestone in molecular biology. It is called the **central dogma of biology**. The two processes involved in the central dogma are **transcription** and **translation.**

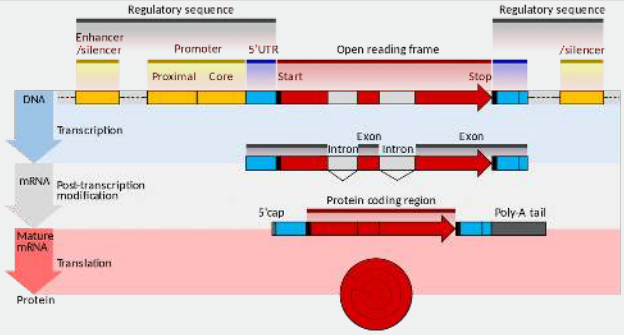



Figure **3.14.2**: An overview of transcription and translation. The top panel shows a gene. A gene is composed of the open reading frame (aka coding sequence) that is flanked by regulatory sequences. At the beginning of the gene, the regulatory sequence contains a promoter where RNA polymerase attaches and starts transcription. At the end of the open reading frame, the regulatory sequence contains a terminator (not shown.)The middle panel shows a pre mRNA which is modified by excising introns and keeping exons. This is called post transcription modification. A mature mRNA contains a 5' cap and poly-A tail. The bottom panel shows a synthesis of protein via translation.

## TRANSCRIPTION

**Transcription** is the first part of the central dogma of molecular biology: **DNA → RNA**. It is the transfer of genetic instructions in DNA to mRNA. Transcription happens in the nucleus of the cell. During transcription, a strand of mRNA is made that is complementary to a strand of DNA called a gene. A gene can easily be identified from the DNA sequence. A gene contains the basic three regions, promoter, coding sequence (reading frame), and terminator. There are more parts of a gene which are illustrated in Figure **3.14.3**.

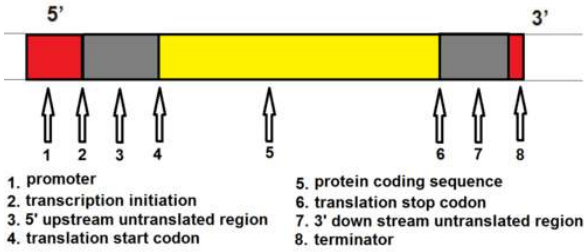



Figure **3.14.3**: The major components of a gene. 1. promoter, 2. transcription initiation, 3. 5' upstream untranslated region, 4. translation start codon site, 5. protein-coding sequence, 6. translation stop codon region, 7. 3' downstream untranslated region, and 8. terminator.

### STEPS OF TRANSCRIPTION

Transcription takes place in three steps, called initiation, elongation, and termination. The steps are illustrated in Figure **3.14.4**.

1. Initiation is the beginning of transcription. It occurs when the enzyme RNA polymerase binds to a region of a gene called the **promoter**. This signals the DNA to unwind so the enzyme can "read" the bases in one of the DNA strands. The enzyme is ready

to make a strand of mRNA with a complementary sequence of bases. The promoter is not part of the resulting mRNA

2. Elongation is the addition of nucleotides to the mRNA strand.
3. Termination is the ending of transcription. As RNA polymerase transcribes the terminator, it detaches from DNA. The mRNA strand is complete after this step.

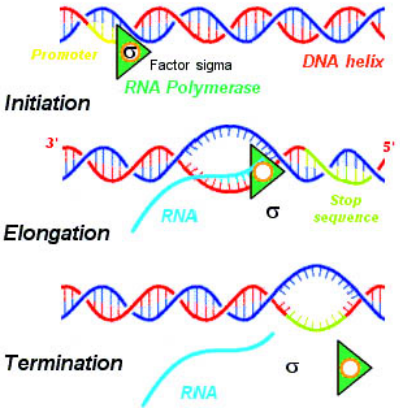



Figure **3.14.4**: Transcription occurs in the three steps - initiation, elongation, and termination

## PROCESSING MRNA

In eukaryotes, the new mRNA is not yet ready for translation. At this stage, it is called pre-mRNA, and it must go through more processing before it leaves the nucleus as mature mRNA. The processing may include the addition of a 5' cap, splicing, editing, and 3' polyadenylation (poly-A) tail. These processes modify the mRNA in various ways. Such modifications allow a single gene to be used to make more than one protein. See Figure **3.14.5** as you read below:

- 5' cap protects mRNA in the cytoplasm and helps in the attachment of mRNA with the ribosome for translation.
- Splicing removes introns from the protein-coding sequence of mRNA. **Introns** are regions that do not code for the protein. The remaining mRNA consists only of regions called **exons** that do code for the protein.
- Editing changes some of the nucleotides in mRNA. For example, a human protein called APOB, which helps transport lipids in the blood, has two different forms because of editing. One form is smaller than the other because editing adds an earlier stop signal in mRNA.
- Polyadenylation adds a “tail” to the mRNA. The tail consists of a string of As (adenine bases). It signals the end of mRNA. It is also involved in exporting mRNA from the nucleus, and it protects mRNA from enzymes that might break it down.

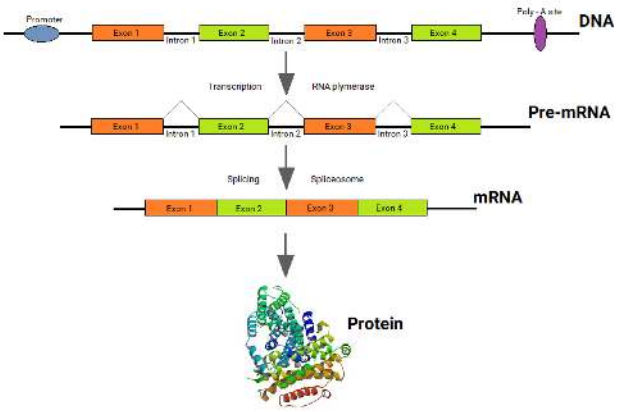



Figure **3.14.5**: Splicing removes introns from mRNA. Mature mRNA is translated to protein.

## TRANSLATION

**The translation** is the second part of the central dogma of molecular biology: **RNA --> Protein**. It is the process in which the genetic code in mRNA is read to make a protein. The translation is illustrated in Figure **3.14.6**. After mRNA leaves the nucleus, it moves to a ribosome, which consists of rRNA and proteins. Translation happens on the ribosomes floating in the cytosol, or on the ribosomes attached to the rough endoplasmic reticulum. The ribosome reads the sequence of codons in mRNA, and molecules of tRNA bring amino acids to the ribosome in the correct sequence.

To understand the role of tRNA, you need to know more about its structure. Each tRNA molecule has an anticodon for the amino acid it carries. An **anticodon** is complementary to the codon for an amino acid. For example, the amino acid lysine has the codon AAG, so the anticodon is UUC. Therefore, lysine would be carried by a tRNA molecule with the anticodon UUC. Wherever the codon AAG appears in mRNA, a UUC anticodon of tRNA temporarily binds. While bound to mRNA, tRNA gives up its amino acid. With the help of rRNA, bonds form between the amino acids as they are brought one by one to the ribosome, creating a polypeptide chain. The chain of amino acids keeps growing until a stop codon is reached.

Ribosomes, which are just made out of rRNA (ribosomal RNA) and protein, have been classified as ribozymes because the rRNA has enzymatic activity. The rRNA is important for the peptidyl transferase activity that bonds amino acids. Ribosomes have two subunits of rRNA and protein. The large subunit has three active sites called E, P, and A sites. These sites are important in the catalytic activity of ribosomes.

Just as with mRNA synthesis, protein synthesis can be divided into three phases: initiation, elongation, and termination. In addition to the mRNA template, many other molecules contribute to the process of translation, such as ribosomes, tRNAs, and various enzymatic factors

**Translation Initiation:** The small subunit binds to a site upstream (on the 5' side) of the start of the mRNA. It proceeds to scan the mRNA in the 5'-->3' direction until it encounters the START codon

(AUG). The large subunit attaches and the initiator tRNA, which carries methionine (Met), binds to the P site on the ribosome.

**Translation Elongation:** The ribosome shifts one codon at a time, catalyzing each process that occurs in the three sites. With each step, a charged tRNA enters the complex, the polypeptide becomes one amino acid longer, and an uncharged tRNA departs. The energy for each bond between amino acids is derived from GTP, a molecule similar to ATP. Briefly, the ribosomes interact with other RNA molecules to make chains of amino acids called polypeptide chains, due to the peptide bond that forms between individual amino acids. Inside the ribosome, three sites participate in the translation process, the A, P, and E sites. Amazingly, the E. coli translation apparatus takes only 0.05 seconds to add each amino acid, meaning that a 200-amino acid polypeptide could be translated in just 10 seconds.

**Translation Termination**: Termination of translation occurs when a stop codon (UAA, UAG, or UGA) is encountered (see Figure **3.14.7**. When the ribosome encounters the stop codon, the growing polypeptide is released with the help of various releasing factors and the ribosome subunits dissociate and leave the mRNA. After many ribosomes have completed translation, the mRNA is degraded so the nucleotides can be reused in another transcription reaction.

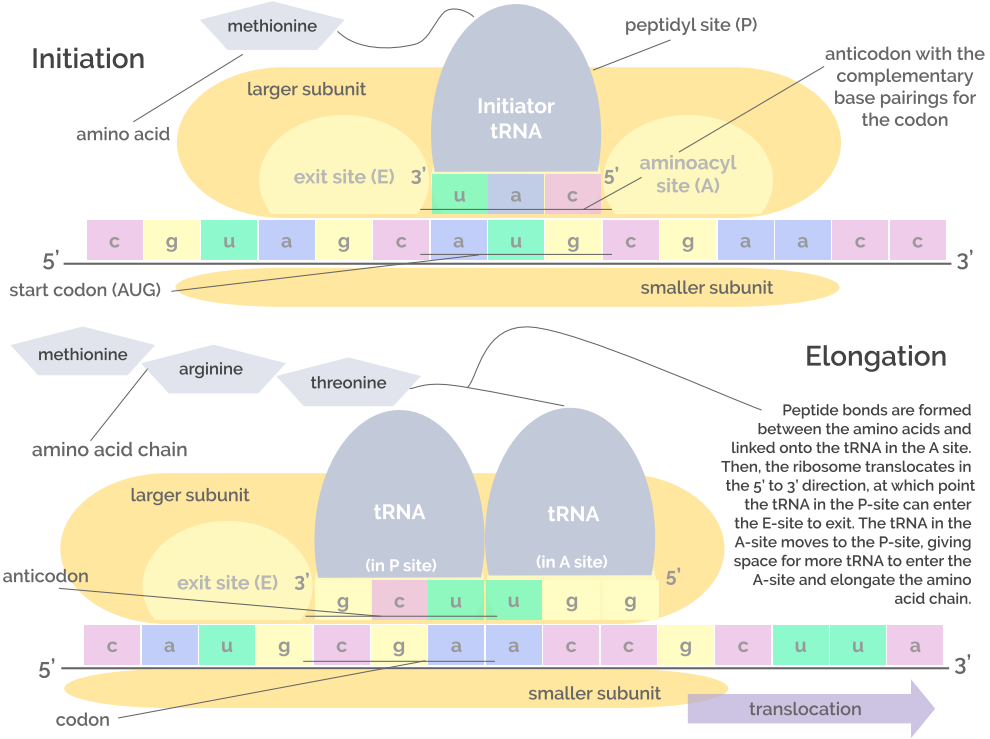



Figure **3.14.6**: At the initiation phase, the initiator tRNA carrying methionine with its anticodon encounters the AUG start codon at the P-site of the ribosome. During elongation, the ribosome translocates in the 5' to 3' direction of the mRNA, at which point the amino acids of tRNA in P-site and amino acid of tRNA in the A-site of the large subunit bond to each other via a peptide bond. This repeated movement of the ribosome creates a long amino acid chain based on the codons in the mRNA. As the ribosome translocates, the tRNA leaves the ribosome through the E-site, while new tRNA enters the A-site in order to continue elongating the amino acid chain.

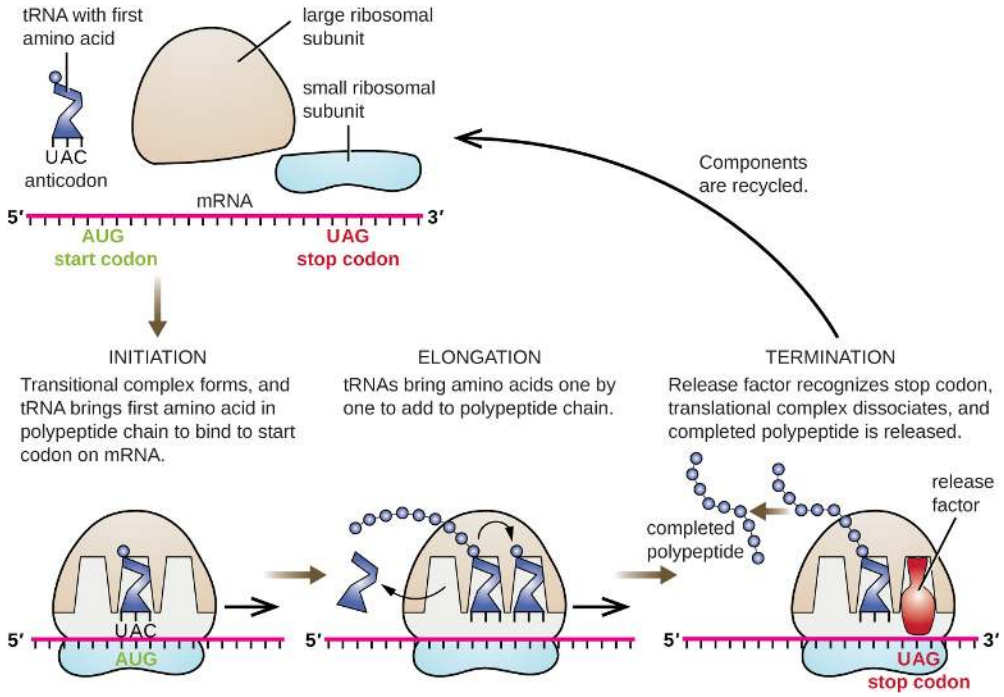



Figure **3.14.7**. Summary of protein translation. During initiation, both ribosomal subunits, mRNA, and initiator tRNA come together. The initiator anticodon of initiator tRNA hydrogen bond with the start codon. During elongation, tRNA brings amino acids one by one to add to the polypeptide chain. During termination, the release factor recognizes stop codon, all components dissociate, and the completed polypeptide is released.

## WHAT HAPPENS NEXT?

After a polypeptide chain is synthesized, it may undergo additional processes. For example, it may assume a folded tertiary shape due to interactions among its amino acids. It may also bind with other polypeptides or with different types of molecules, such as lipids or carbohydrates. Many proteins travel to the Golgi apparatus within the cytoplasm to be modified for the specific job they will do.

## SUMMARY OF CENTRAL DOGMA

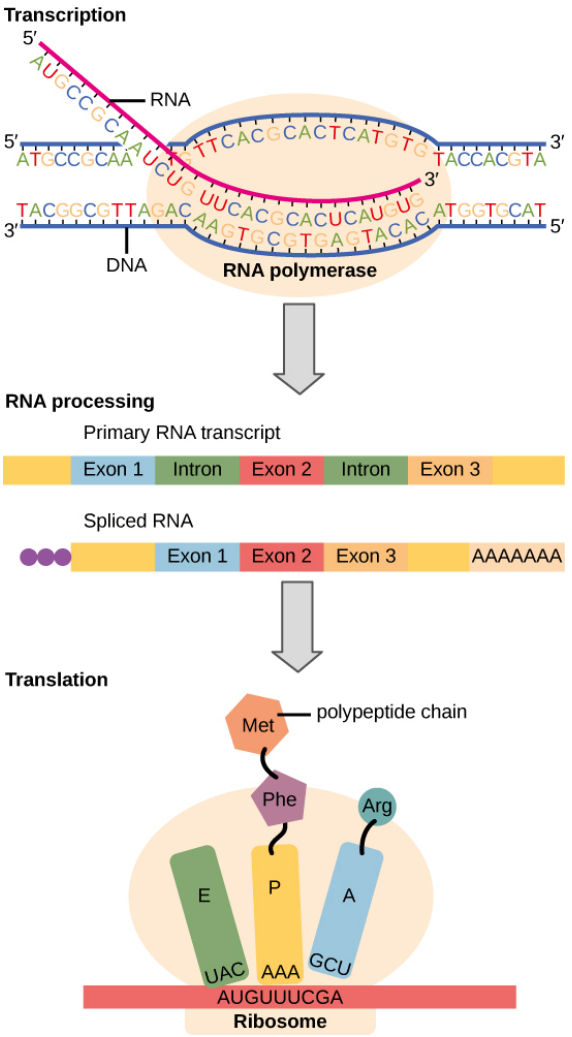



Figure **3.14.8**: The central dogma: Instructions on DNA are transcribed onto messenger RNA. Ribosomes are able to read the genetic information inscribed on a strand of messenger RNA and use this information to string amino acids together into a protein.

## REVIEW

1. Relate protein synthesis and its two major phases to the central dogma of molecular biology.
2. Identify the steps of transcription, and summarize what happens during each step.
3. Explain how mRNA is processed before it leaves the nucleus.
4. Describe what happens during the translation phase of protein synthesis.
5. What additional processes may a polypeptide chain undergo after it is synthesized?
6. Where does transcription take place in eukaryotes?
7. Where does translation take place?
8. Which type of RNA (mRNA, rRNA, or tRNA) best fits each of the statements below? Choose only one type for each.
   A. Contains the codons
   B. Contains the anticodons
   C. Makes up the ribosome, along with proteins
9. If the DNA has a triplet code of CAG in one strand (the strand used as a template for transcription),
   A. What is the complementary sequence on the other DNA strand?
   B. What is the complementary sequence in the mRNA? What is this sequence called?
   C. @hat is the resulting sequence in the tRNA? What is this sequence called? What do you notice about this sequence compared to the original DNA triplet on the template strand?
10. The promoter is a region located in the:
    A. DNA
    B. mRNA
    C. tRNA
    D. Both A and B
11. *True or False.* Introns in mRNA bind to tRNA at the ribosome.
12. *True or False.* tRNAs can be thought of as the link between amino acids and codons in the mRNA.

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# 3.15: GENETIC CODE

## CAN YOU CODE?

If someone asks you whether you can code, you probably assume they are referring to computer code. The image in Figure **3.15.1** represents an important code that you use all the time but not with a computer. It's the genetic code, and it is used by your cells to store information and make proteins.



Figure **3.15.1**: FACIL genetic code logo

## WHAT IS THE GENETIC CODE?

The **genetic code** consists of the sequence of nitrogen bases in a polynucleotide chain of DNA or RNA. The bases are adenine (A), cytosine (C), guanine (G), and thymine (T) (or uracil, U, in RNA). The four bases make up the "letters" of the genetic code. The letters are combined in groups of three to form code "words," called **codons**. Each codon stands for (encodes) one amino acid unless it codes for a start or stop signal. There are 20 common amino acids in proteins. With four bases forming three-base codons, there are 64 possible codons. 61 codons are more than enough to code for the 20 amino acids, thus more than one codon codes for a single amino acid. Please find genetic codes in Table **3.15.1** or in appendix 1.

Table **3.15.1**: Codon Chart. To find the amino acid for a particular codon, find the cell in the table for the first, second, and third bases of the codon. Once you have found the codon, you can find the corresponding amino acid in the adjacent cell on the right side of the codon cell. For example CUG codes for leucine (Leu), AAG codes for lysine (Lys), and GGG codes for glycine (Gly). Text only version of the codon chart.

| | Second base U | Amino acid | Second base C | Amino acid | Second base A | Amino acid | Second base G | Amino acid | |
|---|---|---|---|---|---|---|---|---|---|
| First base U | UUU | Phe | UCU | Ser | UAU | Tyr | UGU | Cys | Third base U |
| First base U | UUC | Phe | UCC | Ser | UAC | Tyr | UGC | Cys | Third base C |
| First base U | UUA | Leu | UCA | Ser | UAA | (stop) no amino acid | UGA | (stop) no amino acid | Third base A |
| First base U | UUA | Leu | UCG | Ser | UAG | (stop) no amino acid | UGG | Trp | Third base G |
| First base C | CUU | Leu | CCU | Pro | CAU | His | CGU | Arg | Third base U |
| First base C | CUC | Leu | CCC | Pro | CAC | His | CGC | Arg | Third base C |
| First base C | CUA | Leu | CCA | Pro | CAA | Gln | CGA | Arg | Third base A |
| First base C | CUG | Leu | CCG | Pro | CAG | Gln | CGG | Arg | Third base G |
| First base A | AUU | Ile | ACU | Thr | AAU | Asn | AGU | Ser | Third base U |
| First base A | AUC | Ile | ACC | Thr | AAC | Asn | AGC | Ser | Third base C |
| First base A | AUA | Ile | ACA | Thr | AAA | Lys | AGA | Arg | Third base A |
| First base A | AUG | Met (start) | ACG | Thr | AAG | Lys | AGG | Arg | Third base G |
| First base G | GUU | Val | GCU | Ala | GAU | Asp | GGU | Gly | Third base U |
| First base G | GUC | Val | GCC | Ala | GAC | Asp | GGC | Gly | Third base C |
| First base G | GUA | Val | GCA | Ala | GAA | Glu | GGA | Gly | Third base A |
| First base G | GUG | Val | GCG | Ala | GAG | Glu | GGG | Gly | Third base G |

## READING THE GENETIC CODE

If you find the codon AUG in Table **3.15.1**, you will see that it codes for the amino acid methionine. This codon is also the start codon that establishes the **reading frame** of the code. The reading frame is the way the bases are divided into codons. It is illustrated in Figure **3.15.2**. After the AUG start codon (not shown in the image), the next three bases are read as the second codon. The next three bases after that are read as the third codon, and so on. The sequence of bases is read, codon by codon, until a stop codon is reached. UAG, UGA, and UAA are all the stop codons. They do not code for any amino acids.

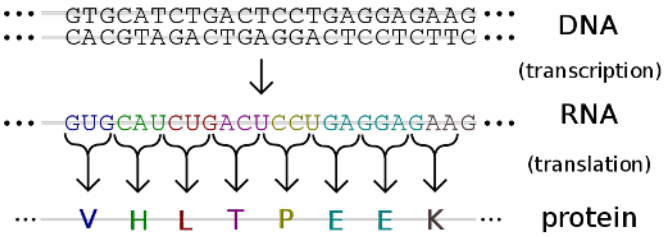



Figure **3.15.2**: Reading the Genetic Code. The genetic code is read three bases at a time. Codons are the code words of the genetic code.

## CHARACTERISTICS OF THE GENETIC CODE

The genetic code has a number of important characteristics:

- The genetic code is universal. All known living things have the same genetic code. This shows that all organisms share a common evolutionary history.

- The genetic code is unambiguous. This means that each codon codes for just one amino acid (or start or stop). This is necessary so there is no question about which amino acid is the correct one.
- The genetic code is redundant. This means that each amino acid is encoded by more than one codon. For example, in the table above, four codons code for the amino acid threonine. Redundancy in the code helps prevent errors in protein synthesis. If a base in codon changes by accident, there is a good chance that it will still code for the same amino acid.

## REVIEW

1. Describe the genetic code.
2. Explain how the genetic code is read.
3. Identify three important characteristics of the genetic code.
4. Summarize how the genetic code was deciphered.
5. Use the table entitled *The Genetic Code*, shown above, to answer the following questions.
   A. Is the code depicted in the table from DNA or RNA? Explain your reasoning.
   B. Which amino acid does the codon CAA code for?
   C. Does UGA code for an amino acid? Why or why not? If so, which one?
   D. Look at the codons that code for the amino acid glycine. How many of them are there? What are their similarities and differences from each other?
   E. Imagine that you are doing an experiment similar to the one performed by Nirenberg and Matthaei with 20 test tubes, each containing bacterial cell contents and all 20 amino acids, with one type of amino acid labeled in each tube. If you added synthetic RNA containing only the base cytosine, a polypeptide chain consisting of which amino acid would be produced? Explain your answer.
6. *True or False.* One codon can encode for more than one amino acid.
7. *True or False.* The codons for tyrosine in plants are the same as ones that encode for tyrosine humans.
8. *True or False.* The start codon encodes for an amino acid, in addition to its function establishing where the reading frame starts.
9. How many possible codons are there?
   A. 64
   B. 20
   C. 3
   D. It depends on the species
10. How many common amino acids are there in proteins?
    A. 64
    B. 20
    C. 3
    D. 4

## EXPLORE MORE

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# 3.16: MUTATIONS

SUPERHERO

Can a mutation really turn a person into a superhero? Of course not, but mutations can sometimes result in drastic changes in living things.



Figure **3.16.1**: Superhero

## WHAT ARE MUTATIONS?

**Mutations** are random changes in the sequence of bases in DNA. The word *mutation* may make you think of Ninja Turtles, but that's a misrepresentation of how most mutations work. First of all, everyone has mutations. In fact, most people have dozens or even hundreds of mutations in their DNA. Secondly, from an evolutionary perspective, mutations are essential. They are needed for evolution to occur because they are the ultimate source of all new genetic variation in any species.

## CAUSES OF MUTATIONS

Is it possible for mutations to occur spontaneously, or does there have to be a cause of the mutation? Well, the answer is that both are possible. Mutagenesis is a process by which the genetic information of an organism is changed in a stable manner, resulting in a mutation. In nature, mutagenesis can lead to changes that are beneficial or harmful or have no effect. Harmful mutations can lead to cancer and various heritable diseases, but beneficial mutations are the driving force of evolution. In 1927, Hermann Muller first demonstrated the effects of mutations with observable changes in chromosomes. He induced mutagenesis by irradiating fruit flies with X-rays,

Mutagenesis may occur spontaneously or be induced. A spontaneous mutation can just happen. These mutations are not caused by an environmental factor but occur during normal cellular processes. A spontaneous mutation may be due to a mistake during DNA replication. Mutations may also occur during mitosis and meiosis. A mutation caused by an environmental factor, or mutagen, is known as an induced mutation. Typical mutagens include chemicals, like those inhaled while smoking, and radiation, such as X-rays, ultraviolet light, and nuclear radiation. Different mutagens have different modes of damaging DNA. For example, UV radiation may cause bonding between the adjacent nucleotides on one strand of DNA molecule (Figure **3.16.2**). This prohibits normal bonding between complementary nucleotides of the opposing strand. This causes a bulge in the DNA double helix. If this damage is not repaired, it leads to mutation. Thus, DNA does not replicate, transcribe, and translate properly.

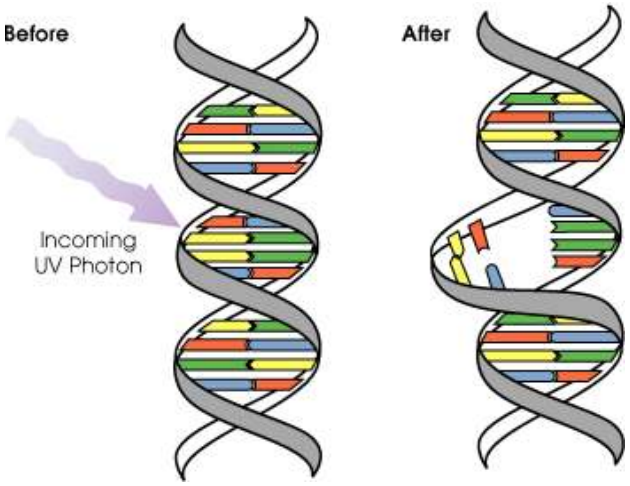



Figure **3.16.2**: Ultraviolet (UV) photons harm the DNA molecules of living organisms in different ways. In one common damage event, adjacent bases bond with each other, instead of across the “ladder.” This makes a bulge, and the distorted DNA molecule does not function properly.

## TYPES OF MUTATIONS

There are a variety of types of mutations. Two major categories of mutations are germline mutations and somatic mutations.

- **Germline mutations** occur in gametes, the sex cells, such as eggs and sperm. These mutations are especially significant because they can be transmitted to offspring and every cell in the offspring will have the mutations.
- **Somatic mutations** occur in other cells of the body. These mutations may have little effect on the organism because they are confined to just one cell and its daughter cells. Somatic mutations also cannot be passed on to offspring.

Mutations also differ in the way that the genetic material is changed. Mutations may change an entire chromosome or just one or a few nucleotides.

### CHROMOSOMAL ALTERATIONS

**Chromosomal alterations** are mutations that change chromosome structure or number. They occur when a section of a chromosome breaks off and rejoins incorrectly or does not rejoin at all. Possible ways these mutations can occur are illustrated in Figure **3.16.3**. Chromosomal alterations are very serious. They often result in the death of the organism in which they occur. If the organism survives, it may be affected in multiple ways. An example of a human chromosomal alteration is the mutation that causes Down Syndrome. It is a duplication mutation that leads to developmental delays and other abnormalities. It occurs when the individual inherits an extra copy of chromosome 21. It is also called trisomy ("three-chromosome") 21.

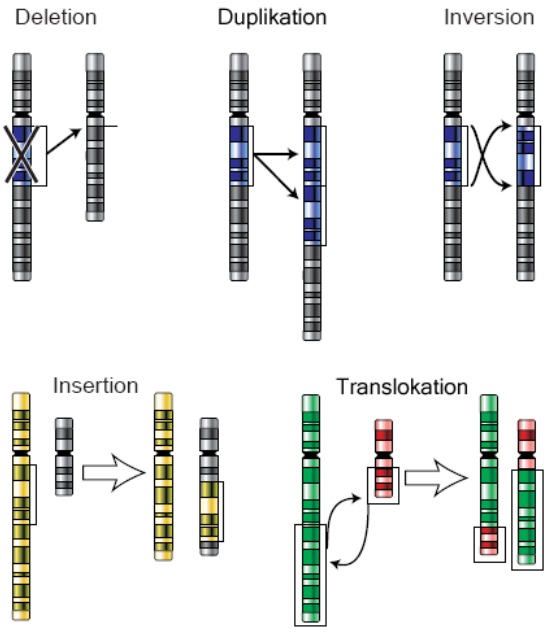



Figure **3.16.3**: Chromosomal Alterations. The chromosomal alterations may occur due to deletion or duplication of genes in a chromosome, inversion of a section of a chromosome, insertion of genes from one chromosome to another, or exchanges of genes between two chromosomes.

A **point mutation** is a change in a single nucleotide in DNA. This type of mutation is usually less serious than a chromosomal alteration. An example of a point mutation is a mutation that changes the codon UUU to the codon UCU. Point mutations can be silent, missense, or nonsense mutations, as shown in Table **3.16.1**. The effects of point mutations depend on how they change the genetic code.

Table **3.16.1**: Point Mutation Types

| Type | Description | Example | Effect |
|---|---|---|---|
| Silent | mutated codon codes for the same amino acid | CAA (glutamine) → CAG (glutamine) | none |
| Missense | mutated codon codes for a different amino acid | CAA (glutamine) → CCA (proline) | variable |
| Nonsense | a mutated codon is a premature stop codon | CAA (glutamine) → UAA (stop) usually | serious |

### FRAMESHIFT MUTATIONS

A **frameshift mutation** is a deletion or insertion of one or more nucleotides that changes the reading frame of the base sequence. Deletions remove nucleotides, and insertions add nucleotides. Consider the following sequence of bases in RNA:

**AUG-AAU-ACG-GCU = methionine-asparagine-threonine-alanine**

Now assume that an insertion occurs in this sequence. Let's say an **A** nucleotide is inserted after the start codon **AUG.** Then the sequence of bases becomes:

**AUG-AAA-UAC-GGC-U = methionine-lysine-tyrosine-glycine**

Even though the rest of the sequence is unchanged, this insertion changes the reading frame and thus all of the codons that follow it. As this example shows, a frameshift mutation can dramatically change how the codons in mRNA are read. This can have a drastic effect on the protein product. Another example of the frameshift mutation due to the deletion of a nucleotide is illustrated in Figure **3.16.4**. In this example, a premature stop codon is created by the mutation.

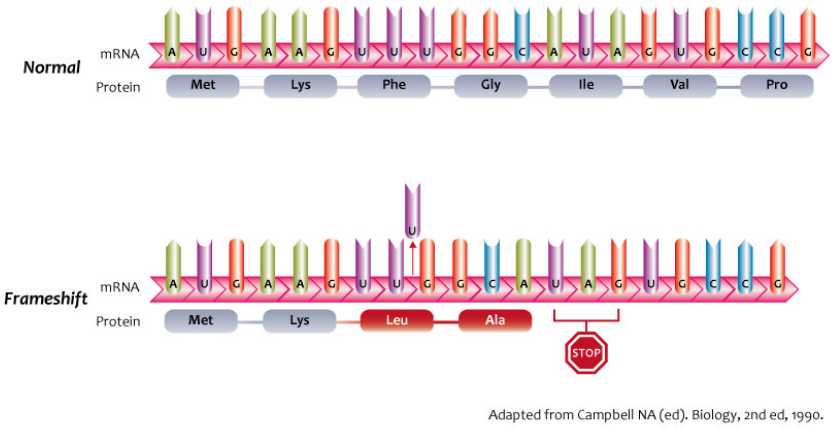



Figure **3.16.4**: The image shows how the frame of the coding sequence of a gene changes when a nucleotide gets deleted due to mutation. Normal gene codes for a polypeptide met-lys-phe-gly-ile-val-pro. When a U from the third position of the third codon gets deleted, the polypeptide reduced to met-lys-leu-ala because the third and fourth codons code for different amino acids and the fifth codon converts to a stop codon.

## EFFECTS OF MUTATIONS

The majority of mutations have neither negative nor positive effects on the organism in which they occur. These mutations are called neutral mutations. Examples include silent point mutations, which are neutral because they do not change the amino acids in the proteins they encode.

Many other DNA damages or errors have no effects on the organism because they are repaired before protein synthesis occurs. Cells have multiple repair mechanisms to fix errors in DNA.

### BENEFICIAL MUTATIONS

Some mutations have a positive effect on the organism in which they occur. They are referred to as beneficial mutations. They generally code for new versions of proteins that help organisms adapt to their environment. If they increase an organism's chances of surviving or reproducing, the mutations are likely to become more common over time. There are several well-known examples of beneficial mutations. Here are just two:

1. Mutations have occurred in bacteria that allow the bacteria to survive in the presence of antibiotic drugs. The mutations have led to the evolution of antibiotic-resistant strains of bacteria.
2. A unique mutation is found in people in a small town in Italy. The mutation protects them from developing atherosclerosis, which is the dangerous buildup of fatty materials in blood vessels. The individual in which the mutation first appeared has even been identified.

### HARMFUL MUTATIONS

Imagine making a random change in a complicated machine such as a car engine. The chance that the random change would improve the functioning of the car is very small. The change is far more likely to result in a car that does not run well or perhaps does not run at all. By the same token, any random change in a gene's DNA is likely to result in the production of a protein that does not function normally or may not function at all. Such mutations are likely to be harmful. Harmful mutations may cause genetic disorders or cancer.

- A genetic disorder is a disease, syndrome, or other abnormal condition caused by a mutation in one or more genes or by a chromosomal alteration. An example of a genetic disorder is cystic fibrosis. A mutation in a single gene causes the body to produce thick, sticky mucus that clogs the lungs and blocks ducts in digestive organs.
- Cancer is a disease in which cells grow out of control and form abnormal masses of cells called tumors. It is generally caused by mutations in genes that regulate the cell cycle. Because of the mutations, cells with damaged DNA are allowed to divide without restrictions.

### FEATURE: MY HUMAN BODY

Inherited mutations are thought to play a role in about 5 to 10 percent of all cancers. Specific mutations that cause many of the known hereditary cancers have been identified. Most of the mutations occur in genes that control the growth of cells or the repair of damaged DNA.

Genetic testing can be done to determine whether individuals have inherited specific cancer-causing mutations. Some of the most common inherited cancers for which genetic testing is available hereditary, breast, and ovarian cancer, caused by mutations in genes named BRCA1 and BRCA2. Besides breast and ovarian cancers, mutations in these genes may also cause pancreatic and prostate cancers. Genetic testing is generally done on a small sample of body fluid or tissue, such as blood, saliva, or skin cells. The sample is analyzed by a lab that specializes in genetic testing, and it usually takes at least a few weeks to get the test results.

Should you get genetic testing to find out whether you have inherited a cancer-causing mutation? Such testing is not done routinely just to screen patients for risk of cancer. Instead, the tests are generally done only when the following three criteria are met:

1. The test can determine definitively whether a specific gene is mutation is present. This is the case with the BRCA1 and BRCA2 gene mutations, for example.
2. The test results would be useful to help guide future medical care. For example, if you found out you had a mutation in the BRCA1 or BRCA2 gene, you might get more frequent breast and ovarian cancer screenings than are generally recommended.
3. You have a personal or family history that suggests you are at risk of inherited cancer.

Criterion number 3 is based, in turn, on such factors as:

- diagnosis of cancer at an unusually young age.
- several different cancers occurring independently in the same individual.
- several close genetic relatives having the same type of cancer (such as a maternal grandmother, mother, and sister all having breast cancer).
- cancer occurring in both organs in a set of paired organs (such as both kidneys or both breasts).

If you meet the criteria for genetic testing and are advised to undergo it, genetic counseling is highly recommended. A genetic counselor can help you understand what the results mean and how to make use of them to reduce your risk of developing cancer. For example, a positive test result that shows the presence of a mutation may not necessarily mean that you will develop cancer. It may depend on whether the gene is located on an autosome or sex chromosome and whether the mutation is dominant or recessive. Lifestyle factors may also play a role in cancer risk even for hereditary cancers, and early detection can often be life-saving if cancer does develop. Genetic counseling can also help you assess the chances that any children you may have will inherit the mutation.

## REVIEW

1. Define mutation.
2. Identify the causes of mutation.
3. Compare and contrast germline and somatic mutations.
4. Describe chromosomal alterations, point mutations, and frameshift mutations. Identify the potential effects of each type of mutation.
5. Why are many mutations neutral in their effects?
6. Give an example of a beneficial mutation and an example of a harmful mutation.
7. Why do you think that exposure to mutagens, such as cigarette smoke, can cause cancer?
8. *True or False.* Mutations are always caused by exposure to toxic substances.
9. *True or False.* Some mutations can make chromosomes longer or shorter.
10. Explain why the insertion or deletion of a single nucleotide can cause a frameshift mutation.
11. Compare and contrast missense and nonsense mutations.
12. A mutation that substitutes one nucleotide for another is called a _____ mutation.
13. Which type of mutation is trisomy 21, or Down Syndrome?
14. Explain why mutations are important for evolution.

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# 3.17: REGULATION OF GENE EXPRESSION

## EXPRESS YOURSELF

This sketch in Figure **3.17.1** illustrates some of the variability in human cells. The shape and other traits that make each type of cell unique depend mainly on the particular proteins that the cell type makes. For example, an ovum is a cell with a large cytoplasm because it nourishes the embryo after fertilization. Sperm is a small cell with essentially just genetic material. The job of the sperm is to transfer genetic material to the ovum. The sketch shows various other cell types. Proteins are encoded in genes. All the cells in an organism have the same genes, so they all have the genetic instructions for the same proteins. Obviously, different types of cells must use, or express, different genes to make different proteins.

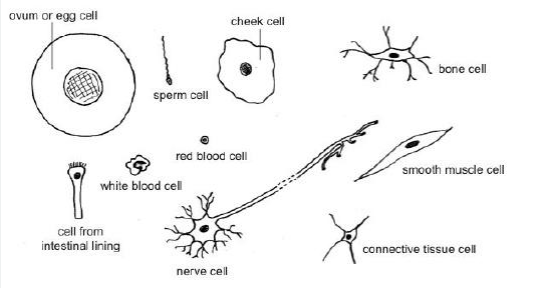



Figure **3.17.1**: Different cells have different shapes to perform their particular jobs.

## WHAT IS GENE EXPRESSION?

Using a gene to make a protein is called **gene expression**. It includes the synthesis of the protein by the processes of transcription of DNA and translation of mRNA. It may also include further processing of the protein after synthesis.

Gene expression is regulated to ensure that the correct proteins are made when and where they are needed. Regulation may occur at any point in the expression of a gene, from the start of the transcription phase of protein synthesis to the processing of a protein after synthesis occurs. The regulation of transcription is one of the most complicated parts of gene regulation in eukaryotic cells and is the focus of this concept.

## REGULATION OF TRANSCRIPTION

As shown in Figure **3.17.2**, transcription is controlled by **regulatory proteins** or **transcription factors**. These proteins bind to regions of DNA, called **regulatory elements** which are located near promoters. The **promoter** is the region of a gene where RNA polymerase binds to initiate transcription of the DNA to mRNA. After regulatory proteins bind to regulatory elements, the proteins can interact with RNA polymerase. Regulatory proteins are typically either activators or repressors. Activators are regulatory proteins that promote transcription by enhancing the interaction of RNA polymerase with the promoter. Repressors are regulatory proteins that prevent transcription by impeding the progress of RNA polymerase along the DNA strand so the DNA cannot be transcribed to mRNA.

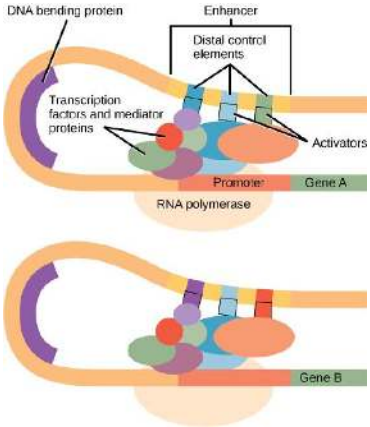



Figure **3.17.2**: An enhancer is a DNA sequence that promotes transcription. Each enhancer is made up of short DNA sequences called distal control elements. Activators bound to the distal control elements interact with mediator proteins and transcription factors. Two different genes may have the same promoter but different distal control elements, enabling differential gene expression.

## ENHANCERS

Although regulatory proteins and elements are typically the key players in the regulation of transcription, other factors may also be involved. For example, regulation of transcription may also involve enhancers. Enhancers are distant regions of DNA that can loop back to interact with a gene's promoter and enhance transcription.

## REGULATION DURING DEVELOPMENT

The regulation of gene expression is extremely important during the early development of an organism. Regulatory proteins must turn on certain genes in particular cells at just the right time so the individual develops normal organs and organ systems. **Homeobox genes** are a large group of genes that regulate development during the embryonic stage. In humans, there are an estimated 235 functional homeobox genes. They are present on every chromosome and generally grouped in clusters. Homeobox genes contain instructions for making chains of 60 amino acids called homeodomains. Proteins containing homeodomains are transcription factors that bind to and control the activities of other genes. The homeodomain is the part of the protein that binds to the target gene and controls its expression.

## REVIEW

1. Define gene expression.
2. Why must gene expression be regulated?
3. Explain how regulatory proteins may activate or repress transcription.
4. Describe homeobox genes and their role in the development of an organism.
5. Discuss the role of regulatory gene mutations in cancer.
6. Explain the relationship between proto-oncogenes and oncogenes.
7. If a newly fertilized egg contained a mutation in a homeobox gene, what effect do you think this might have on the developing embryo? Explain your answer.
8. Which of the following are proteins?
   A. Repressors
   B. Promoters
   C. Regulatory elements
   D. All of the above
9. Which of the following is a region of DNA?
   A. Homeodomain
   B. Activator
   C. TATA box
   D. Both A and C
10. Compare and contrast enhancers and activators.
11. *True or False*. Mutations in genes that normally either promote or suppress cell division can both cause cancer.
12. *True or False*. Gene expression is only regulated at the transcriptional stage.
13. *True or False*. If RNA polymerase cannot bind to the promoter of a gene, it cannot transcribe that gene into mRNA.

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# 3.18: THE HUMAN GENOME

## VITRUVIAN MAN

The drawing in Figure **3.18.2**, named *Vitruvian Man*, was created by Leonardo da Vinci in 1490. It was meant to show normal human body proportions. *Vitruvian Man* is used today to represent a different approach to the human body. It symbolizes a scientific research project that began in 1990, exactly 500 years after da Vinci created the drawing. That project, named the Human Genome Project, is the largest collaborative biological research project ever undertaken.

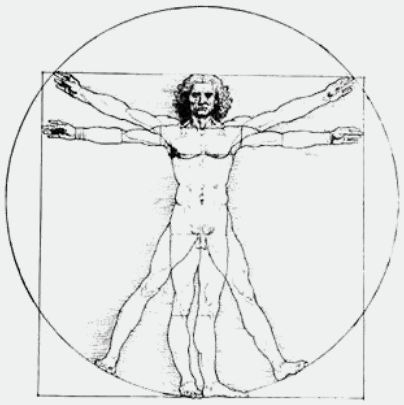


Figure **3.18.1**: Vitruvian man

## WHAT IS THE HUMAN GENOME?

The **human genome** refers to all the DNA of the human species. Human DNA consists of 3.3 billion base pairs and is divided into more than 20,000 genes onto 23 pairs of chromosomes. The human genome also includes noncoding sequences (e.g. intergenic region) of DNA, as shown in Figure **3.18.2**.

## DISCOVERING THE HUMAN GENOME

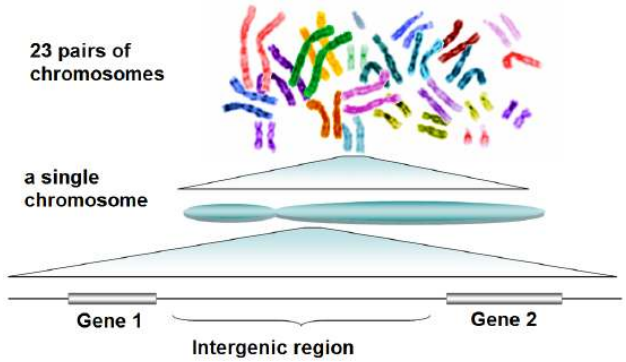



Figure **3.18.2**: Human Genome, Chromosomes, and Genes. Each chromosome of the human genome contains many genes as well as noncoding intergenic (between genes) regions. Each pair of chromosomes is shown here in a different color.

Scientists now know the sequence of all the DNA base pairs in the entire human genome. This knowledge was attained by the **Human Genome Project (HGP),** a $3 billion, international scientific research project that was formally launched in 1990. The project was completed in 2003, two years ahead of its 15-year projected deadline.

Determining the sequence of the billions of base pairs that make up human DNA was the main goal of the HGP. Another goal was mapping the location and determining the function of all the genes in the human genome. There are only about 20,500 genes in human beings.

### A COLLABORATIVE EFFORT

Funding for the HGP came from the U.S. Department of Energy and the National Institutes of Health as well as from foreign institutions. The actual research was undertaken by scientists in 20 universities in the U.S., United Kingdom, Australia, France, Germany, Japan, and China. A private U.S. company named Celera also contributed to the effort. Although Celera had hoped to patent some of the genes it discovered, this was later denied.

### REFERENCE GENOME OF THE HUMAN GENOME PROJECT

In 2003, the HGP published the results of its sequencing of DNA as a human reference genome. Figure **3.18.4** illustrates the process of DNA sequencing. The details of this image are out of the scope of this concept and book. The sequence of the human DNA is stored in databases available to anyone on the Internet. The U.S. National Center for Biotechnology Information (NCBI), part of the NIH, as well as comparable organizations in Europe and Japan, maintain the genomic sequences in a database known as Genbank. Protein sequences are also maintained in this database. The sequences in these databases are the combined sequences of anonymous donors, and as such do not yet address the individual differences that make us unique. However, the known sequence does lay the foundation to identify the unique differences among all of us. Most of the currently identified variations among individuals will be single nucleotide polymorphisms or SNPs. An SNP (pronounced "snip") is a DNA sequence variation occurring at a single nucleotide in the genome. For example, two sequenced DNA fragments from different individuals, GGATCTA to GGATTTA, contain a difference in a single nucleotide. If this, base change occurs in a gene, the base change then results in two alleles: the C allele and the T allele. Remember an allele is an alternative form of a gene. Almost all common SNPs have only two alleles. The effect of these SNPs on protein structure and function and any effect on the resulting phenotype are an extensive field of study.

### BENEFITS OF THE HUMAN GENOME PROJECT

The sequencing of the human genome holds benefits for many fields, including molecular medicine and human evolution.

- Knowing the human DNA sequence can help us understand many human diseases. For example, it is helping researchers identify mutations linked to different forms of cancer. It is also yielding insights into the genetic basis of cystic fibrosis, liver

diseases, blood-clotting disorders, and Alzheimer's disease, among others.

- The human DNA sequence can also help researchers tailor medications to individual genotypes. This is called personalized medicine, and it has led to an entirely new field called pharmacogenomics. **Pharmacogenomics**, also called pharmacogenetics, is the study of how our genes affect the way we respond to drugs. You can read more about pharmacogenomics in the Feature below.
- The analysis of similarities between DNA sequences from different organisms is opening new avenues in the study of evolution. For example, analyses are expected to shed light on many questions about the similarities and differences between humans and our closest relatives the nonhuman primates.

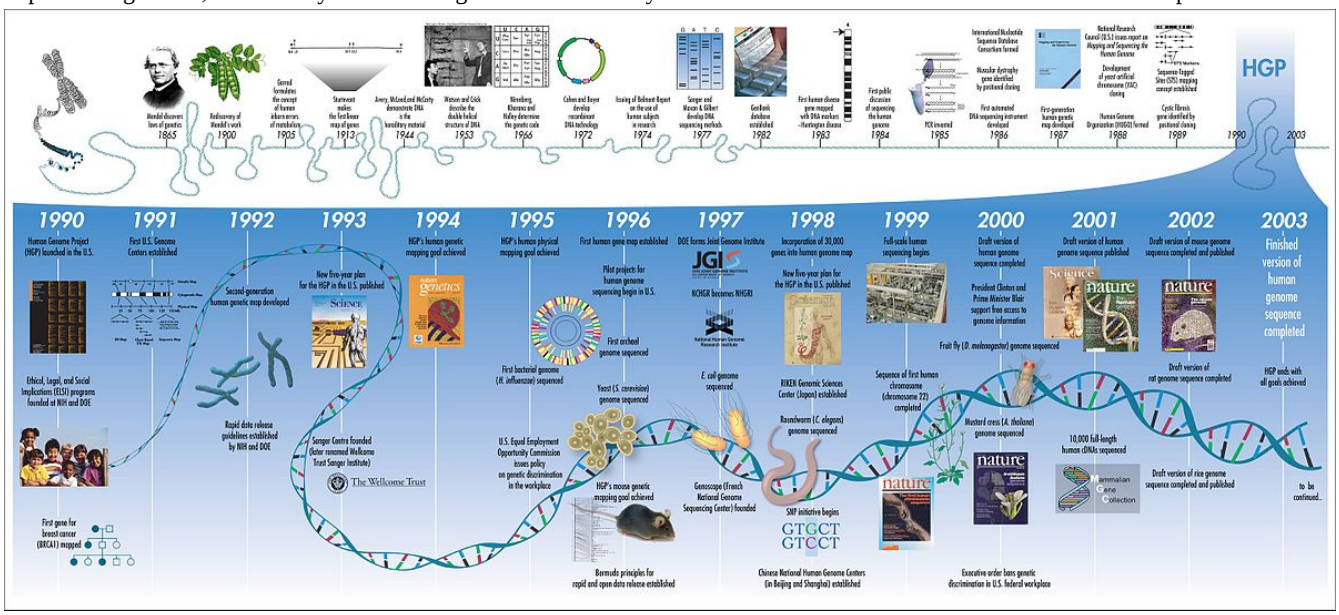



Figure **3.18.3**: Timeline of the human genome project from 1990 to 2003. The details of this timeline are more than we need here. You can see all the details at the NIH site.

## ETHICAL, LEGAL, AND SOCIAL ISSUES OF THE HUMAN GENOME PROJECT

From its launch in 1990, the HGP proactively established and funded a separate committee to oversee potential ethical, legal, and social issues associated with the project. A major concern was the possible use of the knowledge generated by the project to discriminate against people. One issue was the fear that employers and health insurance companies would refuse to hire or insure people based on their genetic makeup, for instance, if they had genes that increased their risk of getting certain diseases. In response, in 1996, the U.S. passed the Health Insurance Portability and Accountability Act (HIPAA). It protects against unauthorized, nonconsensual release of individually identifiable health information to any entity not actively engaged in providing healthcare to a patient. This was followed in 2008 by the Genetic Information Nondiscrimination Act (GINA), which specifically prohibits genetic discrimination by health insurance companies and workplaces.

## REVIEW

1. Describe the human genome.
2. What is the Human Genome Project?
3. Identify two main goals of the Human Genome Project.
4. What is the reference genome of the Human Genome Project? What is it based on?
5. Explain how knowing the sequence of DNA bases in the human genome is beneficial for molecular medicine.
6. What was one surprising finding of the Human Genome Project?
7. Why do you think scientists didn't just sequence the DNA from a single person for the Human Genome Project? Along those lines, why do you think it is important to include samples from different ethnic groups and genders in genome sequencing efforts?
8. *True or False.* The sequenced human genome does not include noncoding regions — it only includes actual genes.
9. *True or False.* Knowing the sequence of the human genome can give insight into human evolution.
10. What is pharmacogenomics?
    A. If a patient were to have pharmacogenomics done to optimize their medication, what do you think the first step would be?
    B. List one advantage and one disadvantage of pharmacogenomics.
11. There are approximately 20,000 human
    A. base pairs
    B. nucleotides
    C. alleles
    D. genes
12. Explain how the sequencing of the human genome relates to ethical concerns about genetic discrimination.

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# 3.19: CASE STUDY CONCLUSION- PARMACOGENOMICS AND CHAPTER SUMMARY

## CASE STUDY CONCLUSION: PHARMACOGENOMICS

Arya asked their doctor about Pharmacogenomics. The doctor explains to Arya that Pharmacogenomics is the tailoring of drug treatments to people's genetic makeup, a form of 'personalized medicine'.

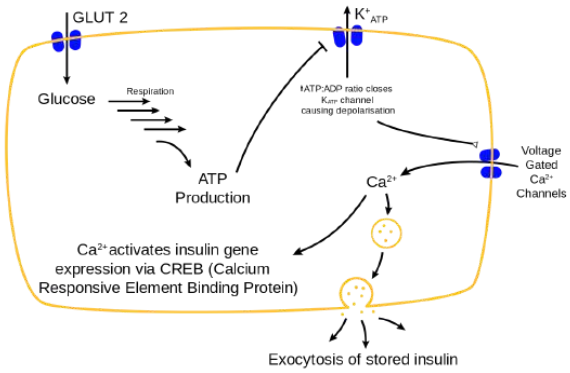



Figure **3.19.1**: Glucose insulin release.

Figure **3.19.1** shows a beta cell of the pancreas. As the blood glucose rises, it enters the cell via the GLUT 2 channel. After entering into the cell, it causes the production of ATP that closes the potassium pump. As potassium stops exiting the cell, it causes calcium channels to open and, finally, that causes insulin release from the cells. This process is even more complicated as many enzymes and proteins are skipped in this brief description of the pathway. The sulfonylurea-based drugs force the closing of a potassium pump by attaching it. This causes the release of insulin by skipping many steps. Because many enzymes and other proteins are involved in this complicated process, people respond differently to medicines. Most respond well and their health improves. Some do not gain any benefits from the treatment, and a minority suffer from side effects. After you take a drug, it is processed (metabolized) by your body. How the drug is processed and how you respond to it is determined, in part, by your genes. Understanding how different genetics affect and how a drug is processed can help doctors to more accurately determine which drug and which dose is best for individual patients. In this chapter, you learned what the genome is and how to recognize genes in the genome. In pharmacogenomics, scientists look at the genome of an individual to identify the genetic factors that influence his or her response to a drug. By finding these genes, medical researchers hope to develop genetic tests that will predict how patients will respond to a drug. This is personalized medicine.

The reason people vary in their responses to drug treatments lies in the genetic differences, or variation, between them. Following the Human Genome Project, research has focused on comparing human genomes to understand genetic variation and work out which genetic variants are important in health and in the way we respond to drugs. We also learned in this chapter that two types of variation are common in the human genome: 1) Single nucleotide polymorphisms (SNPs): changes in single nucleotide bases (A, C, G, and T). This was the case in Arya's physical response to the sulfonylurea. 2) Structural variation: changes affecting chunks of DNA that can consequently alter the structure of the entire chromosome. Structural variation can happen in a number of ways, for example, Copy number variation (CNV): when there is an increase or decrease in the amount of DNA. This can be due to: deletion, where an entire block of DNA is missing; insertion, where a block of DNA is added in duplication; or where there are additional copies of a section of DNA. Inversion: when chromosome breaks in two places and the resulting piece of DNA is reversed and reinserted back into the chromosome (the opposite way round). Translocation: when genetic material is exchanged between two different chromosomes. SNPs are like changing a single letter in the metaphorical 'recipe book of life', while structural variation is the equivalent of whole paragraphs or pages being lost or repeated. Scientists have been aware of SNPs for a long time, but the extent of structural variation was only revealed when it was possible to sequence and compare many genomes. The structural variation appears to be quite common, affecting around 12 percent of the genome. It has been found to cause a variety of genetic conditions.

## FINDING DISEASE VARIANTS

Humans share around 99.5 percent of their genomes. The 0.5 percent that differs between each of us affects our susceptibility to disease and response to drugs. Although this doesn't sound like a lot, it still means that there are millions of differences between the DNA of two individuals. For example, because SNPs are common in the genome, it is difficult to work out which single letter changes cause disease and which are passengers that have just come along for the ride and have no effect on health.

### SO HOW IS IT POSSIBLE TO KNOW WHICH GENETIC VARIANTS CAUSE DISEASE AND WHICH ARE PASSENGERS?

The way scientists look at disease variants is to compare the genetic makeup of a large number of people who have a specific disease with those who do not. This allows scientists to look for genetic variants that are more common in people with a disease compared to people without the disease. For example, if a particular genetic variant is present in 80 percent of patients with the disease but only 20 percent of the healthy population it suggests that this variant is increasing the risk of that disease. However, looking for a disease that is caused by variants in a single gene is the simplest example. There are many complex diseases where variants in many different genes might be involved. As well as the transcriptional and translational regulation of some enzyme production may vary due to the genetic variation in the enhancer and repressors of a gene. So, for this type of comparison to be effective very large groups of people need to be studied, usually in the tens of thousands, to find the variants that have subtle effects on disease risk. Researchers also try to pick individuals with similar phenotypes, in both the diseased and healthy groups, so that the disease genes are easier to identify and study.

## CHALLENGES OF PHARMACOGENOMICS

Although pharmacogenomics is likely to be an important part of future medical care, there are many obstacles to overcome before it becomes routine. It is relatively rare for a particular drug response to be affected by a single genetic variant. A particular genetic variant may increase the likelihood of an adverse reaction but it will not guarantee it.

As a result, some people with the variant may not experience an adverse reaction to a drug. Similarly, if an individual doesn't have the gene variant, it doesn't guarantee they won't experience an adverse reaction. Often, a large number of interacting genetic and environmental factors may influence the response to a drug.

Even when associations between a genetic variant and a drug response have been clearly demonstrated, suitable tests still have to be developed and proven to be effective in clinical trials. A test that has succeeded in a clinical trial still has to be shown to be useful and cost-effective in a healthcare setting. Regulatory agencies will have to consider how they assess and license pharmacogenetic products. Health services will have to adjust to new ways of deciding the best drug to give to an individual.

The behavior of individual doctors will need to change. A lot of side effects are due to patients not taking their drugs as prescribed or to doctors prescribing the wrong dose. Some examples of pharmacogenomics that work effectively, for example, *abacavir* for HIV, show that these challenges can be overcome. However, in most cases, implementing the findings from pharmacogenomics is likely to be a complicated process.

## CHAPTER SUMMARY

- Determining that DNA is the genetic material was an important milestone in biology.
  - In the 1920s, Griffith showed that something in virulent bacteria could be transferred to nonvirulent bacteria and make them virulent as well.
  - In the 1940s, Avery and colleagues showed that the "something" Griffith found was DNA and not protein. This result was confirmed by Hershey and Chase, who demonstrated that viruses insert DNA into bacterial cells.
- In the 1950s, Chargaff showed that in DNA, the concentration of adenine is always the same as the concentration of thymine, and the concentration of guanine is always the same as the concentration of cytosine. These observations came to be known as Chargaff's rules.
- In the 1950s, James Watson and Francis Crick, building on the prior X-ray research of Rosalind Franklin and others, discovered the double-helix structure of the DNA molecule.
- Knowledge of DNA's structure helped scientists understand how DNA replicates, which must occur before cell division. DNA replication is semi-conservative because each daughter molecule contains one strand from the parent molecule and one new strand that is complementary to it.
- Genes that are located on the same chromosome are called linked genes. Linkage explains why certain characteristics are frequently inherited together.
- The central dogma of molecular biology can be summed up as DNA → RNA → Protein. This means that the genetic instructions encoded in DNA are transcribed to RNA, and then from RNA, they are translated into a protein.
- RNA is a nucleic acid. Unlike DNA, RNA consists of just one polynucleotide chain instead of two, contains the base uracil instead of thymine, and contains the sugar ribose instead of deoxyribose.
- The main function of RNA is to help make proteins. There are three main types of RNA: messenger RNA (mRNA), ribosomal RNA (rRNA), and transfer RNA (tRNA).
- According to the RNA world hypothesis, RNA was the first type of biochemical molecule to evolve, predating both DNA and proteins.
- The genetic code was cracked in the 1960s by Marshall Nirenberg. It consists of the sequence of nitrogen bases in a polynucleotide chain of DNA or RNA. The four bases make up the "letters" of the code. The letters are combined in groups of three to form code "words," or codons, each of which encodes for one amino acid or a start or stop signal.

- AUG is the start codon, and it establishes the reading frame of the code. After the start codon, the next three bases are read as the second codon, and so on until a stop codon is reached.
- The genetic code is universal, unambiguous, and redundant.

- Protein synthesis is the process in which cells make proteins. It occurs in two stages: transcription and translation
  - Transcription is the transfer of genetic instructions in DNA to mRNA in the nucleus. It includes the steps of initiation, elongation, and termination. After the mRNA is processed, it carries the instructions to a ribosome in the cytoplasm.
  - Translation occurs at the ribosome, which consists of rRNA and proteins. In translation, the instructions in mRNA are read, and tRNA brings the correct sequence of amino acids to the ribosome. Then rRNA helps bonds form between the amino acids, producing a polypeptide chain.
  - After a polypeptide chain is synthesized, it may undergo additional processing to form the finished protein.
- Mutations are random changes in the sequence of bases in DNA. They are the ultimate source of all new genetic variation in any species
  - Mutations may happen spontaneously during DNA replication or transcription. Other mutations are caused by environmental factors called mutagens.
  - Germline mutations occur in gametes and may be passed on to offspring. Somatic mutations occur in other cells than gametes and cannot be passed on to offspring.
  - Chromosomal alterations are mutations that change chromosome structure or number and usually affect the organism in multiple ways. Down syndrome (trisomy 21) is an example of a chromosomal alteration.
  - Point mutations are changes in a single nucleotide. The effects of point mutations depend on how they change the genetic code and may range from no effects to very serious effects.
  - Frameshift mutations change the reading frame of the genetic code and are likely to have a drastic effect on the encoded protein.
  - Many mutations are neutral and have no effects on the organism in which they occur. Some mutations are beneficial and improve fitness, while others are harmful and decrease fitness.
- Using a gene to make a protein is called gene expression. Gene expression is regulated to ensure that the correct proteins are made when and where they are needed. Regulation may occur at any stage of protein synthesis or processing.
- The regulation of transcription is controlled by regulatory proteins that bind to regions of DNA called regulatory elements, which are usually located near promoters. Most regulatory proteins are either activators that promote transcription or repressors that impede transcription.
- The regulation of gene expression is extremely important during the early development of an organism. Homeobox genes, which encode for chains of amino acids called homeodomains, are important genes that regulate development.
- Some types of cancer occur because of mutations in genes that control the cell cycle. Cancer-causing mutations most often occur in two types of regulatory genes, called tumor-suppressor genes and proto-oncogenes.
- Biotechnology is the use of technology to change the genetic makeup of living things for human purposes.
  - Biotechnology methods include gene cloning and the polymerase chain reaction. Gene cloning is the process of isolating and making copies of a DNA segment such as a gene. The polymerase chain reaction makes many copies of a gene or other DNA segment.
  - Biotechnology can be used to transform bacteria so they are able to make human proteins, such as insulin. It can also be used to create transgenic crops, such as crops that yield more food or resist insect pests.
  - Biotechnology has raised a number of ethical, legal, and social issues including health, environmental, and privacy concerns.
- The human genome refers to all of the DNA of the human species. It consists of more than 3.3 billion base pairs divided into 20,500 genes on 23 pairs of chromosomes.
- The Human Genome Project (HGP) was a multi-billion dollar international research project that began in 1990. By 2003, it had sequenced and mapped the location of all of the DNA base pairs in the human genome. It published the results as a human reference genome that is available to anyone on the Internet.
- The sequencing of the human genome is helping researchers better understand cancer and genetic diseases. It is also helping them tailor medications to individual patients, which is the focus of the new field of pharmacogenomics. In addition, it is helping researchers better understand human evolution.

## REVIEW:

1. Put the following units in order from the smallest to the largest:

   A. chromosome
   B. gene
   C. nitrogen base
   D. nucleotide

E. codon

2. Put the following processes in the correct order of how a protein is produced, from earliest to latest:
   A. tRNA binding to mRNA
   B. transcription
   C. traveling of mRNA out of the nucleus
   D. folding of the polypeptide
3. What are the differences between a sequence of DNA and the sequence of mature mRNA that it produces?
4. Scientists sometimes sequence DNA that they "reverse transcribe" from the mRNA in an organism's cells, which is called complementary DNA (cDNA). Why do you think this technique might be particularly useful for understanding an organism's proteins versus sequencing the whole genome (i.e. nuclear DNA) of the organism?
5. What are proteins are made in the cytoplasm on small organelles called?
6. What might happen if codons encoded for more than one amino acid?
7. Explain why a human gene can be inserted into bacteria and can still produce the correct human protein, despite being in a very different organism.
8. *True or False*. All of your genes are expressed by all the cells of your body.
9. What does The central dogma of molecular biology describe?

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# 3.20: CASE STUDY- GENETIC SIMILARITIES AND DIFFERENCES

## CASE STUDY: ABNORMAL CELL DIVISION

Like the little children in Figure 3.20.1, seven-year-old Kim is battling leukemia, a type of cancer that affects blood cells. Leukemia usually starts in the bone marrow, where blood cells are produced. It causes the production of abnormal blood cells, most commonly white blood cells, but it can affect other types of blood cells depending on the type of leukemia. The abnormal blood cells replace the patient's normal blood cells over time. This can lead to symptoms such as fatigue, frequent infections, and easy bruising or bleeding. Leukemia can be fatal, but fortunately, there are some treatment options available that can prolong life and even may cure the disease.



Figure 3.20.1: Pediatric patients receiving chemotherapy

Kim has undergone chemotherapy to kill the cancerous cells, but his doctors have told his parents that it is not enough. Kim needs a bone marrow transplant in order to replace his abnormal bone marrow with healthy bone marrow. His family members are eager to donate bone marrow to him, but first, they must be tested to see if they are a compatible match.

Unlike blood transfusions where it is relatively easy to find a compatible blood donor, bone marrow transplants require much more specific matching between donor and recipient. They must share several of the same types of proteins, called human leukocyte antigens (HLAs), on the surface of their cells. One type of HLA protein is illustrated in Figure 3.20.2. Different people have different types of HLA proteins, or markers, depending on their specific genes. Typically, eight to ten HLA markers are tested and compared in the potential bone marrow donor and recipient. At least six or seven of these HLA markers need to be identical between them in order for a match to be made.

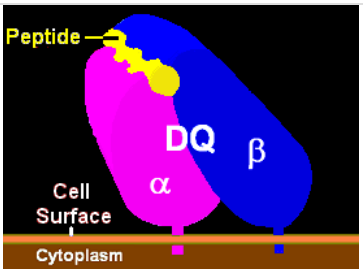



Figure 3.20.2: An illustration of a human leukocyte antigen protein, HLA-DQ, attached to the surface of a cell, showing its α (pink) and β (blue) chains.

If the match is not good, the patient's body could reject the bone marrow transplant, or, conversely, the transplanted bone marrow could produce immune cells that attack the patient's body. A good match between donor and recipient is critical for bone marrow donation to be safe and effective.

A full sibling frequently provides the best match for bone marrow donation because they share many of the same genes from their parents. Kim's sister is tested, but unfortunately, she is not a match for him. This is not all that surprising since there is only about a 25% chance that a sibling will be an identical HLA match. His parents and other family members are also tested, but none of them is a match either. Kim must join the 70% of patients that need to look outside of their families for a bone marrow donor.

Read the rest of this chapter to learn more about how cells originate from cells. Why one damaged cell gives rise to more damaged cells which can lead to diseases like cancer. You will also learn why not every cell becomes cancerous and why cancerous cells divide uncontrollably. You will also learn why two siblings are not exact copies of each other.

## CHAPTER OVERVIEW: CELL REPRODUCTION

In this chapter, you will learn about:

- The phases of the cell cycle and how cells divide through mitosis.
- How cancer can result from an unregulated cell division due to a mutation.
- Sexual reproduction.
- Differences and similarities between sexual and asexual reproduction.

As you read the chapter, think about the following questions:

- How cancer originates?
- Why every person doesn't have cancer?
- How chemotherapy kills cancerous cells?
- Why Kim's sister and other family members do not have exactly the same HLA markers?

## ATTRIBUTIONS

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# 3.21: CELL CYCLE AND CELL DIVISION

## SO MANY CELLS!

The baby in Figure **3.21.1** has a lot of growing to do before they are as big as their mom. Most of their growth will be the result of cell division. By the time the baby is an adult, their body will consist of trillions of cells. Cell division is just one of the stages that all cells go through during their life. This includes cells that are harmful, such as cancer cells. Cancer cells divide more often than normal cells and grow out of control. In fact, this is how cancer cells cause illness. In this concept, you will read about how cells divide, what other stages cells go through, and what causes cancer cells to divide out of control and harm the body.



Figure **3.21.1**: Baby and mother

## THE CELL CYCLE

**Cell division** is the process in which one cell, called the parent cell, divides to form two new cells, referred to as daughter cells. How this happens depends on whether the cell is prokaryotic or eukaryotic. Cell division is simpler in prokaryotes than eukaryotes because prokaryotic cells themselves are simpler. Prokaryotic cells have a single circular chromosome, no nucleus, and few other organelles. Eukaryotic cells, in contrast, have multiple chromosomes contained within a nucleus and many other organelles. All of these cell parts must be duplicated and then separated when the cell divides. Cell division is just one of several stages that a cell goes through during its lifetime. The **cell cycle** is a repeating series of events that include growth, DNA synthesis, and cell division. The cell cycle in prokaryotes is quite simple: the cell grows, its DNA replicates, and the cell divides. This form of division in prokaryotes is called asexual reproduction. In eukaryotes, the cell cycle is more complicated.

### EUKARYOTIC CELL CYCLE

Figure **3.21.2** represents the cell cycle of a eukaryotic cell. As you can see, the eukaryotic cell cycle has several phases. The mitotic phase (M) includes both mitosis and cytokinesis. This is when the nucleus and then the cytoplasm divide. The other three phases ($G_1$, S, and $G_2$) are generally grouped together as **interphase**. During interphase, the cell grows, performs routine life processes, and prepares to divide. These phases are discussed below.

### INTERPHASE

The Interphase of the eukaryotic cell cycle can be subdivided into the following phases (Figure **3.21.2**).

- **Growth Phase 1 ($G_1$):** The cell spends most of its life in the first gap (sometimes referred to as growth) phase, $G_1$. During this phase, a cell undergoes rapid growth and performs its routine functions. During this phase, the biosynthetic and metabolic activities of the cell occur at a high rate. The synthesis of amino acids and hundreds of thousands or millions of proteins that are required by the cell occurs during this phase. Proteins produced include those needed for DNA replication. If a cell is not dividing, the cell enters the $G_0$ phase from this phase.
- **$G_0$ phase:** The $G_0$ phase is a resting phase where the cell has left the cycle and has stopped dividing. Non-dividing cells in multicellular eukaryotic organisms enter $G_0$ from $G_1$. These cells may remain in $G_0$ for long periods of time, even indefinitely, such as with neurons. Cells that are completely differentiated may also enter $G_0$. Some cells stop dividing when issues of sustainability or viability of their daughter cells arise, such as with DNA damage or degradation, a process called **cellular senescence**. Cellular senescence occurs when normal diploid cells lose the ability to divide, normally after about 50 cell divisions.
- **Synthesis Phase (S):** Dividing cells enter the Synthesis (S) phase from $G_1$. For two genetically identical daughter cells to be formed, the cell's DNA must be copied through DNA replication. When the DNA is replicated, both strands of the double helix are used as templates to produce two new complementary strands. These new strands then hydrogen bond to the template strands and two double helices form. During this phase, the amount of DNA in the cell has effectively doubled, though the cell remains in a diploid state.
- **Growth Phase 2 ($G_2$):** The second gap (growth) ($G_2$) phase is a shortened growth period in which many organelles are reproduced or manufactured. Parts necessary for mitosis and cell division are made during $G_2$, including **microtubules** used in the mitotic spindle.

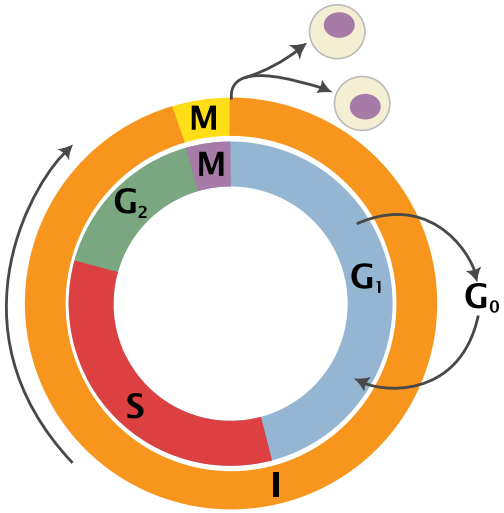



Figure **3.21.2**: Eukaryotic Cell Cycle. The First Gap (G1), Synthesis (S), and Second Gap (G2) phases make up interphase (I). The mitotic phase (yellow M) includes mitosis (purple M) and cytokinesis. During cytokinesis two cells result. Some cells do not divide and they enter into $G_0$ phage.

## MITOTIC PHASE

Before a eukaryotic cell divides, all the DNA in the cell's multiple chromosomes is replicated. Its organelles are also duplicated. This happens in the interphase. Then, when the cell divides (mitotic phase), it occurs in two major steps, called **mitosis** and **cytokinesis**, both of which are described in greater detail in the concept *Mitotic Phase: Mitosis and Cytokinesis*.

- The first step in the mitotic phase of a eukaryotic cell is mitosis, a multi-phase process in which the nucleus of the cell divides. During mitosis, the nuclear envelope (membrane) breaks down and later reforms. The chromosomes are also sorted and separated to ensure that each daughter cell receives a complete set of chromosomes.
- The second major step is cytokinesis. This step, which occurs in prokaryotic cells as well, is when the cytoplasm divides and two daughter cells form.

Table **3.21.2**: Cell Cycle Summary

| State | Name | Description |
|---|---|---|
| Quiescent Senescent | Resting phase (G0) | A resting phase where the cell has left the cycle and has stopped dividing. |
| Interphase | 1st growth phase ($G_1$) Synthesis phase (S) 2ndgrowth phase ($G_2$) | Cells increase in size in G1. Cells perform their normal activities. DNA replication occurs during this phase. The cell will continue to grow and many organelles will divide during their phase. |
| Cell division | Mitosis (M) | Cell growth stops at this stage. Mitosis divides the nucleus into two nuclei, followed by cytokinesis which divides the cytoplasm. Two genetically identical daughter cells result. |

## CONTROL OF THE CELL CYCLE

If the cell cycle occurred without regulation, cells might go from one phase to the next before they were ready. What controls the cell cycle? How does the cell know when to grow, synthesize DNA, and divide? The cell cycle is controlled mainly by regulatory proteins. These proteins control the cycle by signaling the cell to either start or delay the next phase of the cycle. They ensure that the cell completes the previous phase before moving on. Regulatory proteins control the cell cycle at key checkpoints, which are shown in Figure **3.21.3**. There are a number of main checkpoints:

1. The G1 checkpoint: just before entry into the S phase, makes the key decision of whether the cell big enough to divide. If the cell is not big enough, it goes into the resting period ($G_0$)
2. DNA synthesis Checkpoint: The S checkpoint determines if the DNA has been replicated properly.
3. The mitosis checkpoint: This checkpoint ensures that all the chromosomes are properly aligned before the cell is allowed to divide.

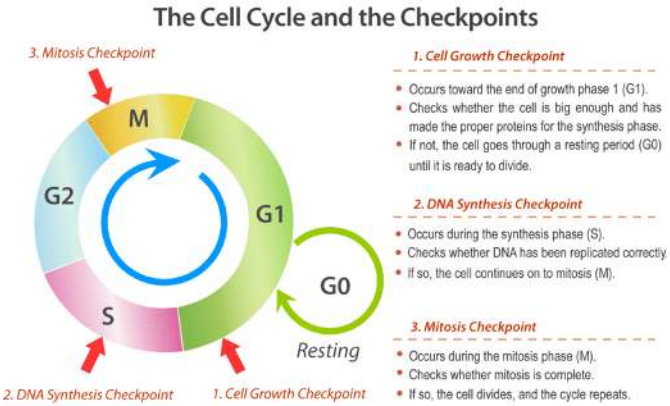



Figure **3.21.3**: Checkpoints in the eukaryotic cell cycle ensure that the cell is ready to proceed before it moves on to the next phase of the cycle.

## CANCER AND THE CELL CYCLE

**Cancer** is a disease that occurs when the cell cycle is no longer regulated. This happens because a cell's DNA becomes damaged. This results in mutations in the genes that regulate the cell cycle. Damage can occur due to exposure to hazards such as radiation or toxic chemicals. Cancerous cells generally divide much faster than normal cells. They may form a mass of abnormal cells called a **tumor** (see Figure **3.21.4**). The rapidly dividing cells take up nutrients and space that normal cells need. This can damage tissues and organs and eventually lead to death. When uncontrolled cell division happens in the bone marrow, abnormal and nonfunctional blood cells are produced because the division is happening before the cell is ready for division. In these types of cancer, there is not any evident tumor.

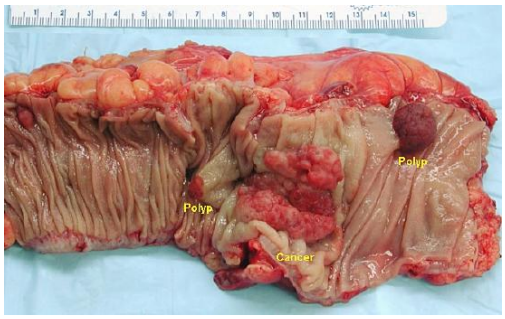



Figure **3.21.4**: Gross appearance of an opened large intestine specimen containing an invasive **colorectal carcinoma** and two **adenomatous polyps**. The cancer cells have grown out of control and forming a tumor.

## FEATURE: HUMAN BIOLOGY IN THE NEWS

Henrietta Lacks sought treatment for her cancer at Johns Hopkins University Hospital at a time when researchers were trying to grow human cells in the lab for medical testing. Despite many attempts, the cells always died before they had undergone many cell divisions. Mrs. Lacks's doctor took a small sample of cells from her tumor without her knowledge and gave them to a Johns Hopkins researcher, who tried to grow them on a culture plate. For the first time in history, human cells grown on a culture plate kept dividing...and dividing and dividing and dividing. Copies of Henrietta's Lacks cells — called HeLa cells for her name — are still alive today. In fact, there are currently many billions of HeLa cells in laboratories around the world!

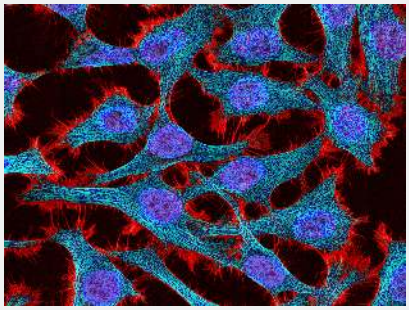


Figure **3.21.5**: Fluorescently dyed HeLa Cells. The woman named Henrietta Lacks died in 1951 of an unusual form of cervical cancer, she was just 31 years old. A poor, African-American tobacco farmer and mother of five, she (or at least her cells) would eventually be called immortal.

Why Henrietta Lacks' cells lived on when other human cells did not is still something of a mystery, but they are clearly extremely hardy and resilient cells. By 1953, when researchers learned of their ability to keep dividing indefinitely, factories were set up to start producing the cells commercially on a large scale for medical research. Since then, HeLa cells have been used in thousands of studies and have made possible hundreds of medical advances. For example, Jonas Salk used the cells in the early 1950s to test his polio vaccine. Over the decades since then, HeLa cells have been used to make important discoveries in the study of cancer, AIDS, and many other diseases. The cells were even sent to space on early space missions to learn how human cells respond to zero gravity. HeLa cells were also the first human cells ever cloned, and their genes were some of the first ever mapped. It is almost impossible to overestimate the profound importance of HeLa cells to human biology and medicine.

You would think that Henrietta Lacks' name would be well known in medical history for her unparalleled contributions to biomedical research. However, until 2010, her story was virtually unknown. That year, a science writer named Rebecca Skloot published a nonfiction book about Henrietta Lacks, named *The Immortal Life of Henrietta Lacks*. Based on a decade of research, the book is riveting, and it became an almost instantaneous best seller. As of 2016, Oprah Winfrey and collaborators planned to make a movie based on the book, and in recent years, numerous articles about Henrietta Lacks have appeared in the press.

Ironically, Henrietta herself never knew her cells had been taken, and neither did her family. While her cells were making a lot of money and building scientific careers, her children were living in poverty, too poor to afford medical insurance. The story of Henrietta Lacks and her immortal cells raises ethical issues about human tissues and who controls them in biomedical research. However, there is no question that Henrietta Lacks deserves far more recognition for her contribution to the advancement of science and medicine.

## REVIEW

1. What are the two main phases of the cell cycle in a eukaryotic cell?
2. Describe the three phases of interphase in a eukaryotic cell.
3. Explain how the cell cycle is controlled.
4. How is cancer-related to the cell cycle?
5. What are the two major steps of cell division in a eukaryotic cell?
6. In which phase of the eukaryotic cell cycle do cells typically spend most of their lives?
7. Which phases of the cell cycle will have cells with twice the amount of DNA? Explain your answer.
8. If there is damage to a gene that encodes for a cell cycle regulatory protein, what do you think might happen? Explain your answer.
9. *True or False*. Cells go into $G_0$ if they do not pass the $G_1$ checkpoint.
10. In which phase within interphase does the cell make final preparations to divide?
    A. Mitosis
    B. Cytokinesis
    C. $G_2$
    D. S
11. What were scientists trying to do when they took tumor cells from Henrietta Lacks? Why did they specifically use tumor cells to try to achieve their goal?

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# 3.22: MITOTIC PHASE - MITOSIS AND CYTOKINESIS

## DIVIDE AND SPLIT

Can you guess what this colorful image represents? It shows a eukaryotic cell during the process of cell division. In particular, the image shows the nucleus of the cell dividing. In eukaryotic cells, the nucleus divides before the cell itself splits in two; and before the nucleus divides, the cell's DNA is replicated, or copied. There must be two copies of the DNA so that each daughter cell will have a complete copy of the genetic material from the parent cell. How is the replicated DNA sorted and separated so that each daughter cell gets a complete set of genetic material? To answer that question, you first need to know more about DNA and the forms it takes.

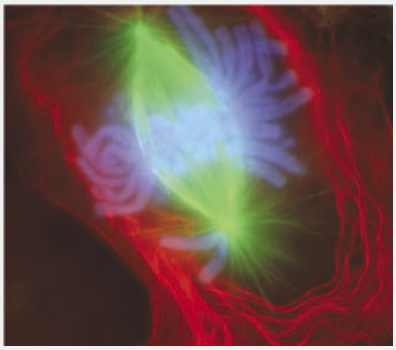


Figure 3.22.1: Dividing cell stained with fluorescent dyes. You can see chromosomes in blue and spindles in green.

## THE FORMS OF DNA

Except when a eukaryotic cell divides, its nuclear DNA exists as a grainy material called **chromatin.** Only when a cell is about to divide and its DNA has replicated does DNA condense and coil into the familiar X-shaped form of a **chromosome,** like the one shown in Figure 3.22.2. Because DNA has already replicated, each chromosome actually consists of two identical copies. The two copies of a chromosome are called sister **chromatids.** Sister chromatids are joined together at a region called a centromere.

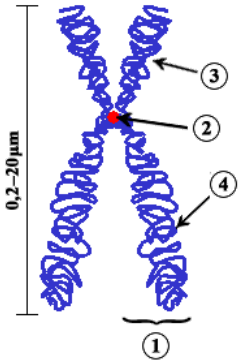



Figure 3.22.2: Chromosome. After DNA replicates, it forms X-shaped chromosomes like the one shown here. 1. Chromatid, 2. Centromere, 3. short arm, 4. long arm. Centromere contains proteins called kinetochores (not shown) where spindles attach during mitosis.

The process in which the nucleus of a eukaryotic cell divides is called **mitosis.** During mitosis, the two sister chromatids that make up each chromosome separate from each other and move to opposite poles of the cell. Mitosis occurs in four phases. The phases are called prophase, metaphase, anaphase, and telophase. They are shown in Figure 3.22.3 and described in detail below.

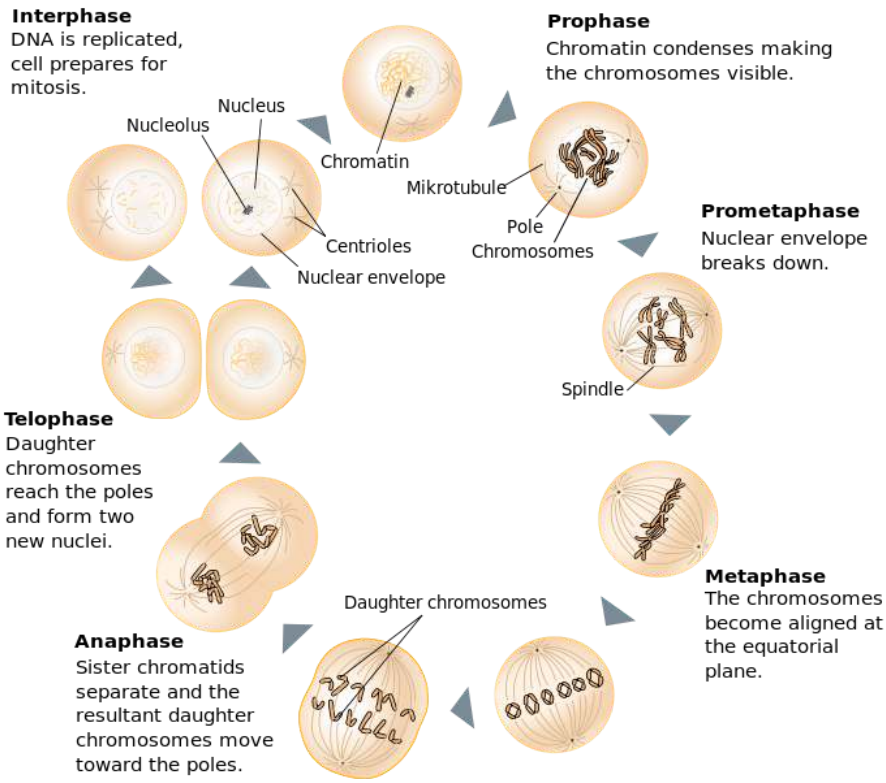



Figure **3.22.3**: Mitosis is the phase of the eukaryotic cell cycle that occurs between DNA replication and the formation of two daughter cells. Mitosis has four substages, prophase, metaphase, anaphase, and telophase.

## PROPHASE

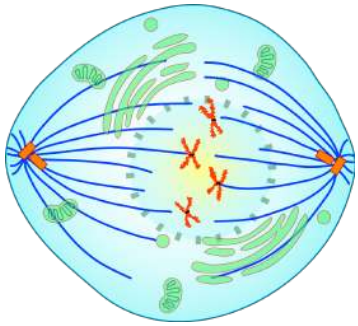


Figure **3.22.4**: Prophase in later stage is called prometaphase. The spindle starts to form during the prophase of mitosis. The spindles start to attach to the Kinetochores of centromeres of sister chromatids during Prometaphase.

The first and longest phase of mitosis is prophase. During prophase, chromatin condenses into chromosomes, and the nuclear envelope (the membrane surrounding the nucleus) breaks down. In animal cells, the centrioles near the nucleus begin to separate and move to opposite poles of the cell. Centrioles are small organelles found only in eukaryotic cells that help ensure the new cells that form after cell division each contain a complete set of chromosomes. As the centrioles move apart, a spindle starts to form between them. The blue spindle, shown in Figure **3.22.4**, consists of fibers made of microtubules.

## METAPHASE

During **metaphase**, spindle fibers fully attach to the centromere of each pair of sister chromatids. As you can see in Figure **3.22.5**, the sister chromatids line up at the equator, or center, of the cell. The spindle fibers ensure that sister chromatids will separate and go to different daughter cells when the cell divides. Some spindles do not attach to the kinetochore protein of the centromeres. These spindles are called non-kinetochore spindles that help in the elongation of the cell. This is visible in Figure **3.22.5**.

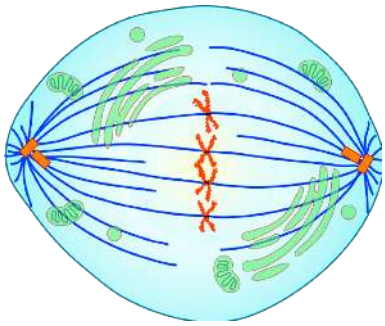


Figure **3.22.5**: Chromosomes, consisting of sister chromatids, line up at the equator or middle of the cell during metaphase. The blue lines are spindles, and the orange rectangles at the cell poles are centrioles. Some spindles from the opposing centrioles attach with each other, and some spindles attach to the kinetochores of the sister chromosomes from their respective sides. Each chromosome is attached to two spindles.

## ANAPHASE

During **anaphase**, sister chromatids separate and the centromeres divide. The sister chromatids are pulled apart by the shortening of the spindle fibers. This is a little like reeling in a fish by shortening the fishing line. One sister chromatid moves to one pole of the cell, and the other sister chromatid moves to the opposite pole (see Figure

3.22.6). At the end of anaphase, each pole of the cell has a complete set of chromosomes

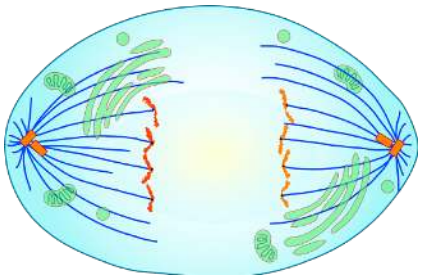


Figure 3.22.6: Anaphase: Sister chromatids break apart and move to the opposite pole with the help of spindles. The newly separated sister chromatids are called chromosomes now.

## TELOPHASE

The chromosomes reach the opposite poles and begin to *decondense* (unravel), relaxing once again into a stretched-out chromatin configuration. The mitotic spindles are depolymerized into tubulin monomers that will be used to assemble cytoskeletal components for each daughter cell. Nuclear envelopes form around the chromosomes, and nucleosomes appear within the nuclear area (see Figure 3.22.7.

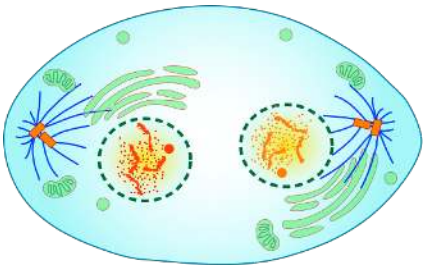


Figure 3.22.7: Telophase: The chromosomes decondense, spindles start to disappear, two nuclei form in a cell.

## CYTOKINESIS

Cytokinesis is the final stage of cell division in eukaryotes as well as prokaryotes. During cytokinesis, the cytoplasm splits in two and the cell divides. The process is different in plant and animal cells, as you can see in Figure 3.22.8. In animal cells, the plasma membrane of the parent cell pinches inward along the cell's equator until two daughter cells form. In the plant cells, a cell plate forms along the equator of the parent cell. Then, a new plasma membrane and cell wall form along each side of the cell plate.

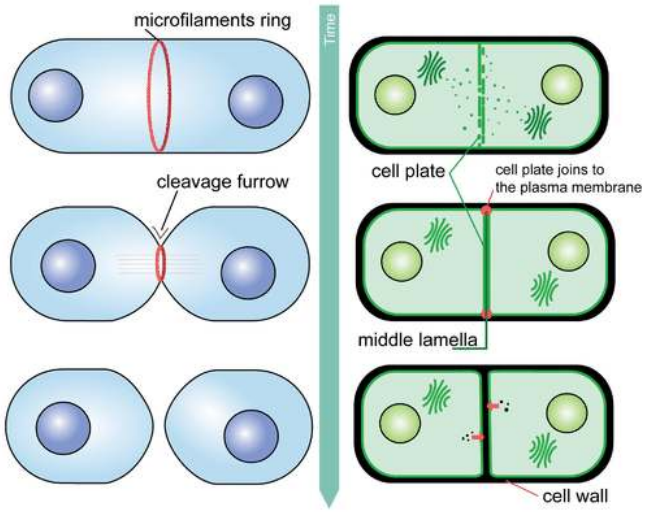



Figure 3.22.8: Cytokinesis is the final stage of eukaryotic cell division. It occurs differently in animal (left) and plant (right) cells. You can see a microfilament ring forming at the center of the elongated animal cell. This creates a depression called cleavage furrow. This invagination ultimately separates the cell cytoplasm into two cells. A cell plate forms at the center of the elongated plant cell. Then a new plasma membrane and cell wall form along each side of the cell plate.

## REVIEW

1. Describe the different forms that DNA takes before and during cell division in a eukaryotic cell.
2. Identify the four phases of mitosis in an animal cell, and summarize what happens during each phase.
3. Explain what happens during cytokinesis in an animal cell.
4. What are the main differences between mitosis and cytokinesis?
5. The familiar X-shaped chromosome represents:
   A. How DNA always looks in eukaryotic cells
   B. How DNA in eukaryotic cells looks once it is replicated and the cell is about to divide
   C. Female sex chromosomes only
   D. How DNA appears immediately after cytokinesis
6. Which of the following is not part of a chromosome in eukaryotic cells?
   A. Centriole
   B. Centromere
   C. Chromatid
   D. DNA
7. What do you think would happen if the sister chromatids of one of the chromosomes did not separate during mitosis?
8. Put the following processes in order of when they occur during cell division, from first to last:
   A. separation of sister chromatids
   B. DNA replication
   C. cytokinesis
   D. lining up of chromosomes in the center of the cell
   E. condensation and coiling of DNA into a chromosome

9. Why do you think the nuclear envelope breaks down at the start of mitosis?
10. What are the fibers made of microtubules that attach to the centromeres during mitosis are called?
11. *True or False.* Chromosomes begin to uncoil during anaphase.
12. *True or False.* During cytokinesis in animal cells, sister chromatids line up along the equator of the cell.
13. *True or False.* After mitosis, the result is typically two daughter cells with identical DNA to each other.

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# 3.23: MUTATIONS AND CANCER

## WHAT WOULD HAPPEN IF THIS CYCLE PROCEEDS AT WILL?

Your cells may grow and divide without performing their necessary functions, or without fully replicating their DNA, or without copying their organelles. Probably not much good could come of that. So the cell cycle needs to be highly regulated and tightly controlled. And it is.

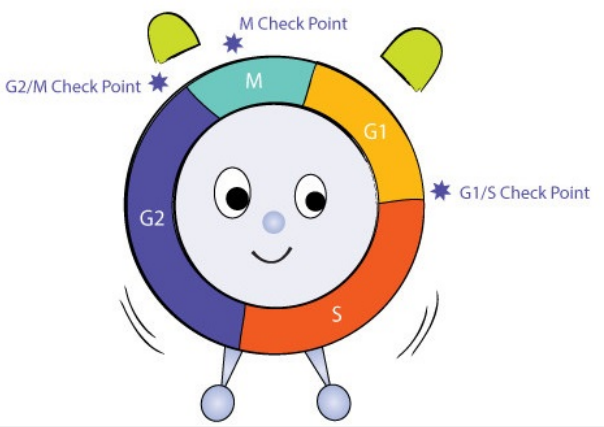



Figure **3.23.1**: Cell Cycle

## CONTROL OF THE CELL CYCLE

How does the cell know when to divide? How does the cell know when to replicate its DNA? How does the cell know when to proceed into mitosis or cytokinesis? The answers to these questions have to do with the control of the cell cycle. But how is the cell cycle controlled or regulated? Regulation of the cell cycle involves processes crucial to the survival of a cell. These include the detection and repair of damage to DNA, as well as the prevention of uncontrolled cell division. Uncontrolled cell division can be deadly to an organism; its prevention is critical for survival.

### CYCLINS AND KINASES

The cell cycle is controlled by a number of protein-controlled feedback processes. Two types of proteins involved in the control of the cell cycle are **kinases** and **cyclins**. Cyclins activate kinases by binding to them, specifically they activate **cyclin-dependent kinases (CDK)**. **Kinases** are enzymes that catalyze the transfer of a phosphate group from ATP to another molecule in a cell. They function as a control switch in many cellular functions, turning a function on or off, and regulating other cellular processes. Many times they are involved in activating a cascade of reactions. Cyclins comprise a group of proteins that are rapidly produced at key stages in the cell cycle. Once activated by a cyclin, CDK enzymes activate or inactivate other target molecules through phosphorylation. It is this precise regulation of proteins that triggers advancement through the cell cycle. Leland H. Hartwell, R. Timothy Hunt, and Paul M. Nurse won the 2001 Nobel Prize in Physiology or Medicine for their discovery of these critical proteins.

## WHAT MAKES A CELL CANCEROUS?

**Cancer** is a disease characterized by a population of cells that grow and divide without respect to normal limits. These cancerous cells invade and destroy adjacent tissues, and they may spread throughout the body. The process by which normal cells are transformed into cancer cells is known as **carcinogenesis**. This process is also known as oncogenesis or tumorigenesis.

Nearly all cancers are caused by mutations in the DNA of abnormal cells. These mutations may be due to the effects of **carcinogens**, cancer-causing agents such as tobacco smoke, radiation, chemicals, or infectious agents. These carcinogens may act as an environmental "trigger," stimulating the onset of cancer in certain individuals and not others. Do all people who smoke get cancer? No. Can secondhand smoke increase a nonsmoking person's chance of developing lung cancer? Yes. It also increases a nonsmoking person's chance of developing heart disease.

Complex interactions between carcinogens and an individual's genome may explain why only some people develop cancer after exposure to an environmental trigger and others do not. Do all cancers need an environmental trigger to develop? No. Cancer-causing mutations may also result from errors incorporated into the DNA during replication, or they may be inherited. Inherited mutations are present in all cells of the organism.

### ONCOGENES AND TUMOR SUPPRESSOR GENES

Some types of cancer occur because of mutations in genes that control the cell cycle. Cancer-causing mutations most often occur in two types of regulatory genes, called proto-oncogenes and tumor-suppressor genes.

- Proto-oncogenes are genes that normally help cells divide. When a proto-oncogene mutates to become an oncogene, it is continuously active, even when it is not supposed to be. This is like a car's accelerator pedal being stuck at full throttle. The car keeps racing at top speed. In the case of a cell, the cell keeps dividing out of control, which can lead to cancer.
- Tumor suppressor genes are genes that normally slow down or stop cell division. When a mutation occurs in a tumor suppressor gene, it can no longer control cell division. This is like a car without brakes. The car can't be slowed or stopped. In the case of a cell, the cell keeps dividing out of control, which can lead to cancer.

## Several Mutations to Cause Cancer

Oncogenes may be growth factors, protein kinases, GTPases or transcription factors. **Growth factors** are naturally occurring substances, usually a protein or steroid hormone, capable of stimulating cellular growth, proliferation, and differentiation. They are important for regulating a variety of cellular processes. Usually, they must bind to an extracellular or intracellular receptor to initiate a cellular reaction.

Typically, a series of several mutations that constitutively activate oncogenes and inactivate tumor suppressor genes is required to transform a normal cell into a cancer cell (Figure **3.23.2**). Cells have developed a number of control mechanisms to overcome mutations in proto-oncogenes. Therefore, a cell needs multiple mutations to transform into a cancerous cell. A mutation in one proto-oncogene would not cause cancer, as the effects of the mutation would be masked by the normal control of the cell cycle and the actions of tumor suppressor genes. Similarly, a mutation in one tumor suppressor gene would not cause cancer either, due to the presence of many "backup" genes that duplicate its functions. It is only when enough proto-oncogenes have mutated into oncogenes and enough tumor suppressor genes have been deactivated that the cancerous transformation can begin. Signals for cell growth overwhelm the signals for growth regulation, and the cell quickly spirals out of control. Often, because many of these genes regulate the processes that prevent most damage to the genes themselves, DNA damage accumulates as one ages.

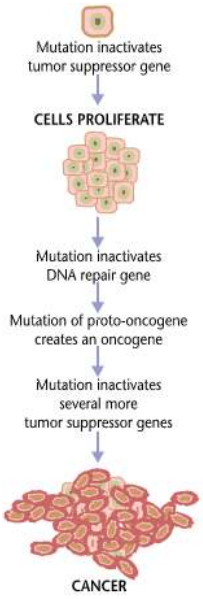



Figure **3.23.2**: How Cancer Develops. Mutations in a tumor suppressor gene allow the proliferation of cells. As many times the cells divide, they acquire more mutation. Some mutations may lead to the inactivation of the DNA repair genes. Also, proto-oncogenes may convert into oncogenes due to mutations. Several other mutations inactivate many tumor suppressor genes. Eventually, a series of mutations in tumor-suppressor genes and proto-oncogenes leads to cancer

Usually, oncogenes are dominant alleles, as they contain gain-of-function mutations. The actions of the mutant allele gene product, many times resulting in a constitutively activated protein, are dominant to the gene product produced by the "normal" allele. Meanwhile, mutated tumor suppressors are generally recessive alleles, as they contain loss-of-function mutations. A proto-oncogene needs only a mutation in one copy of the gene to generate an oncogene; a tumor suppressor gene needs a mutation in both copies of the gene to render both products defective. There are instances when, however, one mutated allele of a tumor suppressor gene can render the other copy non-functional. These instances result in what is known as a dominant negative effect.

## REVIEW

1. Define cancer.
2. What are cyclin-dependent kinases? What is their role?
3. Discuss the role of oncogenes and tumor suppressor genes in carcinogenesis.
4. Why are multiple mutations required for transformation into a cancerous cell?
5. Identify all the categories of oncogenes and describe two categories.

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# 3.24: SEXUAL REPRODUCTION- MEIOSIS AND GAMETOGENESIS

## ALL IN THE FAMILY

The family photo in Figure **3.24.1** illustrates an important point. Children in a family resemble their parents and each other, but the children are never exactly the same unless they are identical twins. Each of the children in the photo inherited a unique combination of traits from the parents. In this concept, you will learn how this happens. It all begins with sex — sexual reproduction, that is.



Figure **3.24.1**: Family photo

## SEXUAL REPRODUCTION

Why do you look similar to your parents, but not identical? First, it is because you have two parents. Second, it is because of sexual reproduction. Whereas asexual reproduction produces genetically identical clones, sexual reproduction produces genetically diverse individuals. **Sexual reproduction** is the creation of a new organism by combining the genetic material of two organisms. As both parents contribute half of the new organism's genetic material, the offspring will have traits of both parents, but will not be exactly like either parent.

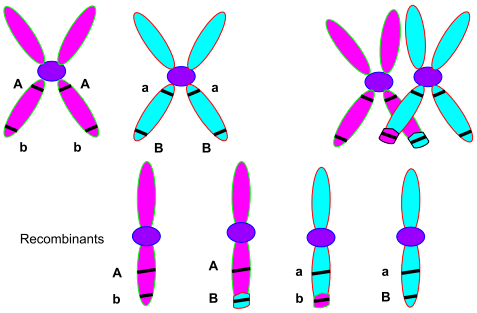



Figure **3.24.2**: Crossing over occurs during meiosis I, and is the process where homologous chromosomes pair up with each other and exchange different segments of their genetic material to form recombinant chromosomes. In some species crossing over is essential for the normal segregation of chromosomes during meiosis. Crossing over also increases genetic variation, because due to the swapping of genetic material during crossing over, the chromatids held together by the centromere are no longer identical. So, when the chromosomes go on to meiosis II and separate, some of the daughter cells receive daughter chromosomes with recombined alleles. Due to this genetic recombination, the offspring have a different set of alleles and genes than their parents do. In the diagram, genes B and b are crossed over with each other, making the resulting recombinants after meiosis Ab, AB, ab, and aB.l.

Organisms that reproduce sexually by joining **gametes**, a process known as **fertilization**, must have a mechanism to produce **haploid** gametes. This mechanism is **meiosis**, a type of cell division that halves the number of chromosomes. During meiosis, the pairs of chromosomes separate and segregate randomly to produce gametes with one chromosome from each pair. Meiosis involves two nuclear and cell divisions without interphase in between, starting with one diploid cell and generating four haploid cells. Each division, named meiosis I and meiosis II, has four stages: prophase, metaphase, anaphase, and telophase. These stages are similar to those of mitosis, but there are distinct and important differences.

Prior to meiosis, the cell's DNA is replicated, generating chromosomes with two sister chromatids. A human cell prior to meiosis will have 46 chromosomes, 22 pairs of homologous autosomes, and 1 pair of sex chromosomes. **Homologous chromosomes** (Figure **3.24.2**), or homologs, are similar in size, shape, and genetic content; they contain the same genes, though they may have different alleles of those genes. The genes/alleles are at the same **loci** on homologous chromosomes. You inherit one chromosome of each pair of homologs from your mother and the other one from your father. Sexual reproduction is the primary method of reproduction for the vast majority of multicellular organisms, including almost all animals and plants. Fertilization joins two haploid gametes into a **diploid** zygote, the first cell of a new organism. The zygote enters G1 of the first cell cycle, and the organism begins to grow and develop through mitosis and cell division.

## MEIOSIS

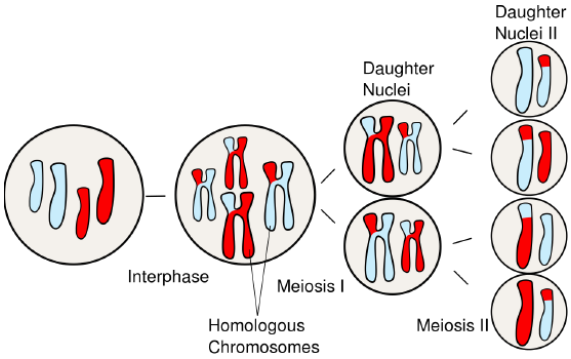



Figure **3.24.3**: Overview of Meiosis. During meiosis, homologous chromosomes separate and go to different daughter cells. This diagram shows just the nuclei of the cells. Notice the exchange of genetic material that occurs prior to the first cell division.

The process that produces haploid gametes is called meiosis. **Meiosis** is a type of cell division in which the number of chromosomes is reduced by half. It occurs only in certain special cells of an organism. In mammals, Meiosis occurs only in gamete producing cells within the gonads. During meiosis, homologous (paired) chromosomes separate, and haploid cells form that have only one chromosome from each pair. Figure **3.24.3** gives an overview of meiosis.

As you can see from the meiosis diagram, two cell divisions occur during the overall process, so a total of four haploid cells are produced. The two cell divisions are called meiosis I and meiosis II.

Meiosis I begins after DNA replicates during interphase. Meiosis II follows meiosis I without DNA replicating again. Both meiosis I and meiosis II occur in four phases, called prophase, metaphase, anaphase, and telophase. You may recognize these four phases from mitosis, the division of the nucleus that takes place during routine cell division of eukaryotic cells.

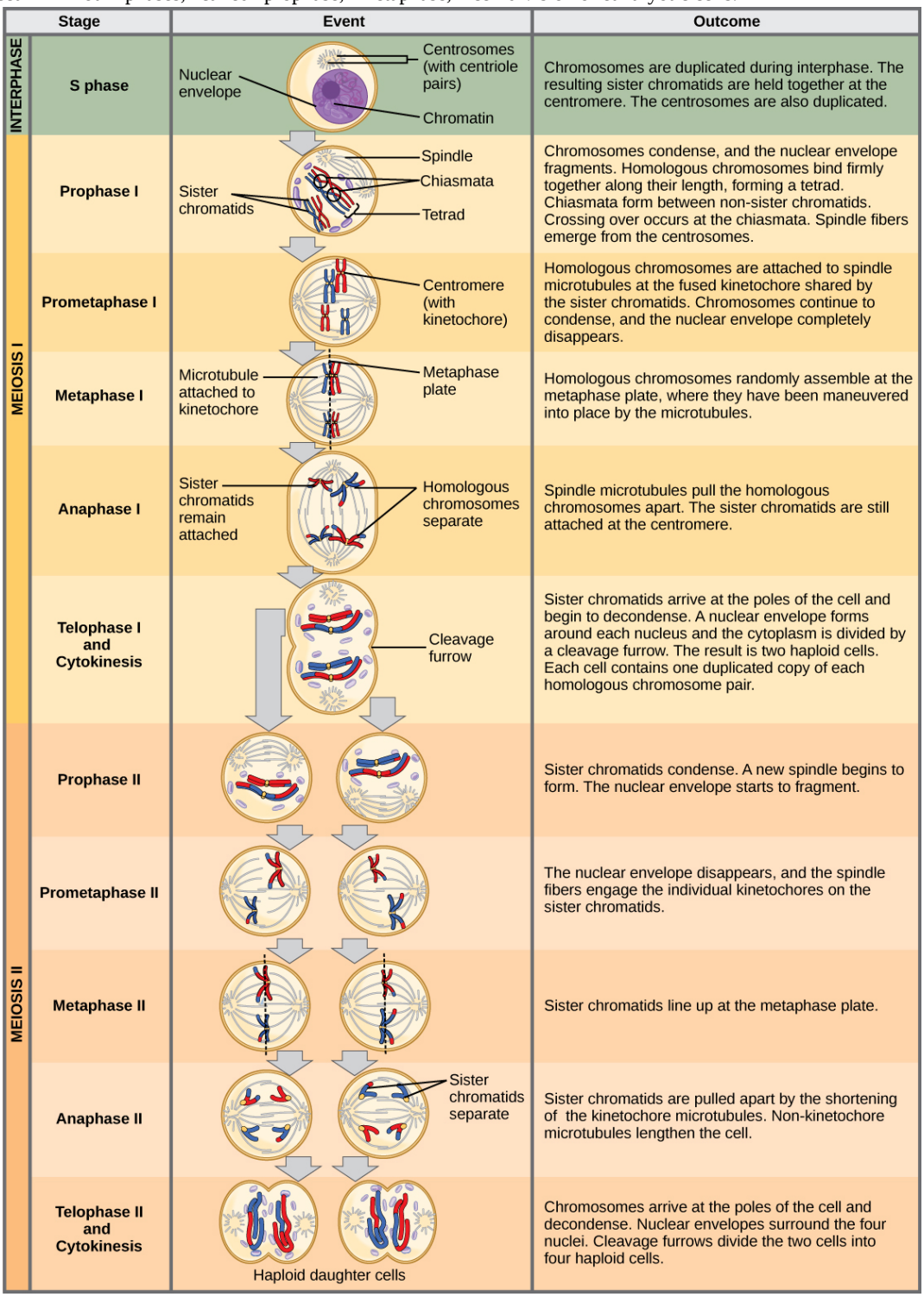



Figure **3.24.4**: Complete Stages of Meiosis: An animal cell with a diploid number of four (2n = 4) proceeds through the stages of meiosis to form four haploid daughter cells.

## MEIOSIS I

1. **Prophase I**: The nuclear envelope begins to break down, and the chromosomes condense. Centrioles start moving to opposite poles of the cell, and a spindle begins to form. Importantly, homologous chromosomes pair up, which is unique to prophase I. In prophase of mitosis and meiosis II, homologous chromosomes do not form pairs in this way. During prophase I,

crossing-over occurs. The significance of crossing-over is discussed in the next section called variations.

2. **Metaphase I**: Spindle fibers attach to the paired homologous chromosomes. The paired chromosomes line up along the equator of the cell. This occurs only in metaphase I. In metaphase of mitosis and meiosis II, it is sister chromatids that line up along the equator of the cell.
3. **Anaphase I**: Spindle fibers shorten, and the chromosomes of each homologous pair start to separate from each other. One chromosome of each pair moves toward one pole of the cell, and the other chromosome moves toward the opposite pole.
4. **Telophase I** and Cytokinesis: The spindle breaks down, and new nuclear membranes form. The cytoplasm of the cell divides, and two haploid daughter cells result. The daughter cells each have a random assortment of chromosomes, with one from each homologous pair. Both daughter cells go on to meiosis II.

### MEIOSIS II

1. **Prophase II**: The nuclear envelope breaks down and the spindle begins to form in each haploid daughter cell from meiosis I. The centrioles also start to separate.
2. **Metaphase II**: Spindle fibers line up the sister chromatids of each chromosome along the equator of the cell.
3. **Anaphase II**: Sister chromatids separate and move to opposite poles.
4. **Telophase II** and **Cytokinesis**: The spindle breaks down, and new nuclear membranes form. The cytoplasm of each cell divides, and four haploid cells result. Each cell has a unique combination of chromosomes.

## GAMETOGENESIS

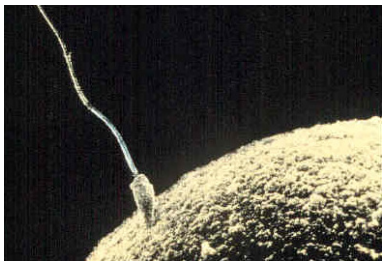


Figure **3.24.5**: A human sperm is a tiny cell with a tail. A human egg is much larger. Both cells are mature haploid gametes that are capable of fertilization. What process is shown in this photograph?

At the end of meiosis, four haploid cells have been produced, but the cells are not yet gametes. The cells need to develop before they become mature gametes capable of fertilization. The development of diploid cells into gametes is called **gametogenesis**. It differs between males and females.

- A gamete produced by a male is called a **sperm,** and the process that produces a mature sperm is called **spermatogenesis**. During this process, a sperm cell grows a tail and gains the ability to “swim,” like the human sperm cell shown in the figure below.
- A gamete produced by a female is called an **egg,** and the process that produces a mature egg is called **oogenesis**. Just one egg is produced from the four haploid cells that result from meiosis. The single egg is a very large cell, as you can see from the human egg also shown in Figure **3.24.5**.

### *SPERMATOGENESIS*

Spermatogenesis occurs in the wall of the **seminiferous tubules**, with **stem cells** at the periphery of the tube and the spermatozoa at the **lumen** of the tube. Immediately under the capsule of the tubule are diploid, undifferentiated cells. These stem cells, called spermatogonia (singular: spermatagonium), go through mitosis with one offspring going on to differentiate into a sperm cell, while the other gives rise to the next generation of sperm.

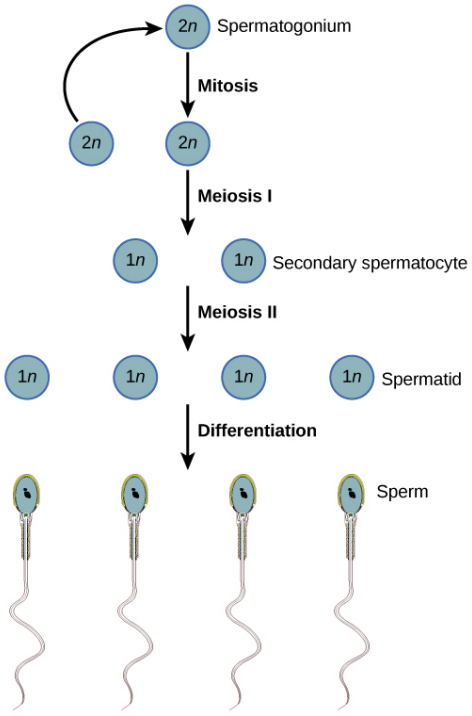



Figure **3.24.6**: Spermatogenesis During spermatogenesis, four sperm result from each primary spermatocyte, which divides into two haploid secondary spermatocytes; these cells will go through a second meiotic division to produce four spermatids.

Meiosis begins with a cell called a primary spermatocyte. At the end of the first meiotic division, a haploid cell is produced called a secondary spermatocyte. This haploid cell must go through another meiotic cell division. The cell produced at the end of meiosis is called a spermatid. When it reaches the lumen of the tubule and grows a flagellum (or "tail"), it is called a sperm cell. Four sperm result from each primary spermatocyte that goes through meiosis.

Stem cells are deposited during gestation and are present at birth through the beginning of adolescence but in an inactive state. During adolescence, gonadotropic hormones from the anterior pituitary cause the activation of these cells and the production of viable sperm. This continues into old age.

### *OOGENESIS*

Oogenesis occurs in the outermost layers of the ovaries. As with sperm production, oogenesis starts with a germ cell, called an oogonium (plural: oogonia), but this cell undergoes mitosis to

increase in number, eventually resulting in up to one to two million cells in the embryo.

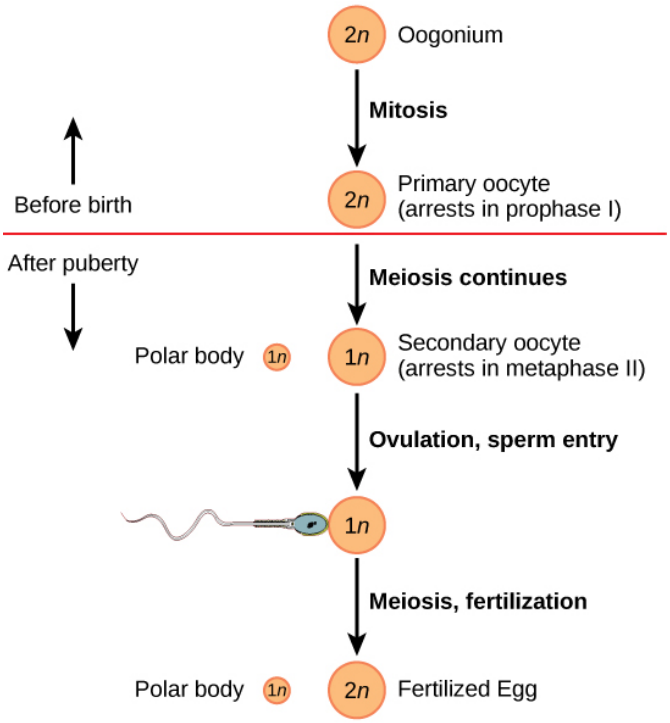



Figure **3.24.7**: Oogenesis The process of oogenesis occurs in the ovary's outermost layer. A primary oocyte begins the first meiotic division but then arrests until later in life when it will finish this division in a developing follicle. This results in a secondary oocyte, which will complete meiosis if it is fertilized.

The cell starting meiosis is called a primary oocyte. This cell will begin the first meiotic division, but be arrested in its progress in the first prophase stage. At the time of birth, all future eggs are in the prophase stage. At adolescence, anterior pituitary hormones cause the development of a number of follicles in an ovary. This results in the primary oocyte finishing the first meiotic division. The cell divides unequally, with most of the cellular material and organelles going to one cell, called a secondary oocyte, and only one set of chromosomes and a small amount of cytoplasm going to the other cell. This second cell is called a polar body and usually dies. A secondary meiotic arrest occurs, this time at the metaphase II stage. At ovulation, this secondary oocyte will be released and travel toward the uterus through the oviduct. If the secondary oocyte is fertilized, the cell continues through the meiosis II, completing meiosis, producing a second polar body and a fertilized egg containing all 46 chromosomes of a human being, half of them coming from the sperm.

## REVIEW

1. Explain how sexual reproduction occurs at the cellular level.
2. Summarize what happens during meiosis.
3. Compare and contrast gametogenesis in males and females.
4. Explain mechanisms that increase genetic variation in offspring produced by sexual reproduction.
5. Why do gametes need to be haploid? What would happen to the chromosome number after fertilization if they were diploid?
6. Describe one difference between prophase I of meiosis and prophase of mitosis.
7. Do all of the chromosomes that you got from your mother go into one of your gametes? Why or why not?
8. *True or False*. Crossing-over is the exchange of genetic material between sister chromatids.
9. *True or False*. Human sperms are haploid.
10. *True or False*. Sister chromatids separate from each other during meiosis I.
11. How many cells are produced after a single cell goes through meiosis?
12. Which stage of meiosis (prophase I or II; metaphase I or II; anaphase I or II; telophase I or II) best fits the descriptions below? Choose only one for each description.

    A. Pairs of homologous chromosomes line up along the equator of the cell
    B. Sister chromatids separate
    C. Homologous chromosomes separate from each other

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## ATTRIBUTIONS


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# 3.25: GENETIC VARIATION

**WHAT HELPS ENSURE THE SURVIVAL OF A SPECIES?**

Genetic variation. It is this variation that is the essence of evolution. Without genetic differences among individuals, "survival of the fittest" would not be likely. Either all survive, or all perish.



Figure **3.25.1**: Profile photos

## GENETIC VARIATION

**Sexual reproduction** results in infinite possibilities of genetic variation. In other words, sexual reproduction results in offspring that are genetically unique. They differ from both parents and also from each other. This occurs for a number of reasons.

- When homologous chromosomes form pairs during prophase I of meiosis I, crossing-over can occur. **Crossing-over** is the exchange of genetic material between homologous chromosomes. It results in new combinations of genes on each chromosome.
- When cells divide during meiosis, homologous chromosomes are randomly distributed to daughter cells, and different chromosomes segregate independently of each other. This called is called **independent assortment**. It results in gametes that have unique combinations of chromosomes.
- In sexual reproduction, two gametes unite to produce an offspring. But which two of the millions of possible gametes will it be? This is likely to be a matter of chance. It is obviously another source of genetic variation in offspring. This is known as **random fertilization.**

All of these mechanisms working together result in an amazing amount of potential variation. Each human couple, for example, has the potential to produce more than 64 trillion genetically unique children. No wonder we are all different!

### CROSSING-OVER

Crossing-over occurs during prophase I, and it is the exchange of genetic material between non-sister chromatids of homologous chromosomes. Recall during prophase I, homologous chromosomes line up in pairs, gene-for-gene down their entire length, forming a configuration with four chromatids, known as a **tetrad**. At this point, the chromatids are very close to each other and some material from two chromatids switch chromosomes, that is, the material breaks off and reattaches at the same position on the homologous chromosome (Figure **3.25.2**). This exchange of genetic material can happen many times within the same pair of homologous chromosomes, creating unique combinations of genes. This process is also known as **recombination**.

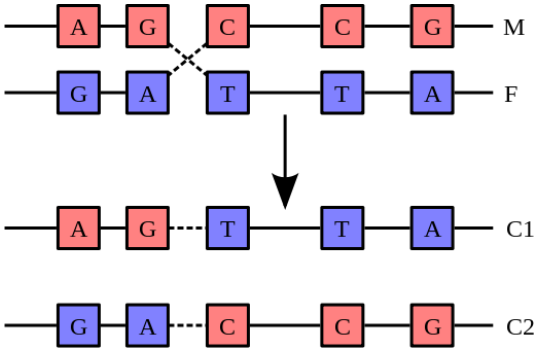



Figure **3.25.2**: Crossing-over. A maternal strand of DNA is shown in red. A paternal strand of DNA is shown in blue. Crossing over produces two chromosomes that have not previously existed. The process of recombination involves the breakage and rejoining of parental chromosomes (M, F). This results in the generation of novel chromosomes (C1, C2) that share DNA from both parents.

During prophase I, chromosomes condense and become visible inside the nucleus. As the nuclear envelope begins to break down, homologous chromosomes move closer together. The synaptonemal complex, a lattice of proteins between the homologous chromosomes, forms at specific locations, spreading to cover the entire length of the chromosomes. The tight pairing of the homologous chromosomes is called synapsis. In synapsis, the genes on the chromatids of the homologous chromosomes are aligned with each other. The synaptonemal complex also supports the exchange of chromosomal segments between non-sister homologous chromatids in a process called crossing over. The crossover events are the first source of genetic variation produced by meiosis. A single crossover event between homologous non-sister chromatids leads to an exchange of DNA between chromosomes. Following crossover, the synaptonemal complex breaks down and the cohesin connection between homologous pairs is also removed. At the end of prophase I, the pairs are held together only at the chiasmata; they are called tetrads because the four sister chromatids of each pair of homologous chromosomes are now visible.

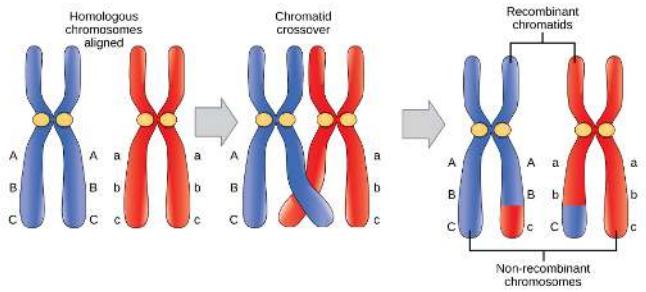



Figure 3.25.3: Crossover between homologous chromosomes Crossover occurs between non-sister chromatids of homologous chromosomes. The result is an exchange of genetic material between homologous chromosomes. This occurs when homologous chromosomes align. Chromatids from each chromosome can cross over and recombine (swap sections). This results in two recombinant chromosomes and two non-recombinant chromosomes.

## INDEPENDENT ASSORTMENT AND RANDOM FERTILIZATION

During metaphase I, the tetrads move to the metaphase plate with kinetochores facing opposite poles. The homologous pairs orient themselves randomly at the equator. This event is the second mechanism that introduces variation into the gametes or spores. In each cell that undergoes meiosis, the arrangement of the tetrads is different. The number of variations is dependent on the number of chromosomes making up a set. There are two possibilities for orientation at the metaphase plate. The possible number of alignments, therefore, equals $2^n$, where n is the number of chromosomes per set. Given these two mechanisms, it is highly unlikely that any two haploid cells resulting from meiosis will have the same genetic composition.

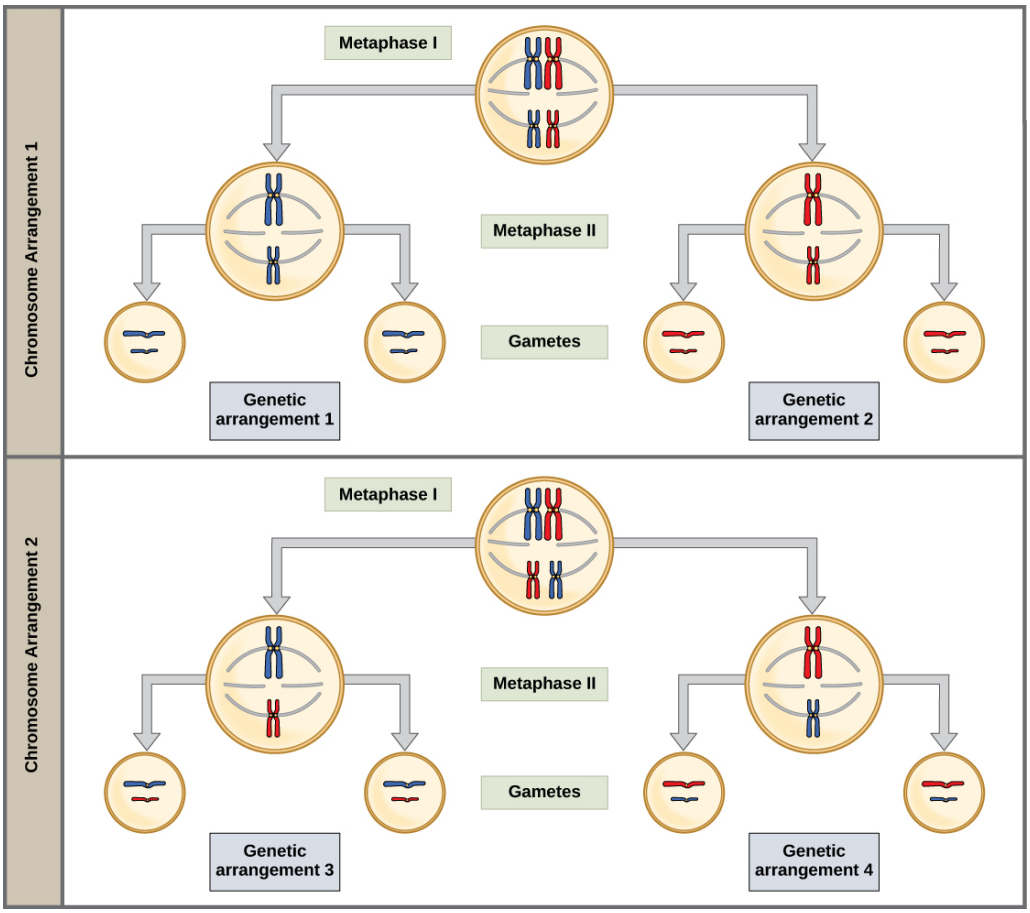



Figure 3.25.4: Meiosis I ensures unique gametes Random, independent assortment during metaphase I can be demonstrated by considering a cell with a set of two chromosomes (n = 2). In this case, there are two possible arrangements at the equatorial plane in metaphase I. The total possible number of different gametes is 2n, where n equals the number of chromosomes in a set. In this example, there are four possible genetic combinations for the gametes. With n = 23 in human cells, there are over 8 million possible combinations of paternal and maternal chromosomes.

In humans, there are over 8 million configurations in which the chromosomes can line up during metaphase I of meiosis. It is the specific process of meiosis, resulting in four unique haploid cells, that results in these many combinations. This independent assortment, in which the chromosome inherited from either the father or mother can sort into any gamete, produces the potential for tremendous genetic variation. Together with random fertilization, more possibilities for genetic variation exist between any two people than the number of individuals alive today. Sexual reproduction is the random fertilization of a gamete from the female using a gamete from the male. A sperm cell, with over 8 million chromosome combinations, fertilizes an egg cell, which also has over 8 million chromosome combinations. That is over 64 trillion unique combinations, not counting the unique combinations produced by crossing-over.

## REVIEW

1. What is crossing-over and when does it occur?
2. Describe how crossing-over, independent assortment, and random fertilization lead to genetic variation.
3. How many combinations of chromosomes are possible from sexual reproduction in humans?
4. Create a diagram to show how crossing-over occurs and how it creates new gene combinations on each chromosome.

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# 3.26: MITOSIS VS. MEIOSIS AND DISORDERS

## MITOSIS OR MEIOSIS?

Figure **3.26.1** shows a tiny embryo just beginning to form. Once an egg is fertilized, the resulting single cell must divide many times to develop a fetus. Both mitosis and meiosis involve cell division; is this type of cell division an example of mitosis or meiosis? The answer is mitosis. With each division, you are making a genetically exact copy of the parent cell, which only happens through mitosis.



Figure **3.26.1**: 4-celled embryo

## MITOSIS VS. MEIOSIS

Both **mitosis** and **meiosis** result in eukaryotic cell division. The primary difference between these divisions is the differing goals of each process. The goal of mitosis is to produce two **daughter cells** that are genetically identical to the parent cell. Mitosis happens when you grow. You want all your new cells to have the same DNA as the previous cells. The goal of meiosis is to produce sperm or eggs, also known as **gametes**. The resulting gametes are not genetically identical to the parent cell. Gametes are **haploid** cells, with only half the DNA present in the **diploid** parent cell. This is necessary so that when a sperm and an egg combine at **fertilization**, the resulting **zygote** has the correct amount of DNA—not twice as much as the parents. The zygote then begins to divide through mitosis.

Table **3.26.1**: comparison of mitosis and meiosis

| | Mitosis | Meiosis |
|---|---|---|
| Purpose | To produce new cells | To produce gametes |
| Number of Cells Produced | 2 | 4 |
| Rounds of Cell Division | 1 | 2 |
| Haploid or Diploid | Diploid | Haploid |
| Are daughter cells identical to parent cells? | Yes | No |
| Are daughter cells identical to each other? | Yes | No |

Figure **3.26.2** shows a comparison of mitosis, meiosis, and binary fission.

- Binary fission occurs in bacterial. Note that bacterial cells have a single loop of DNA. The DNA of the cell is replicated. Each loop of DNA moves to the opposite side of the cell and the cell splits in half.
- Mitosis and Meiosis both occur in eukaryotic cells. In the example below the cell has 4 total chromosomes. These are replicated during the S phase.
  - In mitosis, the chromosomes line up in the center of the cell. Then, sister chromatids separate and move to the opposite poles of the cell. The cell divides, producing two cells with 4 total chromosomes
  - In meiosis, the homologous chromosomes line up in the center of the cell. Then each chromosome moves to opposite poles and the cell divides.
    - Next, the chromosomes line up in the center of the cell. Then, sister chromatids separate and move to the opposite poles of the cell. This produces four cells with 2 chromosomes each. These are the gametes.
    - Two gametes combine to form a zygote with 4 total chromosomes.

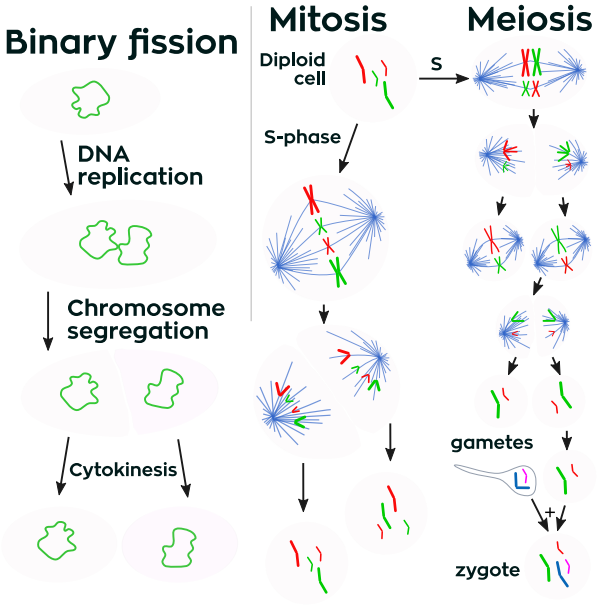



Figure **3.26.2**: A comparison between binary fission, mitosis, and meiosis.

## CHROMOSOME DISORDERS

### Changes in Chromosome Number

What would happen if an entire chromosome were missing or duplicated? What if a human had only 45 chromosomes? Or 47? This real possibility is usually due to mistakes during meiosis; the chromosomes do not fully separate from each other during sperm or egg formation. Specifically, **nondisjunction** occurs when

homologous chromosomes or sister chromatids fail to separate during meiosis, resulting in an abnormal chromosome number. Nondisjunction may occur during meiosis I or meiosis II Most human atypical chromosome numbers result in the death of the developing embryo, often before a woman even realizes she is pregnant. Occasionally, a zygote with an extra chromosome can become a viable embryo and develop.

**Trisomy** is a state where humans have an extra autosome. That is, they have three of a particular chromosome instead of two. For example, trisomy 18 results from an extra chromosome 18, resulting in 47 total chromosomes. To identify the chromosome number (including an abnormal number), a sample of cells is removed from an individual or developing fetus. Metaphase chromosomes are photographed and a karyotype is produced. A **karyotype** will display any abnormalities in chromosome number or large chromosomal rearrangements. Trisomy 8, 9, 12, 13, 16, 18, and 21 have been identified in humans. Trisomy 16 is the most common trisomy in humans, occurring in more than 1% of pregnancies. This condition, however, usually results in spontaneous miscarriage in the first trimester. The most common trisomy in viable births is **Trisomy 21**.

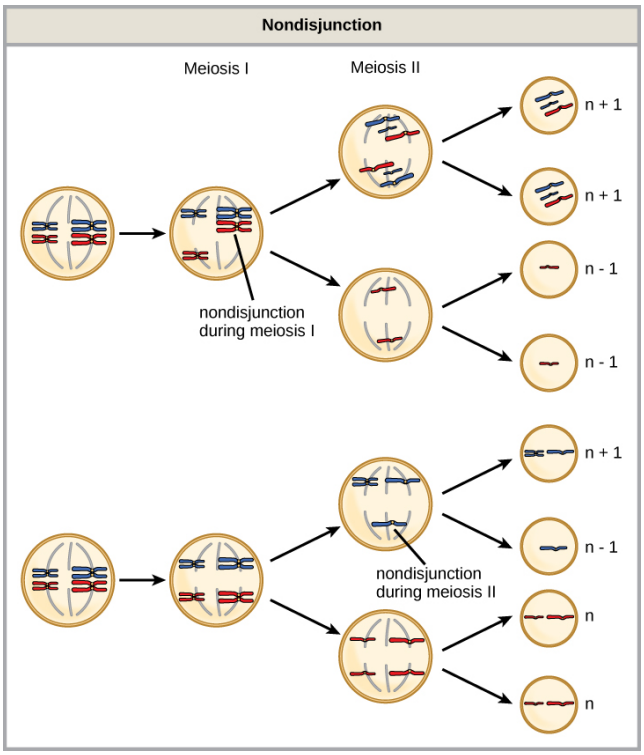



Figure **3.26.3**: Nondisjunction in Meiosis: Nondisjunction occurs when homologous chromosomes or sister chromatids fail to separate during meiosis, resulting in an abnormal chromosome number. Nondisjunction may occur during meiosis I or meiosis II. If nondisjunction occurs in meiosis I, the homologous pair of chromosomes remain bound. This results in an extra chromosome (n + 1) in two of the gametes and a missing chromosome (n - 1) in two of the gametes. If nondisjunction occurs in meiosis II, two cells enter meiosis II with the correct number of chromosomes. Nondisjunction occurs in one of these cells when one of the sister chromatids does not separate. This results in a cell with an extra chromosome (n +1), a cell missing a chromosome (n - 1), and two cells with the expected number of chromosomes (n).

## TRISOMY 21: DOWN SYNDROME



Figure **3.26.4**: A child with Down syndrome, exhibiting characteristic facial appearance.

One of the most common chromosome abnormalities is **Down syndrome**, due to nondisjunction of chromosome 21 resulting in an extra complete chromosome 21, or part of chromosome 21 (Figure **3.26.5**). Down syndrome is the only autosomal trisomy where an affected individual may survive to adulthood. Individuals with Down syndrome often have some degree of mental and physical impairments and a specific facial appearance. With proper assistance, individuals with Down

syndrome can become successful, contributing members of society. The risk of having a child with Down syndrome is significantly higher among women age 35 and older.

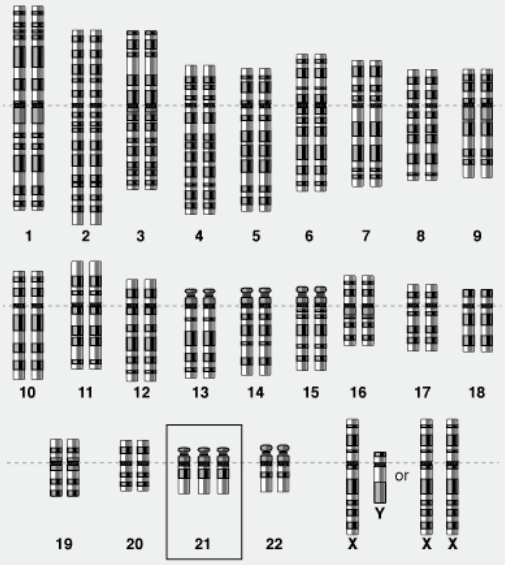



Figure **3.26.5**: Trisomy 21 (Down Syndrome) Karyotype. A karyotype is a picture of a cell's chromosomes. Note that there are two of each chromosome but three copies of chromosome 21.

## REVIEW

1. Define genetic disorder.
2. What is nondisjunction? Why may it cause genetic disorders?
3. Explain why genetic disorders caused by abnormal numbers of chromosomes most often involve the X chromosome.
4. How is Down syndrome detected *in utero*?
5. Compare and contrast genetic disorders and congenital disorders.
6. Explain why parents that do not have Down syndrome can have a child with Down syndrome.
7. What is the goal of mitosis? Or meiosis?
8. How many cells are created from cytokinesis following mitosis? Following meiosis?
9. Which process, mitosis or meiosis, creates genetically identical cells?
10. "Gametes are haploid cells." What does this sentence mean?

## EXPLORE MORE

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# 3.27: CASE STUDY CONCLUSION- GENES AND CHAPTER SUMMARY

## CASE STUDY CONCLUSION: GENETIC SIMILARITIES AND DIFFERENCES

Humans are much more genetically similar to each other than they are different. Any two people on Earth are 99.9% genetically identical to each other. But the mere 0.1% that is different can be very important, as in the case of bone marrow donation to treat diseases such as leukemia. These variations are passed on in a family with sexual reproduction. A good match must exist between a bone marrow donor and recipient in genes that encode for human leukocyte antigen (HLA) proteins. If a patient receives a bone marrow transplant from a donor that has different types of HLAs than the patient does, antibodies in their immune system will identify the antigens as “nonself” and will launch an attack on the transplanted cells. Also, since bone marrow produces immune cells, antibodies in the transplanted tissue can actually attack the patient’s own cells through the same mechanism.

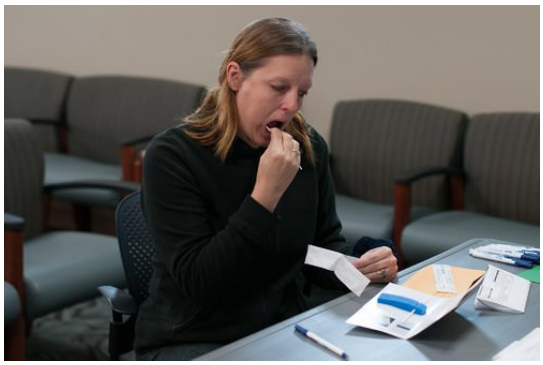


Figure **3.27.1**: Swabbing for DNA match

As you have also learned, a good HLA match is often difficult to find, even between full siblings. This is due to the genetic variations within gametes of a single person due to crossing over and random assortment. The variations are multiplied when two unique gametes fertilize. Kim has to find his match outside of his family. Every year, about 14,000 people in the United States must try to find a compatible donor from a bone marrow registry. These registries store information on HLA type from potential donors, like the woman shown above. She is swabbing her cheeks for a DNA match. It can take months to years to find a compatible match — if one is found at all.

In the meantime, Kim has to stop the production of abnormal WBCs with chemotherapy. Chemotherapy is the treatment of cancer with drugs ("anticancer drugs") that can destroy cancer cells. In current usage, the term "chemotherapy" usually refers to cytotoxic drugs which affect rapidly dividing cells in general, in contrast with targeted therapy (see below). Chemotherapy drugs interfere with cell division in various possible ways, e.g. with the duplication of DNA or the separation of newly formed chromosomes. Chemotherapy has the potential to harm healthy tissue, especially those tissues that have a high replacement rate (e.g. intestinal lining). Due to these side effects, patients may lose their hair follicles, Digestive system lining, and taste buds. These cells usually repair themselves after chemotherapy. Because some drugs work better together than alone, two or more drugs are often given at the same time. This is called "combination chemotherapy"; most chemotherapy regimens are given in a combination.

## CHAPTER SUMMARY

In this chapter, you learned about human sexual and asexual reproduction.

- The cell cycle is a repeating series of events that include growth, DNA synthesis, and cell division. It is more complicated in eukaryotic than prokaryotic cells.
- In a eukaryotic cell, the cell cycle has two major phases: interphase and mitotic phase. During interphase, the cell grows, performs routine life processes, and prepares to divide. During the mitotic phase, first, the nucleus divides (mitosis) and then the cytoplasm divides (cytokinesis), which produces two daughter cells.
    - Except when a eukaryotic cell divides, its nuclear DNA exists as a grainy material called chromatin. After DNA replicates and the cell is about to divide, the DNA condenses and coils into the X-shaped form of a chromosome. Each replicated chromosome consists of two sister chromatids, which are joined together at a centromere.
    - During mitosis, sister chromatids separate from each other and move to opposite poles of the cell. This happens in four phases, called prophase, metaphase, anaphase, and telophase.
- The cell cycle is controlled mainly by regulatory proteins that signal the cell to either start or delay the next phase of the cycle at key checkpoints.
- Cancer is a disease that occurs when the cell cycle is no longer regulated, for example, because the cell's DNA has become damaged. Cancerous cells grow out of control and may form a mass of abnormal cells called a tumor.
- In sexual reproduction, two parents produce gametes that unite in the process of fertilization to form a single-celled zygote. Gametes are haploid cells with only one of each pair of homologous chromosomes, and the zygote is a diploid cell with two of each pair of chromosomes.
- Meiosis is the type of cell division that produces four haploid daughter cells that may become gametes. Meiosis occurs in two stages, called meiosis I and meiosis II, each of which occurs in four phases (prophase, metaphase, anaphase, and telophase).
- Meiosis is followed by gametogenesis, the process in which the haploid daughter cells change into mature gametes. Males produce gametes called sperm in a process known as spermatogenesis, and females produce gametes called eggs in the process known as oogenesis.
- Sexual reproduction produces offspring that are genetically unique. Crossing-over, independent assortment, and the random

union of gametes work together to result in an amazing amount of potential genetic variation.

- Sexual reproduction has the potential to produce tremendous genetic variation in offspring.
- During prophase I, the homologous chromosomes condense and become visible as the x shape we know, pair up to form a tetrad, and exchange genetic material by crossing over.
- In metaphase I, the tetrads line themselves up at the metaphase plate and homologous pairs orient themselves randomly.
- This variation is due to independent assortment and crossing-over during meiosis, and random union of gametes during fertilization.
- The goal of mitosis is to produce a new cell that is identical to the parent cell.
- The goal of meiosis is to produce gametes that have half the DNA of the parent cell.
- When chromosomes do not divide equally among gametes, the damaged gametes produce. This process is called nondisjunction.
- Trisomy is a state where humans have an extra autosome; they have three of a particular chromosome instead of two.
- The most common trisomy in viable births is Trisomy 21 (Down Syndrome) due to nondisjunction.

## CHAPTER SUMMARY REVIEW

1. What are cyclin-dependent kinases? What is their role?
2. What are cell cycle checkpoints?
3. What is interphase?
4. Summarize each phase of the cell cycle.
5. Describe the structure of a chromosome in the prophase of mitosis.
6. What is cytokinesis and when does it occur?
7. What is centromere?
8. Describe the main steps of mitosis.
9. Cells go through a series of events that include growth, DNA synthesis, and cell division. Why are these events best represented by a cycle diagram?
10. Explain how the cell cycle is regulated.
11. Define and explain random assortment and random fertilization.
12. Why is DNA replication essential to the cell cycle?
13. *True or False*. When a eukaryotic cell divides, the nucleus divides first in the process of mitosis.
14. What happens during mitosis?
15. What is meiosis?
16. What is diploid? How many chromosomes are in a diploid human cell?
17. What is a zygote? How does the zygote form the organism?
18. What is the result of crossing-over?
19. How many cell divisions occur during meiosis?
20. Why are you genetically distinct?
21. Describe the steps of Meiosis I and Meiosis II.
22. Describe nondisjunction. List and explain some of the chromosome disorders.
23. Compare and contrast mitosis and meiosis.

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# CHAPTER OVERVIEW

## 4: THE INTEGUMENTARY SYSTEM

This chapter describes the structure and functions of the epidermis and dermis, hair, and nails. In addition, the chapter outlines the types of skin cancer and risk factors for skin cancer.


4.1: Case Study- Skin Cancer

4.2: Introduction to the Integumentary System

4.3: Skin

4.4: Hair and Nails

4.5: Case Study Conclusion- Skin Cancer and Chapter Summary


*Skin and its layers. Shown is a drawing of the layers of skin and associated glands and vessels (epidermis, dermis, fatty tissue, blood vessels, follicle, oil gland, sweat gland).(Public Domain; National Cancer Institute; NIH).*

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# 4.1: CASE STUDY- SKIN CANCER

The summer sun may feel good on your body, but its invisible UV rays wreak havoc on your skin. Exposing the skin to UV light causes photo-aging: premature wrinkling, brown discolorations, and other unattractive signs of sun exposure. Even worse, UV light increases your risk of skin cancer.



Figure **4.1.1**: two individuals sunbathing

Exposure to UV radiation causes about 90% of all skin cancer cases. The connection between skin cancer and UV light is so strong that the World Health Organization has classified UV radiation (whether from tanning beds or the sun) as a Group 1 carcinogen (cancer-causing agent). Group 1 carcinogens are those carcinogens that are known with virtual certainty to cause cancer. In addition to UV light, Group 1 carcinogens include tobacco and plutonium. In terms of the number of cancers caused, UV radiation is far worse than tobacco. More people develop skin cancer because of UV light exposure than develop lung cancer because of smoking. The increase in cancer risk due to UV light is especially great if you have ever had blistering sunburns as a child or teen.

Besides UV light exposure, other risk factors for skin cancer include:

- having light-colored skin
- having a lot of moles
- being diagnosed with precancerous skin lesions
- having a family history of skin cancer
- having a personal history of skin cancer
- having a weakened immune system
- being exposed to other forms of radiation or to certain toxic substances such as arsenic

What exactly is skin cancer? Skin cancer is a disease in which skin cells grow out of control. It is caused mainly by excessive exposure to UV light, which damages DNA. Therefore, skin cancer most often develops on areas of the skin that are frequently exposed to UV light. However, it can also occur in areas that are rarely exposed to UV light. Skin cancer affects people of all skin colors, including those with dark skin. It also affects more people altogether than all other cancers combined. One in five Americans develops skin cancer in his or her lifetime.

At the end of the chapter, you will learn about the different types of skin cancer and how to identify if a growth is a mole or potentially cancerous.

## CHAPTER OVERVIEW: INTEGUMENTARY SYSTEM

In this chapter, you will learn about the structure and functions of the integumentary system. Specifically, you will learn about:

- The functions of the organs of the integumentary system—the skin, hair, and nails—including protecting the body, helping to regulate homeostasis, and sensing and interacting with the external world.
- The two main layers of the skin: the thinner outer layer called the epidermis and the thicker inner layer called the dermis.
- The cells and layers of the epidermis and their functions, including synthesizing vitamin D and protecting the body against injury and pathogens, UV light exposure, and water loss.
- The composition and layers of the dermis and their functions, including cushioning other tissues, regulating body temperature, sensing the environment, and excreting wastes.
- The specialized structures in the dermis, which include sweat and sebaceous (oil) glands, hair follicles, and sensory receptors that detect touch, temperature, and pain.
- The structure and biological functions of hair, which include retaining body heat, detecting sensory stimuli, and protecting the body against UV light, pathogens, and small particles.
- The structure and functions of nails, which include protecting the fingers and toes, enhancing the detection of sensory stimuli, and acting like tools.

**As you read this chapter and learn more about the skin, think about the following questions:**

1. What is skin cancer and how does it form?
2. What are the similarities and differences of various types of cancer?
3. How can people decrease their risk of getting skin cancer?

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# 4.2: INTRODUCTION TO THE INTEGUMENTARY SYSTEM

## ART FOR ALL ERAS

This is Maud Stevens Wagner, a tattoo artist who is pictured in Figure **4.2.1**. Maud was pictured in 1907. Clearly, tattoos are not just a late 20th and early 21st-century trend. They have been popular in many eras and cultures. Tattoos literally illustrate the biggest organ of the human body: the skin. The skin is very thin, but it covers a large area — about 2 $m^2$ in adults. The skin is the major organ in the integumentary system.



Figure **4.2.1**: Maud Stevens Wagner

## WHAT IS THE INTEGUMENTARY SYSTEM?

In addition to the skin, the **integumentary system** includes the hair and nails, which are organs that grow out of the skin. Because the organs of the integumentary system are mostly external to the body, you may think of them as little more than accessories, like clothing or jewelry, but they serve vital physiological functions. They provide a protective covering for the body, sense the environment, and help the body maintain homeostasis.

## THE SKIN

The **skin** is remarkable not only because it is the body's largest organ. It is remarkable for other reasons as well. The average square inch of skin has 20 blood vessels, 650 sweat glands, and more than a thousand nerve endings. It also has an incredible 60,000 pigment-producing cells. All of these structures are packed into a stack of cells that is just 2 mm thick, or about as thick as the cover of a book. Although the skin is thin, it consists of two distinct layers, the epidermis and dermis, as shown in Figure **4.2.2**.

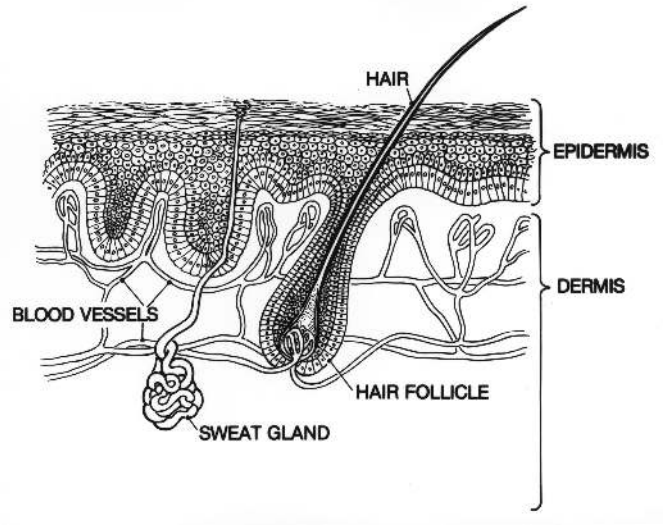



Figure **4.2.2**: The epidermis is the thinner outer layer of skin which is composed of tightly packed epithelial cells. The dermis is the thicker inner layer of skin that contains structures such as blood vessels, hair follicles, and sweat glands.

### OUTER LAYER OF SKIN

The outer layer of skin is the epidermis. This layer is thinner than the inner layer, the dermis. The epidermis consists mainly of epithelial cells, called **keratinocytes,** which produce the tough, fibrous protein **keratin.** The innermost cells of the epidermis are stem cells that divide continuously to form new cells. The newly formed cells move up through the epidermis toward the skin surface, while producing more and more keratin. The cells become filled with keratin and die by the time they reach the surface, where they form a protective, waterproof layer. As the dead cells are shed from the surface of the skin, they are replaced by other cells that move up from below. The epidermis also contains melanocytes, the cells that produce the brown pigment melanin, which gives skin most of its color. Although the epidermis contains some sensory receptor cells, called Merkel cells, it contains no nerves, blood vessels, or other structures.

### INNER LAYER OF SKIN

The dermis is the inner and thicker layer of skin. It consists mainly of tough connective tissue and is attached to the epidermis by collagen fibers. The dermis contains many structures, as shown in the figure above, including blood vessels, sweat glands, and hair follicles, which are structures where hairs originate. In addition, the dermis contains many sensory receptors, nerves, and oil glands.

### FUNCTIONS OF THE SKIN

The skin has multiple roles in the body. Many of these roles are related to homeostasis. The skin's main functions include preventing water loss from the body and serving as a barrier to the entry of microorganisms. Another function of the skin is synthesizing vitamin D, which occurs when the skin is exposed to ultraviolet

(UV) light. Melanin in the epidermis blocks some of the UV light and protects the dermis from its damaging effects.

Another important function of the skin is helping to regulate body temperature. For example, when the body is too warm, the skin lowers body temperature by producing sweat, which cools the body when it evaporates. The skin also increases the amount of blood flowing near the body surface through vasodilation (widening of blood vessels), bringing heat from the body core to radiate out into the environment.

### HAIR

Hair is a fiber that is found only in mammals. It consists mainly of keratin-producing keratinocytes. Each hair grows out of a follicle in the dermis. By the time the hair reaches the surface, it consists mainly of dead cells filled with keratin. Hair serves several homeostatic functions. Head hair is important in preventing heat loss from the head and protecting its skin from UV radiation. Hairs in the nose trap dust particles and microorganisms in the air and prevent them from reaching the lungs. Hair all over the body provides sensory input when objects brush against it or it sways in moving air. Eyelashes and eyebrows protect the eyes from water, dirt, and other irritants.

### NAILS

Fingernails and toenails consist of dead keratinocytes that are filled with keratin. The keratin makes them hard but flexible, which is important for the functions they serve. Nails prevent injury by forming protective plates over the ends of the fingers and toes. They also enhance sensation by acting as a counterforce to the sensitive fingertips when objects are handled. In addition, fingernails can be used as tools.

## INTERACTIONS WITH OTHER ORGAN SYSTEMS

The skin and other parts of the integumentary system work with other organ systems to maintain homeostasis.

- The skin works with the immune system to defend the body from pathogens by serving as a physical barrier to microorganisms.
- Vitamin D is needed by the digestive system to absorb calcium from food. By synthesizing vitamin D, the skin works with the digestive system to ensure that calcium can be absorbed.
- Most immune cells, such as B and T cells have Vitamin D receptors. Vitamin D levels in the body are associated with autoimmune diseases and immune deficiencies.
- To control body temperature, the skin works with the cardiovascular system to either lose body heat or conserve it through vasodilation or vasoconstriction.
- To detect certain sensations from the outside world, the nervous system depends on nerve receptors in the skin.

## REVIEW

1. Name the organs of the integumentary system.
2. Compare and contrast the epidermis and dermis.
3. Identify the functions of the skin.
4. What is the composition of hair?
5. Describe three physiological roles played by the hair.
6. What do nails consist of?
7. List two functions of nails.
8. What do the outermost surface of the skin, the nails, and hair have in common, in terms of their composition?
9. The innermost layer of the epidermis consists of _____ cells than the outermost layer of the epidermis.

   A. older

   B. younger

   C. more sweat glands

   D. more blood vessel
10. Identify two types of cells found in the epidermis of the skin and describe their functions.
11. *True or False*. Keratin-producing cells in the epidermis are a type of epithelial cell.
12. *True or False*. Vasodilation is used to warm the body.
13. Which structure and layer of skin do hair grow out of?
14. Identify three main functions of the integumentary system and give an example of each.
15. What are two ways in which the integumentary system protects the body against UV radiation?

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# 4.3: SKIN

## FEEL THE BURN

The person in Figure **4.3.1** is no doubt feeling the burn — sunburn that is. **Sunburn** occurs when the outer layer of the skin is damaged by UV light from the sun or tanning lamps. Some people deliberately allow UV light to burn their skin because after the redness subsides, they are left with a tan. A tan may look healthy, but it is actually a sign of skin damage. People who experience one or more serious sunburns are significantly more likely to develop skin cancer. Natural pigment molecules in the skin help protect it from UV light damage. These pigment molecules are found in the layer of the skin called the epidermis.



Figure **4.3.1**: sunburn

The **epidermis** is the outer of the two main layers of the skin, the inner layer being the dermis. It averages about 0.10 mm thick and is much thinner than the dermis. The epidermis is thinnest on the eyelids (0.05 mm) and thickest on the palms of the hands and soles of the feet (1.50 mm). The epidermis covers almost the entire body surface. It is continuous with, but structurally distinct from, the mucous membranes that line the mouth, anus, urethra, and vagina.

## STRUCTURE OF THE EPIDERMIS

There are no blood vessels and very few nerve cells in the epidermis. Without blood to bring epidermal cells oxygen and nutrients, the cells must absorb oxygen directly from the air and obtain nutrients via diffusion of fluids from the dermis below. However, as thin as it is, the epidermis still has a complex structure. It has a variety of cell types and multiple layers.

### CELLS OF THE EPIDERMIS

There are several different types of cells in the epidermis. All of the cells are necessary for the important functions of the epidermis.

- The epidermis consists mainly of stacks of keratin-producing epithelial cells called keratinocytes. These cells make up at least 90 percent of the epidermis. Near the top of the epidermis, these cells are also called squamous cells.
- Another 8 percent of epidermal cells are melanocytes. These cells produce the pigment melanin that protects the dermis from UV light.
- About 1 percent of epidermal cells are Langerhans cells. These are immune system cells that detect and fight pathogens entering the skin.
- Less than 1 percent of epidermal cells are Merkel cells, which respond to light touch and connect to nerve endings in the dermis.

### LAYERS OF THE EPIDERMIS

The epidermis in most parts of the body consists of four distinct layers. A fifth layer occurs in the palms of the hands and soles of the feet, where the epidermis thicker than it is in the rest of the body. The layers of the epidermis are shown in Figure **4.3.2** and described in the following text.

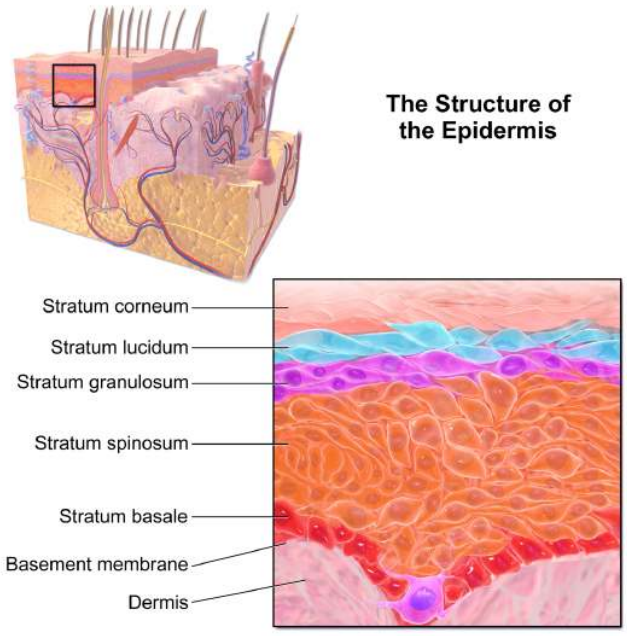



Figure **4.3.2**: Five layers of epidermis: stratum corneum, stratum lucidum, stratum granulosum, stratum spinosum, stratum basale, from top to bottom. The epidermis is connected with Dermis with the help of the basement membrane.

## STRATUM BASALE

The stratum basale is the innermost or the deepest layer of the epidermis. It is separated from the dermis by a membrane called the basement membrane. The stratum basale contains stem cells, called basal cells, which divide to form all the keratinocytes of the epidermis. When keratinocytes first form, they are cube-shaped and contain almost no keratin. As more keratinocytes are produced, previously formed cells are pushed up through the stratum basale. Melanocytes and Merkel cells are also found in the stratum basale. The Merkel cells are especially numerous in touch-sensitive areas such as the fingertips and lips.

## STRATUM SPINOSUM

Just above the stratum basale is the stratum spinosum. This is the thickest of the four epidermal layers. The keratinocytes in this layer have begun to accumulate keratin, and they have become tougher and flatter. Spiny cellular projections form between the keratinocytes and hold them together. In addition to keratinocytes, the stratum spinosum contains the immunologically active Langerhans cells.

## STRATUM GRANULOSUM

The next layer above the stratum spinosum is the stratum granulosum. In this layer, keratinocytes have become nearly filled with keratin, giving their cytoplasm a granular appearance. Lipids are released by keratinocytes in this layer to form a lipid barrier in the epidermis. Cells in this layer have also started to die because they are becoming too far removed from blood vessels in the dermis to receive nutrients. Each dying cell digests its own nucleus and organelles, leaving behind only a tough, keratin-filled shell.

## STRATUM LUCIDUM

Only on the palms of the hands and soles of the feet, the next layer above the stratum granulosum is the stratum lucidum. This is a layer consisting of stacks of translucent, dead keratinocytes that provide extra protection to the underlying layers.

## STRATUM CORNEUM

The uppermost layer of the epidermis everywhere on the body is the stratum corneum. This layer is made of flat, hard, tightly packed dead keratinocytes that form a waterproof keratin barrier to protect the underlying layers of the epidermis. Dead cells from this layer are constantly shed from the surface of the body. The shed cells are continually replaced by cells moving up from the lower layers of the epidermis. It takes a period of about 48 days for newly formed keratinocytes in the stratum basale to make their way to the top of the stratum corneum to replace shed cells.

# FUNCTIONS OF THE EPIDERMIS

The epidermis has several crucial functions in the body. These functions include protection, water retention, and vitamin D synthesis.

### *PROTECTIVE FUNCTIONS*

The epidermis provides protection to underlying tissues from physical damage, pathogens, and UV light.

## PROTECTION FROM PHYSICAL DAMAGE

Most of the physical protection of the epidermis is provided by its tough outer layer, the stratum corneum. Because of this layer, minor scrapes and scratches generally do not cause significant damage to the skin or underlying tissues. Sharp objects and rough surfaces have difficulty penetrating or removing the tough, dead, keratin-filled cells of the stratum corneum. If cells in this layer are pierced or scraped off, they are quickly replaced by new cells moving up to the surface from lower skin layers.

## PROTECTION FROM PATHOGENS

When pathogens such as viruses and bacteria try to enter the body, it is virtually impossible for them to enter through intact epidermal layers. Generally, pathogens can enter the skin only if the epidermis has been breached, for example by a cut, puncture, or scrape in Figure **4.3.3**. That's why it is important to clean and cover even a minor wound in the epidermis. This helps ensure that pathogens do not use the wound to enter the body. Protection from pathogens is also provided by conditions at or near the skin surface. These include relatively high acidity (pH of about 5.0), low amounts of water, the presence of antimicrobial substances produced by epidermal cells, and Langerhans cells, which phagocytize bacteria or other pathogens.



Figure **4.3.3**: This scrape on the arm provides an opportunity for bacteria to enter the body through the broken skin.

## PROTECTION FROM UV LIGHT

The UV light that penetrates the epidermis can damage epidermal cells. In particular, it can cause mutations in DNA that lead to the development of skin cancer, in which epidermal cells grow out of control. The UV light can also destroy vitamin B9 (in forms such as folate or folic acid), which is needed for good health and successful reproduction. In a person with light skin, just an hour of exposure to intense sunlight can reduce the body's vitamin B9 level by 50 percent.

Melanocytes in the stratum basale of the epidermis contain small organelles called melanosomes, which produce, store, and transport the dark brown pigment melanin. As melanosomes become full of melanin, they move into thin extensions of the melanocytes. From there, the melanosomes are transferred to keratinocytes in the epidermis, where they absorb UV light that strikes the skin. This prevents the light from penetrating deeper into the skin and causing damage. The more melanin there is in the skin, the more UV light that can be absorbed.

### *WATER RETENTION*

The ability of the skin to hold water and not lose it to the surrounding environment is due mainly to the stratum corneum. Lipids arranged in an organized way among the cells of the stratum corneum form a barrier to water loss from the epidermis. This is critical for maintaining healthy skin and preserving proper water balance in the body.

Although the skin is impermeable to water, it is not impermeable to all substances. Instead, the skin is selectively permeable, allowing certain fat-soluble substances to pass through the epidermis. The selective permeability of the epidermis is both a benefit and a risk.

- Selective permeability allows certain medications to enter the bloodstream through the capillaries in the dermis. This is the basis of medications that are delivered using topical ointments or

patches that are applied to the skin. These include steroid hormones such as estrogen (for hormone replacement therapy), scopolamine (for motion sickness), nitroglycerin (for heart problems), and nicotine (for people trying to quit smoking).
- Selective permeability of the epidermis also allows certain harmful substances to enter the body through the skin. Examples include the heavy metal lead and many pesticides.

#### *VITAMIN D SYNTHESIS*

Vitamin D is a nutrient that is needed in the human body for the absorption of calcium from food. Molecules of a lipid compound named 7-dehydrocholesterol are precursors of vitamin D. These molecules are present in the stratum basale and stratum spinosum layers of the epidermis. When UV light strikes the molecules, it changes them to vitamin D3. In the kidneys, vitamin D3 is converted to calcitriol, which is the form of vitamin D that is active in the body.

### WHAT GIVES SKIN ITS COLOR?

Melanin in the epidermis is the main substance that determines the color of human skin and explains most of the variation in skin color in people around the world. However, two other substances also contribute to skin color, especially in light-skinned people: carotene and hemoglobin.

- The pigment **carotene** is present in the epidermis and gives skin a yellowish tint, especially in the skin with low levels of melanin.
- Hemoglobin is a red pigment found in red blood cells. It is visible through the skin as a pinkish tint, again mainly in the skin with low levels of melanin. The pink color is most visible when capillaries in the underlying dermis dilate, allowing greater blood flow near the surface.

### BACTERIA ON SKIN

The surface of the human skin normally provides a home to countless numbers of bacteria. Just one square inch of skin normally has an average of about 50 million bacteria. These generally harmless bacteria represent roughly 1,000 bacterial species (Figure **4.3.4**) from 19 different bacterial phyla. Typical variations in the moistness and oiliness of the skin produce a variety of rich and diverse habitats for these microorganisms. For example, the skin in the armpits is warm and moist and often hairy, whereas the skin on the forearms is smooth and dry. These two areas of the human body are as diverse to microorganisms as rainforests and deserts are to larger organisms. The density of bacterial populations on the skin depends largely on the region of the skin and its ecological characteristics. For example, oily surfaces, such as the face, may contain over 500 million bacteria per square inch. Despite the huge number of individual microorganisms living on the skin, their total volume is only about the size of a pea.



Figure **4.3.4**: The bacterium *Staphylococcus epidermidis* is a common microorganism living on healthy human skin

In general, the normal microorganisms living on the skin keep one another in check and thereby play an important role in keeping the skin healthy. However, if the balance of microorganisms is disturbed, there may be an overgrowth of certain species, and this may result in an infection. For example, when a patient is prescribed antibiotics, it may kill off normal bacteria and allow an overgrowth of single-celled yeast. Even if the skin is disinfected, no amount of cleaning can remove all of the microorganisms it contains. Disinfected areas are also quickly recolonized by bacteria residing in deeper areas such as hair follicles and in adjacent areas of the skin.

### WHAT IS DERMIS?

The **dermis** is the inner of the two major layers that make up the skin, the outer layer being the epidermis. The dermis consists mainly of connective tissues. It also contains most skin structures such as glands and blood vessels. The dermis is anchored to the tissues below it by flexible collagen bundles that permit most areas of the skin to move freely over subcutaneous ("below-the-skin") tissues. Functions of the dermis include cushioning subcutaneous tissues, regulating body temperature, sensing the environment, and excreting wastes.

### ANATOMY OF THE DERMIS




Figure **4.3.5**: This photomicrograph shows a section of the papillary and reticular layers of the dermis

The basic anatomy of the dermis is a matrix, or sort of scaffolding, composed of connective tissues. These tissues include collagen fibers, which provide toughness; and elastin fibers, which provide elasticity. Surrounding these fibers, the matrix also includes a gel-like substance made of proteins. The tissues of the matrix give the dermis both strength and flexibility.

The dermis is divided into two layers: the papillary layer and the reticular layer.

### PAPILLARY LAYER

The **papillary layer** is the upper layer of the dermis, just below the basement membrane that connects the dermis to the epidermis above it. The papillary layer is the thinner of the two dermal layers. It is composed mainly of loosely arranged collagen fibers. The papillary layer is named for its fingerlike projections, or papillae, that extend upward into the epidermis. The papillae contain capillaries and sensory touch receptors.

The papillae give the dermis a bumpy surface that interlocks with the epidermis above it, strengthening the connection between the two layers of skin. On the palms and soles, the papillae create epidermal ridges. Epidermal ridges on the fingers are commonly called fingerprints (see the photo below). Fingerprints are genetically determined, so no two people (other than identical twins) have exactly the same fingerprint pattern. Therefore, fingerprints can be used as a means of identification, for example, at crime scenes. Fingerprints were much more commonly used forensically before DNA analysis was introduced for this purpose.



Figure **4.3.6**: Epidermal ridges on a finger

### RETICULAR LAYER

The **reticular layer** is the lower layer of the dermis, below the papillary layer. It is the thicker of the two dermal layers. It is composed of densely woven collagen and elastin fibers. These protein fibers give the dermis its properties of strength and elasticity. This layer of the dermis cushions subcutaneous tissues of the body from stress and strain. The reticular layer of the dermis also contains most of the structures in the dermis, such as glands and hair follicles.

## STRUCTURES IN THE DERMIS

Both papillary and reticular layers of the dermis contain numerous sensory receptors, which make the skin the body's primary sensory organ for the sense of touch. Both dermal layers also contain blood vessels. They provide nutrients to and remove wastes from dermal cells as well as cells in the lowest layer of the epidermis, the stratum basale. The circulatory components of the dermis are shown in Figure **4.3.7**.

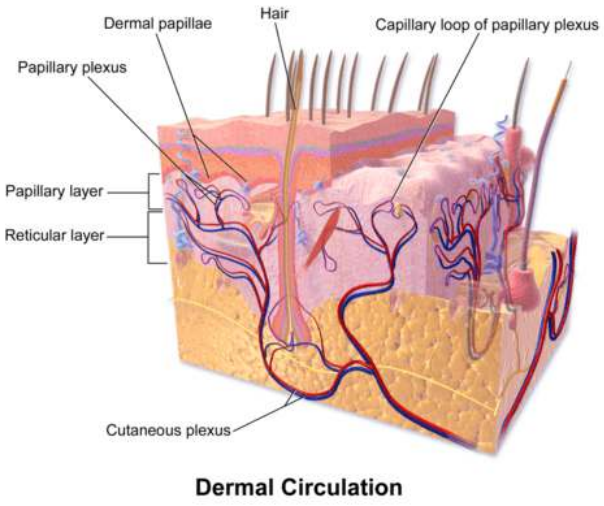



Figure **4.3.7**: Both the papillary layer and the reticular layer of the dermis contain blood vessels

### GLANDS

Glands in the reticular layer of the dermis include sweat glands and sebaceous (oil) glands. Both are exocrine glands, which are glands that release their secretions through ducts to nearby body surfaces. The diagram below shows these glands and also several other structures in the dermis.

**Sweat glands** produce the fluid called sweat, which contains mainly water and salts. The glands have ducts that carry the sweat to hair follicles or to the surface of the skin. There are two different types of sweat glands: eccrine glands and apocrine glands.

- Eccrine sweat glands occur in the skin all over the body. Their ducts empty through tiny openings called pores onto the skin surface. These sweat glands are involved in temperature regulation.
- Apocrine sweat glands are larger than eccrine glands and occur only in the skin of the armpits and groin. The ducts of apocrine glands empty into hair follicles, and then the sweat travels along hairs to reach the surface. Apocrine glands are inactive until puberty, at which point they start producing an oily sweat that is consumed by bacteria living on the skin. The digestion of apocrine sweat by bacteria is the cause of body odor.

**Sebaceous glands** are exocrine glands that produce a thick, fatty substance called sebum. Sebum is secreted into hair follicles and makes its way to the skin surface along with hairs. It waterproofs the hair and skin and helps prevent them from drying out. Sebum also has antibacterial properties, so it inhibits the growth of microorganisms on the skin. Sebaceous glands are found in every part of the skin except for the palms of the hands and soles of the feet where hair does not grow.

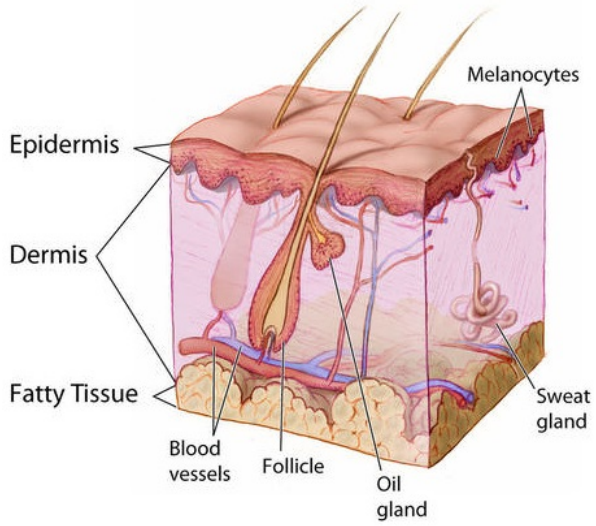



Figure **4.3.8**: The dermis contains sweat and oil (sebaceous) glands as well as hair follicles and blood vessels

**Hair Follicles**

Hair follicles are the structures where hairs originate (Figure **4.3.8**). Hairs grow out of follicles, pass through the epidermis, and exit at the surface of the skin. Associated with each hair follicle is a sebaceous gland, which secretes sebum that coats and waterproofs the hair. Each follicle also has a bed of capillaries, a nerve ending, and a tiny muscle called arrector pili.

## FUNCTIONS OF THE DERMIS

The main functions of the dermis are regulating body temperature, enabling the sense of touch, and eliminating wastes from the body.

### *TEMPERATURE REGULATION*

Several structures in the reticular layer of the dermis are involved in regulating body temperature. For example, when the body temperature rises, the hypothalamus of the brain sends nerve signals to sweat glands, causing them to release sweat. An adult can sweat up to four liters an hour. As the sweat evaporates from the surface of the body, it uses energy in the form of body heat, thus cooling the body. The hypothalamus also causes dilation of blood vessels in the dermis when the body temperature rises. This allows more blood to flow through the skin, bringing body heat to the surface, where it can radiate into the environment.

When the body is too cool, sweat glands stop producing sweat, and blood vessels in the skin constrict, thus conserving body heat. The arrector pili muscles also contract, moving hair follicles and lifting hair shafts. This results in more air being trapped under the hairs to insulate the surface of the skin. These contractions of arrector pili muscles are the cause of goosebumps.

### *SENSING THE ENVIRONMENT*

Sensory receptors in the dermis are mainly responsible for the body's tactile senses. The receptors detect such tactile stimuli as warm or cold temperature, shape, texture, pressure, vibration, and pain. They send nerve impulses to the brain which interprets and responds to the sensory information. Sensory receptors in the dermis can be classified on the basis of the type of touch stimulus they sense. Mechanoreceptors sense mechanical forces such as pressure, roughness, vibration, and stretching. Thermoreceptors sense variations in temperature that are above or below body temperature. Nociceptors sense painful stimuli. Figure **4.3.9** shows several specific kinds of tactile receptors in the dermis. Each kind of receptor senses one or more types of touch stimuli.

- Free nerve endings sense pain and temperature variations.
- Merkel cells sense light touch, shapes, and textures.
- Meissner's corpuscles sense light touch.
- Pacinian corpuscles sense pressure and vibration.
- Ruffini corpuscles sense stretching and sustained pressure.

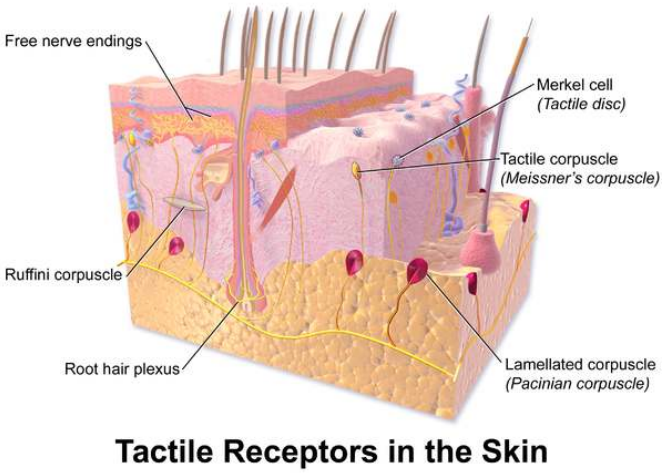



Figure **4.3.9**: A variety of types of tactile receptors are located in the dermis of the skin

### *EXCRETING WASTES*

The sweat released by eccrine sweat glands is one way the body excretes waste products. Sweat contains excess water, salts (electrolytes), and other waste products that the body must get rid of to maintain homeostasis. The most common electrolytes in sweat are sodium and chloride. Potassium, calcium, and magnesium electrolytes may be excreted in sweat as well. When these electrolytes reach high levels in the blood, extra electrolytes are excreted in sweat. This helps to bring their blood levels back into balance. Besides electrolytes, sweat contains small amounts of waste products from metabolism including ammonia and urea. Sweat may also contain alcohol in someone who has been drinking alcoholic beverages.

### FEATURE: MY HUMAN BODY

**Acne** is the most common skin disorder in the United States. At least 40 million Americans have acne at any given time. Acne occurs most commonly in teens and young adults, but it can occur at any age. Even newborn babies can get acne.

The main sign of acne is the appearance of pimples (pustules) on the skin, like those in the photo above. Other signs of acne may include whiteheads, blackheads, nodules, and other lesions. Besides the face, acne can appear on the back, chest, neck,

shoulders, upper arms, and buttocks. Acne can permanently scar the skin, especially if it isn't treated appropriately. Besides its physical effects on the skin, acne can also lead to low self-esteem and depression.

Acne is caused by clogged, sebum-filled pores that provide a perfect environment for the growth of bacteria. The bacteria cause infection, and the immune system responds with inflammation. Inflammation, in turn, causes swelling and redness and may be associated with the formation of pus. If the inflammation goes deep into the skin, it may form an acne nodule.

Mild acne often responds well to treatment with over-the-counter (OTC) products containing benzoyl peroxide or salicylic acid. Treatment with these products may take a month or two to clear up the acne. Once the skin clears, treatment generally needs to be continued for some time to prevent future breakouts.

If acne fails to respond to OTC products, nodules develop, or acne is affecting self-esteem, a visit to a dermatologist is in order. A dermatologist can determine which treatment is best for a given patient. A dermatologist can also prescribe prescription medications (which are likely to be more effective than OTC products) and provide other medical treatments such as laser light therapies or chemical peels.

What can you do to maintain healthy skin and prevent or reduce acne? Dermatologists recommend the following tips:

- Wash affected or acne-prone skin (such as the face) twice a day and after sweating.
- Use your fingertips to apply a gentle, non-abrasive cleanser. Avoid scrubbing, which can make acne worse.
- Use only alcohol-free products and avoid any products that irritate the skin, such as harsh astringents or exfoliants.
- Rinse with lukewarm water, and avoid using very hot or cold water.
- Shampoo your hair regularly.
- Do not pick, pop, or squeeze acne. If you do, it will take longer to heal and is more likely to scar.
- Keep your hands off your face. Avoid touching your skin throughout the day.
- Stay out of the sun and tanning beds. Some acne medications make your skin very sensitive to UV light.

## REVIEW

1. What is the dermis?
2. Describe the basic anatomy of the dermis.
3. Compare and contrast the papillary and reticular layers of the dermis.
4. What causes epidermal ridges, and why can they be used to identify individuals?
5. Name the two types of sweat glands in the dermis and state how they differ.
6. What is the function of sebaceous glands?
7. Describe structures associated with hair follicles.
8. Explain how the dermis helps regulate body temperature.
9. Identify three specific kinds of tactile receptors in the dermis and the type of stimuli they sense.
10. How does the dermis excrete wastes, and what waste products does it excrete?
11. What are the subcutaneous tissues? Which layer of the dermis provides cushioning for subcutaneous tissues and why does this layer provide most of the cushioning instead of the other layer?
12. For each of the following functions, describe which structure within the dermis carries it out.
    A. Brings nutrients to and removes wastes from dermal and lower epidermal cells
    B. Causes hairs to move
    C. Detects painful stimuli on the skin
13. What is the epidermis?
14. Identify the types of cells in the epidermis.
15. Describe the layers of the epidermis.
16. State one function of each of the four epidermal layers found all over the body.
17. Explain three ways the epidermis protects the body.
18. What makes the skin waterproof?
19. Why is the selective permeability of the epidermis both a benefit and risk?
20. How is vitamin D synthesized in the epidermis?
21. Identify three pigments that impart color to the skin.
22. Describe bacteria that normally reside on the skin, and explain why they do not usually cause infections.
23. Explain why the keratinocytes at the surface of the epidermis are dead, while keratinocytes located deeper in the epidermis are still alive.
24. Which layer of the epidermis contains keratinocytes that have begun to die?
25. *True or False.* The extra layer of epidermis found on the palms of the hands and soles of the feet is located on the very outer surface of the skin.
26. *True or False.* Melanin can be found in keratinocytes.
27. Explain why our skin is not permanently damaged if we rub off some of the surface layers by using a rough washcloth.

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# 4.4: HAIR AND NAILS

## FASHION STATEMENT

This pink hairstyle makes quite a fashion statement. Many people spend a lot of time and money on their hair, even if they don't have such an exceptional hairstyle as this one. Besides its display value, hair actually has important physiological functions.



Figure **4.4.1**: dyed hair

**Hair** is a filament that grows from a **hair follicle** in the dermis of the skin. It consists mainly of tightly packed, keratin-filled cells called keratinocytes. The human body is covered with hair follicles except for a few areas, including the mucous membranes, lips, palms of the hands, and soles of the feet.

## STRUCTURE OF HAIR

The part of the hair that is located within the follicle is called the **hair root.** The root is the only living part of the hair. The part of the hair that is visible above the surface of the skin is the hair shaft. The shaft of the hair has no biochemical activity and is considered dead.

### FOLLICLE AND ROOT

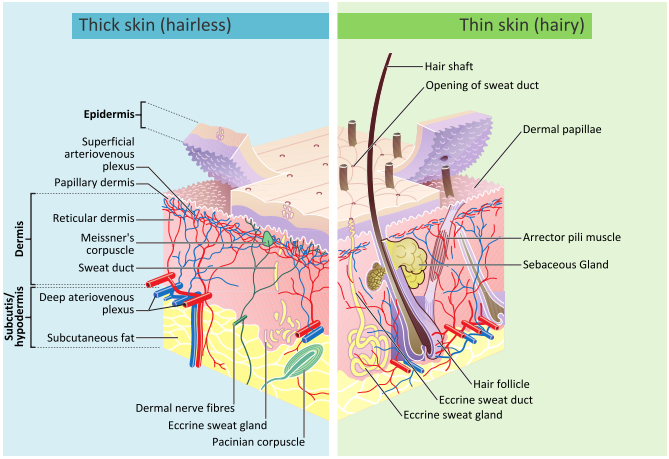



Figure **4.4.2**: A hair follicle has sebaceous glands and arrector pili muscles associated with it. The part of the hair that is visible from the outside is called the hair shaft. The thick skin of palms and soles does not contain hair follicles.

Hair growth begins inside a follicle (Figure **4.4.2**:). Each hair follicle contains stem cells that can keep dividing and allow hair to grow. The stem cells can also regrow new hair after one falls out. Another structure associated with a hair follicle is a sebaceous gland that produces oily sebum, which lubricates and helps to waterproof the hair. A tiny arrector pili muscle is also attached to the follicle. When it contracts, the follicle moves and the hair in the follicle stands up.

### FUNCTIONS OF HAIR

In humans, one function of head hair is to provide insulation and help the head retain heat. Head hair also protects the skin on the head from damage by UV light. The function of hair in other locations on the body is debated. One idea is that body hair helps to keep us warm in cold weather. When the body is too cold, the arrector pili muscles contract and cause hairs to stand up, trapping a layer of warm air above the epidermis. However, this is more effective in mammals that have thick hair or fur than it is in relatively hairless human beings.

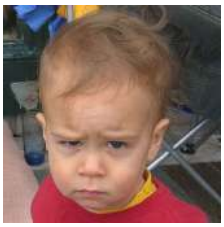


Figure **4.4.3**: This young child is using his eyebrows to good effect to convey his displeasure

Human hair has an important sensory function as well. Sensory receptors in the hair follicles can sense when the hair moves, whether it moves because of a breeze or the touch of a physical object. The receptors may also provide sensory awareness of the presence of parasites on the skin. Some hairs, such as eyelashes, are especially sensitive to the presence of potentially harmful matter. The eyebrows protect the eyes from dirt, sweat, and rain. In addition, the eyebrows play a key role in nonverbal communication (Figure **4.4.3**). They help express emotions such as sadness, anger, surprise, and excitement.

## WHAT ARE NAILS?

**Nails** are accessory organs of the skin. They are made of sheets of dead keratinocytes and are found on the far, or distal, ends of the fingers and toes. The keratin in nails makes them hard but flexible. Nails serve a number of purposes, including protecting the digits, enhancing sensations, and acting like tools.

### NAIL ANATOMY

A nail has three main parts: the root, plate, and free margin. Other structures around or under the nail include the nail bed, cuticle, and nail fold. Nails grow from a deep layer of living epidermal tissue, known as the **nail matrix,** at the proximal end of the nail. The nail matrix surrounds the nail root. It contains stem cells that divide to form keratinocytes, which are cells that produce keratin and make up the nail. These structures are shown in Figure **4.4.4**.

- The **nail root** is the portion of the nail found under the surface of the skin at the near, or proximal, end of the nail. It is where the nail begins.
- The **nail plate** (or body) is the portion of the nail that is external to the skin. It is the visible part of the nail.
- The free margin is the portion of the nail that protrudes beyond the distal end of the finger or toe. This is the part that is cut or filed to keep the nail trimmed.
- The **nail bed** is the area of skin under the nail plate. It is pink in color due to the presence of capillaries in the dermis.
- The cuticle is a layer of dead epithelial cells that overlaps and covers the edge of the nail plate. It helps to seal the edges of the nail to prevent infection of the underlying tissues.
- The nail fold is a groove in the skin in which the side edges of the nail plate are embedded.

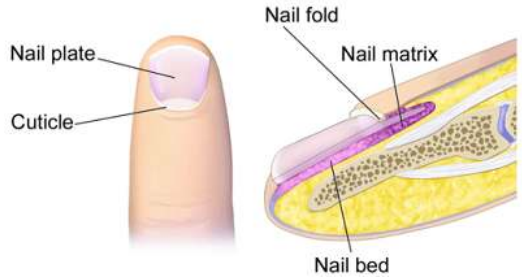



Figure 4.4.4: The left diagram in this figure shows the external, visible part of the nail and the cuticle. The right diagram shows internal structures in a cross-section of the nail, matrix, and nail bed.

## NAILS AND HEALTH

Healthcare providers, particularly EMTs, often examine the fingernail beds as a quick and easy indicator of oxygen saturation of the blood or the amount of blood reaching the extremities. If the nail beds are bluish or purple, it is generally a sign of low oxygen saturation. To see if blood flow to the extremities is adequate, a blanch test may be done. In this test, a fingernail is briefly depressed to turn the nail bed white by forcing the blood out of its capillaries. When the pressure is released, the pink color of the nail bed should return within a second or two if there is normal blood flow. If the return to a pink color is delayed, then it can be an indicator of low blood volume due to dehydration or shock. Nails — especially toenails — are common sites of fungal infections, causing nails to become thickened and yellowish in color. Toenails are more often infected than fingernails because they are often confined in shoes. This provides a dark, warm, moist environment where fungi can thrive. Toes also tend to have less blood flow than fingers, making it harder for the immune system to detect and stop infections in toenails. Although nails are harder and tougher than the skin, they are more permeable than the skin. Harmful substances, such as herbicides may be absorbed through the nails and cause health problems.

### FEATURE: RELIABLE SOURCES

Do you get regular manicures or pedicures from a nail technician? If so, there is a chance that you are putting your health at risk. Nail tools that are not properly disinfected between clients may transmit infections from one person to another. Cutting the cuticles with scissors may create breaks in the skin that let infective agents enter the body. Products such as acrylics, adhesives, and UV gels that are applied to the nails may be harmful, especially if they penetrate the nails and enter the skin.

Use the Internet and find several reliable sources that address the health risks of professional manicures or pedicures. Try to find answers to the following questions:

1. What training and certification are required for professional nail technicians?
2. What licenses and inspections are required for nail salons?
3. What hygienic practices should be followed in nail salons to reduce the risk of infections being transmitted to clients?
4. Which professional nail products are potentially harmful to the human body and which are safer?
5. How likely is it to have an adverse health consequence when you get a professional manicure or pedicure?
6. What steps can you take to ensure that a professional manicure or pedicure is safe?

## REVIEW

1. Compare and contrast the hair root and hair shaft.
2. Describe hair follicles.
3. Identify the three zones of a hair shaft.
4. Describe two functions of human hair.
5. True or False. Eyelashes can have a sensory function.
6. Hair consists mainly of:
   - A. Melanocytes
   - B. Keratinocytes
   - C. Epidermocytes
   - D. Hirocytes
7. What are the nails?
8. Describe three parts of the nail.
9. Explain why most of the nail plate looks pink.
10. Describe a lunula.
11. Explain how a nail grows.
12. Identify three functions of nails.
13. Give several examples of how nails are related to health.
14. *True or False*. Nails grow from the distal end to the proximal end of your fingers and toes.
15. *True or False*. The nail bed refers to the middle portion of the hard nail plate
16. Nails are composed mainly of a protein called:

    A. Elastin

    B. Collagen

    C. Keratin

    D. Melanin

17. a. What is the cuticle of the nail composed of?

    b. What is the function of the cuticle?

    c. Why is it a bad idea to cut the cuticle during a manicure?

18. What is the name of the part of the nail that you trim?
19. Is the nail plate composed of living or dead cells?

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# 4.5: CASE STUDY CONCLUSION- SKIN CANCER AND CHAPTER SUMMARY

## CASE STUDY CONCLUSION

Skin cancer begins in the outer layer of skin, the epidermis. There are three common types of skin cancer: basal cell carcinoma, squamous cell carcinoma, and melanoma.

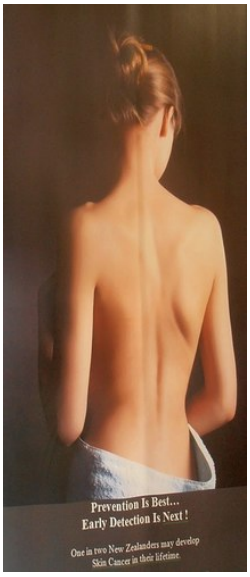



Figure **4.5.1**: cancer screening poster

### BASAL CELL CARCINOMA

**Basal cell carcinoma** occurs in basal cells of the epidermis. Basal cells are stem cells in the stratum basale layer that divide to form all the keratinocytes of the epidermis. Basal cell carcinoma is the most common form of skin cancer. More than four million cases occur in the United States each year. A basal cell carcinoma may appear as a pearly or waxy bump, like the one shown in Figure **4.5.2**. Basal cell carcinomas rarely spread (or undergo **metastasis),** so they can generally be cured with a **biopsy,** in which the lesion is cut out of the skin and analyzed in a medical lab.

### SQUAMOUS CELL CARCINOMA

**Squamous cell carcinoma** occurs in squamous cells of the epidermis. Squamous cells are flattened, keratin-filled cells in the upper layers of the epidermis. Squamous cell carcinoma is the second most common form of skin cancer. More than two million cases occur in the United States each year. A squamous cell carcinoma may appear as a firm, red nodule, or as a flat lesion with a scaly or crusty surface, like the one pictured in Figure **4.5.3**. Squamous cell carcinomas are generally localized and unlikely to metastasize, so they are usually curable surgically.

### MELANOMA

**Melanoma** occurs in the melanocytes of the epidermis. Melanocytes are the melanin-producing cells in the stratum basale of the epidermis. Melanoma is the rarest type of skin cancer, accounting for less than one percent of all skin cancer cases. Melanoma, however, is the most deadly type of skin cancer. It causes the vast majority of skin cancer deaths because melanoma is malignant. If not treated, it will metastasize and spread to other parts of the body. If melanoma is detected early and while it is still localized in the skin, most patients survive for at least five years. If melanoma is discovered only after it has already metastasized to distant organs, there is only a 17 percent chance of patients surviving for five years. You can see an example of melanoma in Figure **4.5.4**.



Figure **4.5.2**: Basal cell carcinoma



Figure **4.5.3**: Squamous cell carcinoma



Figure **4.5.4**: Melanoma

Melanoma can develop anywhere on the body. It may develop in otherwise normal skin, or an existing mole may become cancerous. Signs of melanoma may include a:

- mole that changes in size, feel, or color
- mole that bleeds
- large brown spot on the skin sprinkled with darker specks
- small lesion with an irregular border and parts that appear red, white, blue, or blue-black
- dark lesion on the palms, soles, fingertips, toes, or mucous membranes

As with most types of cancer, skin cancer is the easiest to treat and most likely to be cured the earlier it is detected. The skin is one of the few organs that you can monitor for cancer yourself, as long as you know what to look for. A brown spot on the skin is likely to be a harmless mole, but it could be a sign of skin cancer. As shown in Figure **4.5.5**, unlike moles, skin cancers may be asymmetrical, have irregular borders, be very dark in color, and may have a relatively great diameter. These characteristics can be remembered with the mnemonic ABCD.




Figure **4.5.5**: ABCDs of skin cancer

With the help of mirrors, you should check all of your skin regularly. Look for new skin growths or changes in any existing moles, freckles, bumps, or birthmarks. Report anything suspicious or different to your doctor.

If you have risk factors for skin cancer, it's a good idea to have an annual skin check by a dermatologist. This helps ensure that cancerous or precancerous lesions will be detected before they grow too large and become difficult to cure—or, in the case of melanoma, before they metastasize.

## CHAPTER REVIEW

In this chapter, you learned about the structures and functions of the organs of the integumentary system. Specifically, you learned that:

- The integumentary system consists of the skin, hair, and nails. Functions of the integumentary system include providing a protective covering for the body, sensing the environment, and helping the body maintain homeostasis.
- The skin's main functions include preventing water loss from the body, serving as a barrier to the entry of microorganisms, synthesizing vitamin D, blocking UV light, and helping to regulate body temperature.
- The skin consists of two distinct layers: a thinner outer layer called the epidermis and a thicker inner layer called the dermis.
    - The epidermis consists mainly of epithelial cells called keratinocytes, which produce keratin. New keratinocytes form at the bottom of the epidermis. They become filled with keratin and die as they move upward toward the surface of the skin, where they form a protective, waterproof layer.
    - The dermis consists mainly of tough connective tissues that provide strength and stretch; and almost all skin structures, including blood vessels, sensory receptors, hair follicles, and oil and sweat glands.
- Cell types in the epidermis include keratinocytes which make up 90 percent of epidermal cells; melanocytes that produce melanin; Langerhans cells that fight pathogens in the skin; and Merkel cells that respond to light touch.
- The epidermis in most parts of the body consists of four distinct layers. A fifth layer occurs only in the epidermis of the palms of the hands and soles of the feet.
    - The innermost layer of the epidermis is the stratum basale, which contains stem cells that divide to form new keratinocytes. The next layer is the stratum spinosum, which is the thickest layer and contains Langerhans cells and spiny keratinocytes. This is followed by the stratum granulosum, in which keratinocytes are filling with keratin and starting to die. The stratum lucidum is next, but only on the palms and soles. It consists of translucent dead keratinocytes. The outermost layer is the stratum corneum, which consists of flat, dead, tightly packed keratinocytes that form a tough, waterproof barrier for the rest of the epidermis.
- Functions of the epidermis include protecting underlying tissues from physical damage and pathogens. Melanin in the epidermis absorbs and protects underlying tissues from UV light. The epidermis also prevents the loss of water from the body and synthesizes vitamin D.
    - Melanin is the main pigment that determines the color of human skin. However, the pigments of carotene and hemoglobin also contribute to skin color, especially in the skin with low levels of melanin.
    - The surface of healthy skin normally is covered by vast numbers of bacteria representing about 1,000 species from 19 phyla. Different areas of the body provide diverse habitats for skin microorganisms. Usually, microorganisms on the skin keep each other in check unless their balance is disturbed.
- The thicker inner layer of the skin, the dermis, has two layers. The upper papillary layer has papillae extending upward into the epidermis and loose connective tissues. The lower reticular layer has denser connective tissues and structures such as glands and hair follicles. Glands in the dermis include eccrine and apocrine sweat glands and sebaceous glands. Hair follicles are structures where hairs originate.
- Functions of the dermis include cushioning subcutaneous tissues, regulating body temperature, sensing the environment, and excreting wastes. The dense connective tissues of the dermis provide cushioning. The dermis regulates body temperature mainly by sweating and by vasodilation or vasoconstriction. The many tactile sensory receptors in the dermis make it the main organ for the sense of touch. Wastes excreted in sweat include excess water, electrolytes, and certain metabolic wastes.
- Hair is a filament that grows from a hair follicle in the dermis of the skin. It consists mainly of tightly packed, dead keratinocytes that are filled with keratin. The human body is almost completely covered with hair follicles.
- Hair helps prevent heat loss from the head and protects its skin from UV light. Hair in the nose filters the incoming air, and the eyelashes and eyebrows keep harmful substances out of the eyes. Hair all over the body provides tactile sensory input. The eyebrows also play a role in nonverbal communication.
- The part of the hair that is within the follicle is the hair root. This is the only living part of a hair. The part of the hair that is visible above the skin surface is the hair shaft. It consists of dead cells.
    - Hair growth begins inside a follicle when stem cells within the follicle divide to produce new keratinocytes.
    - A hair shaft has three zones: the outermost zone called the cuticle; the middle zone called the cortex, and the innermost zone called the medulla.
- Genetically controlled, visible characteristics of hair include hair color, hair texture, and the extent of balding in adult males.

Melanin (eumelanin and/or pheomelanin) is the pigment that gives hair its color. Aspects of hair texture include curl pattern, thickness, and consistency.

- Among mammals, humans are nearly unique in having undergone a significant loss of body hair during their evolution, probably because sweat evaporates more quickly from the less hairy skin. Curly hair also is thought to have evolved at some point during human evolution, perhaps because it provided better protection from UV light.
- Hair has social significance for human beings, being an indicator of biological sex, age, and ethnic ancestry. Human hair also has cultural significance. For example, hairstyle may be an indicator of a social group membership.
- Nails consist of sheets of dead, keratin-filled keratinocytes. The keratin in nails makes them hard but flexible. They help protect the ends of the fingers and toes, enhance the sense of touch in the fingertips, and may be used as tools.
- A nail has three main parts: the nail root, which is under the epidermis; the nail plate, which is the visible part of the nail; and the free margin, which is the distal edge of the nail. Other structures under or around a nail include the nail bed, cuticle, and nail fold.
- A nail grows from a deep layer of living epidermal tissues, called the nail matrix, at the proximal end of the nail. Stem cells in the nail matrix keep dividing to allow nail growth, forming first the nail root and then the nail plate as the nail continues to grow longer and emerges from the epidermis.
- Fingernails grow faster than toenails. Actual rates of growth depend on many factors, such as age, sex, and season.
- The color of the nail bed can be used to quickly assess oxygen and blood flow in a patient. How the nail plate grows out can reflect recent health problems, such as illness or nutrient deficiency. Nails — and especially toenails — are prone to fungus infections. Nails are more permeable than skin and can absorb several harmful substances such as herbicides.
- Skin cancer is a disease in which skin cells grow out of control. It is caused mainly by excessive exposure to UV light, which damages DNA. Skin cancer affects more Americans than all other cancers combined.
- There are three common types of skin cancer: basal cell carcinoma, squamous cell carcinoma, and melanoma. Carcinomas are more common and unlikely to metastasize. Melanoma is rare and likely to metastasize. It causes the most skin cancer deaths.
- Besides exposure to UV light, risk factors for skin cancer include having light-colored skin, many moles, and a family history of skin cancer, among several others.

Now that you have learned about the organs on the surface of the body, read the next chapter to travel inside and learn about the skeletal system, which protects and supports us internally, among other functions.

## CHAPTER SUMMARY REVIEW

1. What is skin cancer?
2. How common is skin cancer?
3. Compare and contrast the three common types of skin cancer.
4. Identify factors that increase the risk of skin cancer.
5. How does exposure to UV light cause skin cancer?
6. In which layer of the skin does skin cancer normally start?
7. Which two skin cancers described in this section start in the same sublayer? Include the name of the sublayer and the cells affected in each of these cancers in your answer.
8. If a type of skin cancer spreads to other organs, which type is it most likely to be? Explain your answer.
9. *True or False*. A mole is a form of cancer.
10. *True or False*. Exposure to UV light can contribute to wrinkles.
11. *True or False*. Skin cancers are always dark in color.
12. Which form of skin cancer is the most deadly?
13. What are some ways people can reduce their risk of getting skin cancer? Explain your answer.
14. *True or False*. UV radiation causes more cancers than tobacco use.
15. Describe one way in which the integumentary system works with another organ system to carry out a particular function.
16. Put the following layers of skin in order, from the deepest layer to the layer closest to the surface:

    A. papillary layer
    B. stratum basale
    C. reticular layer
    D. stratum spinosum

17. The basement membrane is between the:

    A. Dermis and epidermis
    B. Dermis and the subcutaneous tissues beneath it
    C. Dermis and the hair in the follicle
    D. Nail matrix and the nail bed

18. For each of the descriptions below (A-D), match it to the protein that is best described by it (protein choices: keratin, collagen, melanin, elastin).

    A. Helps provide strength and elasticity in the lower layer of the dermis
    B. Makes up the loosely arranged fibers in the upper layer of the dermis
    C. The predominant protein in hair, skin, and nails
    D. Protects against damage from UV light.

19. Keratinocytes are found in:

    A. Skin
    B. Hair
    C. Nails
    D. All of the above

20. Papillae extend from the :

    A. sebaceous glands to the surface of the skin
    B. sweat glands to the surface of the skin
    C. epidermis down into the dermis

D. dermis up into the epidermis

21. Describe two types of waterproofing used in the integumentary system. Include the types of molecules and where they are located in your answer.
22. Explain why nails enhance touch sensations.
23. Why do you think light-colored skin is a risk factor for skin cancer?
24. Which vitamin is synthesized by the skin?
    A. Vitamin A
    B. Vitamin D
    C. Vitamin B9
    D. Vitamin E
25. Describe the similarities between how the epidermis, hair, and nails all grow.
26. *True or False.* The inside of the mouth is considered to be epidermal tissue.
27. *True or False.* Epidermal cells are filled with an increasing amount of keratin as they go from the lowest layer to the outermost layer.
28. *True or False.* Cells in the stratum corneum of the skin do not have a nucleus or organelles.
29. What does the whitish crescent-shaped area at the base of your nails (towards your hands) represent? What is its function?
30. What is one difference between human hair and the hair of non-human primates?
31. *True or False.* Blood vessels extend through the entire thickness of the skin.
32. *True or False.* Cells that produce melanin are located in the dermis of the skin.
33. Describe the relationship between skin and hair.
34. What kind of skin cancer is a cancer of a type of stem cell?
35. For the skin and hair, describe one way in which they each protect the body against pathogens.
36. If sweat glands are in the dermis, how is sweat released to the surface of the body?
37. Explain why you think that physicians usually insist that patients remove any nail polish before having surgery.
38. *True or False.* Langerhans cells are immune cells located in the epidermis.
39. *True or False.* Fingerprints are due to structures on the surface of the epidermis.
40. Describe generally how the brain gets touch information from the skin.

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# CHAPTER OVERVIEW

## 5: THE SKELETAL SYSTEM

This chapter describes the structure and functions of the skeletal system and its two major divisions, the axial skeleton and the appendicular skeleton. It details the structure of bone, how bones grow, and how they are remodeled and repaired. The chapter also explains how joints work and how they are classified as well as the causes and effects of major skeletal system disorders.


5.1: Case Study- Your Support System

5.2: Introduction to the Skeletal System

5.3: Divisions of the Skeletal System

5.4: Structure of Bone

5.5: Bone Growth, Remodeling, and Repair

5.6: Joints

5.7: Disorders of the Skeletal System

5.8: Case Study Conclusion- Heels and Chapter Summary


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# 5.1: CASE STUDY- YOUR SUPPORT SYSTEM

## CASE STUDY: A PAIN IN THE FOOT

Amari loves wearing high heels when they go out at night, like the stiletto heels shown in Figure **5.1.1**. Amari uses gender-neutral pronouns, such as they, them, and their. They know high heels are not the most practical shoes, but they like how they look. Lately, Amari has been experiencing pain in the balls of their feet—the area just behind the toes. Even when they trade heels for comfortable sneakers, it still hurts when they stand or walk.



Figure **5.1.1**: high heels

What could be going on? Amari searches online to try to find some answers. They find a reputable source for foot pain information—a website from a professional organization of physicians that peer reviews the content by experts in the field. There, Amari reads about a condition called metatarsalgia, which produces pain in the ball of the foot that sounds very similar to what they are experiencing.

Amari learns that a common cause of metatarsalgia is the wearing of high heels because they push the foot into an abnormal position. This results in excessive pressure being placed onto the ball of the foot. Looking at the photograph above, you can imagine how much of the body weight is focused on the ball of the foot because of the shape of the high heels. If they were not wearing high heels, the weight would be more evenly distributed across the foot.

As they read more about the hazards of high heels, Amari learns that heels can also cause foot deformities such as hammertoes and bunions, small cracks in the bone called stress fractures, and may even contribute to the development of osteoarthritis of the knees at an early age.

These conditions caused by high heels are all problems of the skeletal system, which includes bones and connective tissues that hold bones together and cushion them at joints such as the knee. The skeletal system supports the body's weight and protects internal organs, but as you will learn as you read this chapter, it also carries out a variety of other important physiological functions.

At the end of the chapter, you will find out why high heels can cause these skeletal system problems and the steps Amari takes to recover from their foot pain and prevent long-term injury.

## CHAPTER OVERVIEW: SKELETAL SYSTEM

In this chapter, you will learn about the structure, functions, growth, repair, and disorders of the skeletal system. Specifically, you will learn about:

- The components of the skeletal system, which include bones, ligaments, and cartilage.
- The functions of the skeletal system, which include supporting and giving shape to the body, protecting internal organs, facilitating movement, producing blood cells, helping maintain homeostasis, and producing endocrine hormones.
- The organization and functions of the two main divisions of the skeletal system: the axial skeletal system, which includes the skull, spine, and rib cage; and the appendicular skeletal system, which includes the limbs and girdles that attach the limbs to the axial skeleton.
- The tissues and cells that make up bones and their specific functions, including making new bone, breaking down bone, producing blood cells, and regulating mineral homeostasis.
- The different types of bones in the skeletal system, based on shape and location.
- How bones grow, remodel, and repair themselves.
- The different types of joints between bones, where they are located, and the ways in which they allow different types of movement depending on their structure.
- The causes, risk factors, and treatments for the two most common disorders of the skeletal system: osteoporosis and osteoarthritis.

As you read this chapter, think about the following questions:

1. Amari suspects they have a condition called metatarsalgia. This term is related to the term "metatarsals." What are metatarsals, where are they located, and how do you think they are related to metatarsalgia?
2. High heels can cause stress fractures, which are small cracks in the bone that usually appear after repeated mechanical stress, instead of after a significant acute injury. What other condition described in this chapter involves a similar process?
3. What are bunions and osteoarthritis of the knee? Why do you think they can be caused by wearing high heels?

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# 5.2: INTRODUCTION TO THE SKELETAL SYSTEM

## SKULL AND CROSS-BONES

The skull and cross-bones symbol has been used for a very long time to represent death, perhaps because after death and decomposition, bones are all that remain. Many people think of bones as being dead, dry, and brittle. These adjectives may correctly describe the bones of a preserved skeleton, but the bones of a living human being are very much alive. Living bones are also strong and flexible. Bones are the major organs of the skeletal system.




Figure **5.2.1**: skull and cross-bones flag

The **skeletal system** is the organ system that provides an internal framework for the human body. Why do you need a skeletal system? Try to imagine what you would look like without it. You would be a soft, wobbly pile of skin containing muscles and internal organs but no bones. You might look something like a very large slug. Not that you would be able to see yourself — folds of skin would droop down over your eyes and block your vision because of your lack of skull bones. You could push the skin out of the way if you could only move your arms, but you need bones for that as well!

### COMPONENTS OF THE SKELETAL SYSTEM

In adults, the skeletal system includes 206 bones, many of which are shown in Figure **5.2.2**. Bones are organs made of dense connective tissues, mainly the tough protein collagen. Bones contain blood vessels, nerves, and other tissues. Bones are hard and rigid due to deposits of calcium and other mineral salts within their living tissues. Locations, where two or more bones meet, are called joints. Many joints allow bones to move like levers. For example, your elbow is a joint that allows you to bend and straighten your arm.

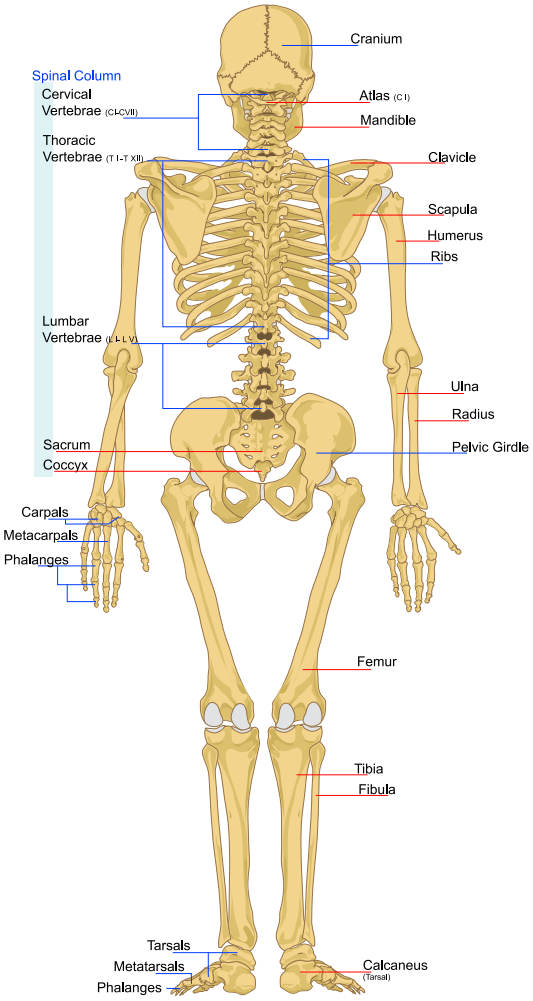



Figure **5.2.2**: Some of the 206 bones are labeled on the adult human skeleton.

Besides bones, the skeletal system includes cartilage and ligaments.

- **Cartilage** is a type of dense connective tissue, made of tough protein fibers. It is strong but flexible and very smooth. It covers the ends of bones at joints, providing a smooth surface for bones to move over.
- **Ligaments** are bands of fibrous connective tissue that hold bones together. They keep the bones of the skeleton in place.

### AXIAL AND APPENDICULAR SKELETONS

The skeleton is traditionally divided into two major parts: the axial skeleton and the appendicular skeleton, both of which are pictured in Figure **5.2.3**.

- The axial skeleton forms the axis of the body. It includes the skull, vertebral column (spine), and rib cage. The bones of the axial skeleton, along with ligaments and muscles, allow the human body to maintain its upright posture. The axial skeleton also transmits weight from the head, trunk, and upper extremities

down the back to the lower extremities. In addition, the bones protect the brain and organs in the chest.

- The appendicular skeleton forms the appendages and their attachments to the axial skeleton. It includes the bones of the arms and legs, hands and feet, and shoulder and pelvic girdles. The bones of the appendicular skeleton make possible locomotion and other movements of the appendages. They also protect the major organs of digestion, excretion, and reproduction.

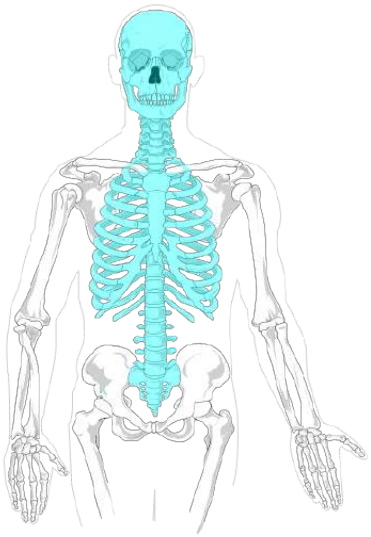


Figure **5.2.3**: Axial skeleton represented in blue

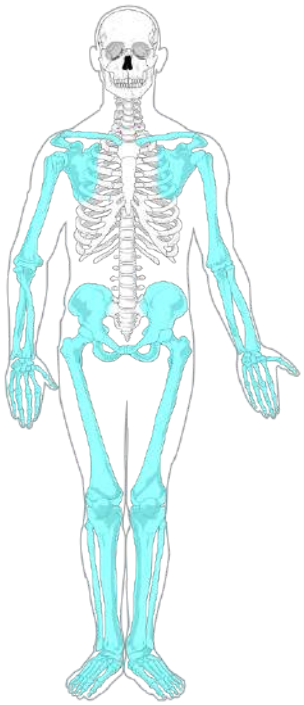


Figure **5.2.3**: Appendicular skeleton represented in blue

## FUNCTIONS OF THE SKELETAL SYSTEM

The skeletal system has many different functions that are necessary for human survival. Some of the functions, such as supporting the body, are relatively obvious. Other functions are less obvious but no less important. For example, three tiny bones (hammer, anvil, and stirrup) inside the middle ear transfer sound waves into the inner ear.

### SUPPORT, SHAPE, AND PROTECTION

The skeleton supports the body and gives it shape. Without the rigid bones of the skeletal system, the human body would be just a bag of soft tissues, as described above. The bones of the skeleton are very hard and provide protection to the delicate tissues of internal organs. For example, the skull encloses and protects the soft tissues of the brain, and the vertebral column protects the nervous tissues of the spinal cord. The vertebral column, ribs, and sternum (breast bone) protect the heart, lungs, and major blood vessels. Providing protection to these latter internal organs requires the bones to be able to expand and contract. The ribs and the cartilage that connects them to the sternum and vertebrae are capable of small shifts that allow breathing and other internal organ movements.

### MOVEMENT

The bones of the skeleton provide attachment surfaces for skeletal muscles. When the muscles contract, they pull on and move the bones. The figure below, for example, shows the muscles attached to the bones at the knee. They help stabilize the joint and allow the leg to bend at the knee. The bones at joints act like levers moving at a fulcrum point, and the muscles attached to the bones apply the force needed for movement.

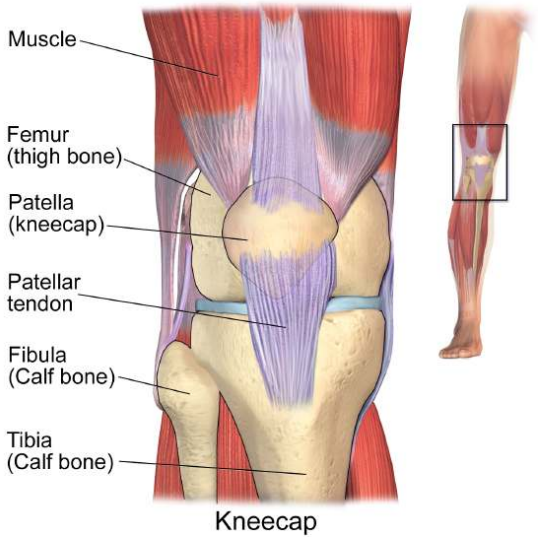



Figure **5.2.4**: Bones that meet at the knee joint include the tibia and fibula in the lower leg, the femur in the upper leg, and the kneecap at the front of the knee. These bones provide attachment surfaces for muscles that move the bones at the joint. Muscles are attached to the bones via tendons.

### HEMATOPOIESIS

**Hematopoiesis** is the process in which blood cells are produced. This process occurs in a tissue called red marrow, which is found

inside some bones, including the pelvis, ribs, and vertebrae. Red marrow synthesizes red blood cells, white blood cells, and platelets. Billions of these blood cells are produced inside the bones every day.

### MINERAL STORAGE AND HOMEOSTASIS

Another function of the skeletal system is storing minerals, especially calcium and phosphorus. This storage function is related to the role of bones in maintaining mineral homeostasis. Just the right levels of calcium and other minerals are needed in the blood for the normal functioning of the body. When mineral levels in the blood are too high, bones absorb some of the minerals and store them as mineral salts, which is why bones are so hard. When blood levels of minerals are too low, bones release some of the minerals back into the blood. Bone minerals are alkaline (basic), so their release into the blood buffers the blood against excessive acidity (low pH), whereas their absorption back into bones buffers the blood against excessive alkalinity (high pH). In this way, bones help maintain acid-base homeostasis in the blood.

Another way bones help to maintain homeostasis is by acting as an endocrine organ. One endocrine hormone secreted by bone cells is **osteocalcin,** which helps regulate blood glucose and fat deposition. It increases insulin secretion and also the sensitivity of cells to insulin. In addition, it boosts the number of insulin-producing cells and reduces fat stores.

## REVIEW

1. What is the skeletal system? How many bones are there in the adult skeleton?
2. Describe the composition of bones.
3. Besides bones, what other organs are included in the skeletal system?
4. Identify the two major divisions of the skeleton.
5. List several functions of the skeletal system.
6. Discuss sexual dimorphism in the human skeleton.
7. Bones, cartilage, and ligaments are all made of types of _____ tissue.
8. *True or False.* Bones contain living tissue and can affect processes in other parts of the body.
9. *True or False.* Bone cells contract to pull on muscles in order to initiate a movement.
10. If a person has a problem with blood cell production, what type of bone tissue is most likely involved? Explain your answer.
11. Are the pelvic girdles part of the axial or appendicular skeleton?
12. What are three forms of homeostasis that the skeletal system regulates? Briefly explain how each one is regulated by the skeletal system.
13. What do you think would happen to us if we did not have ligaments? Explain your answer.
14. a. Define a joint in the skeletal system.

    b. How is cartilage related to joints?

    c. Identify one joint in the human body and describe its function.

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# 5.3: DIVISIONS OF THE SKELETAL SYSTEM

## SKULLS ON DISPLAY

This somewhat macabre display can be viewed at the Slovak National Museum in Bratislava, Slovakia. The skulls are meant to represent normal human skeletal anatomy. The skull is part of the axial skeleton, which is one of the two major divisions of the human skeleton. The other division is the appendicular skeleton.



Figure **5.3.1**: Skulls on Display

## AXIAL SKELETON

The **axial skeleton,** shown in blue in Figure **5.3.2**, consists of a total of 80 bones. Besides the skull, it includes the rib cage and vertebral column. It also includes the three tiny ossicles (hammer, anvil, and stirrup) in the middle ear and the hyoid bone in the throat, to which the tongue and some other soft tissues are attached.

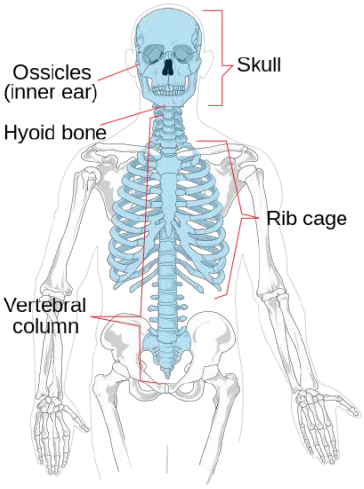



Figure **5.3.2**: The bones of the axial skeleton are shown here in blue.

### SKULL

The **skull** is the part of the human skeleton that provides a bony framework for the head. It consists of 22 different bones. There are 8 bones in the cranium, which encloses the brain, and 14 bones in the face.

#### *CRANIUM*

The **cranium,** sometimes called the braincase, forms the entire upper portion of the skull. As shown in Figure **5.3.3**, it consists of eight bones: one frontal bone, two parietal bones, two temporal bones, one occipital bone, one sphenoid bone, and one ethmoid bone. The ethmoid bone separates the nasal cavity from the brain. The sphenoid bone is one of several bones, including the frontal bone, that helps form the eye sockets. The other bones of the cranium are large and plate-like. They cover and protect the brain. The bottom of the skull has openings for major blood vessels and nerves. A large opening, called the foramen magnum, allows the spinal cord and brain to connect.

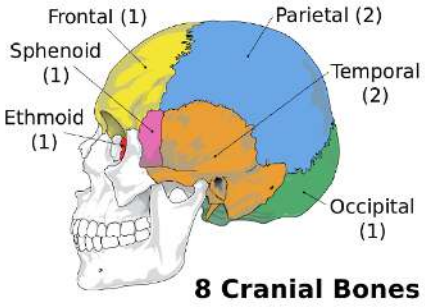



Figure **5.3.3**: The cranium consists of eight bones that are fused together at their joints.

#### *FACIAL BONES*

The 14 facial bones of the skull are located below the frontal bone of the cranium. They are depicted in Figure **5.3.4**. Large bones in the face include the upper jawbones, or **maxillae (singular, maxilla),** which form the middle part of the face and the bottom of the two eye sockets. The maxillae are fused together except for an opening between them for the nose. The lower edge of the maxillae contains sockets for the upper teeth. The lower jaw bone, or **mandible,** is also large. The top edge of the mandible contains sockets for the lower teeth. The mandible opens and closes to chew food and is controlled by strong muscles. There are two zygomatic or cheekbones and two nasal bones. The nasal region also contains seven smaller bones, as indicated in the figure.

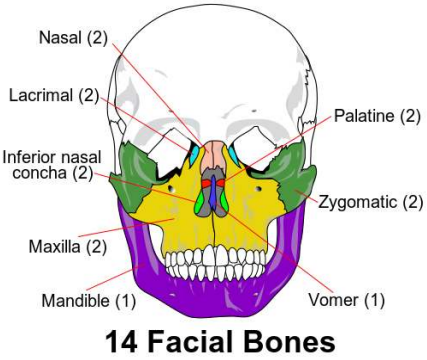



Figure **5.3.4**: The 14 bones that make up the face are labeled in this drawing of the skull.

### VERTEBRAL COLUMN

The **vertebral column,** also called the spine or backbone, is the flexible column of **vertebrae (singular, vertebra)** that connects the trunk with the skull and encloses the spinal cord. It consists of 33 vertebrae that are divided into five regions, as shown in Figure **5.3.5**: the cervical, thoracic, lumbar, sacral, and coccygeal regions. From

the neck down, the first 24 vertebrae (cervical, thoracic, and lumbar) are individual bones. The five sacral vertebrae are fused together, as are the four coccygeal vertebrae.

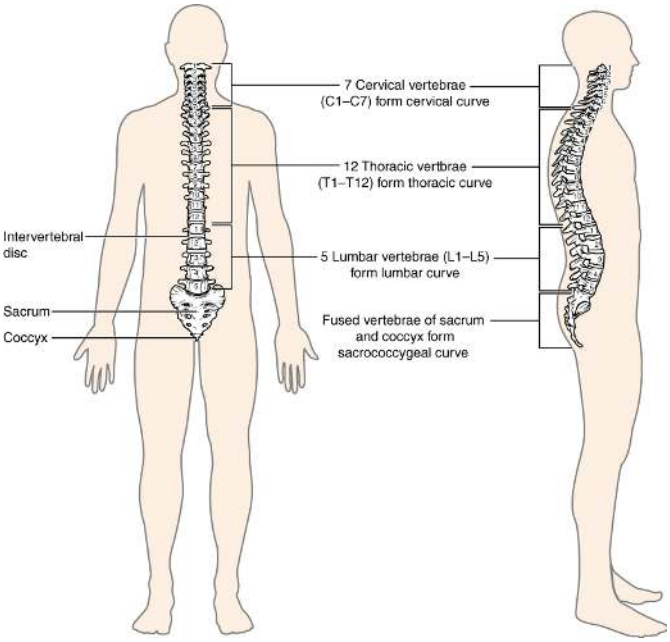



Figure **5.3.5**: The vertebral column consists of 24 individual vertebrae that are separated by intervertebral discs of cartilage. An additional 9 vertebrae are fused together at the base of the spine. Note the S-shaped curve of the vertebral column in the profile view on the right.

The human vertebral column reflects adaptations for upright bipedal locomotion. For example, the vertebral column is less like a rigid column than an S-shaped spring (see a profile view in the figure above). Although newborn infants have a relatively straight spine, the curves develop as the backbone starts taking on its support functions, such as keeping the trunk erect, holding up the head, and helping to anchor the limbs. The S shape of the vertebral column allows it to act as a shock absorber, absorbing much of the jarring of walking and running so the forces are not transmitted directly from the pelvis to the skull. The S shape also helps protect the spine from breaking, which would be more likely with a straight, more rigid vertebral column. In addition, the S shape helps to distribute the weight of the body, and particularly of the internal organs, so the weight load is not all at the bottom, as would occur with a straight spine.

### RIB CAGE

The **rib cage** (also called thoracic cage) is aptly named because it forms a sort of cage that holds within it the organs of the upper part of the trunk, including the heart and lungs (Figure **5.3.6**). The rib cage includes the 12 thoracic vertebrae and the breastbone (or sternum) as well as 12 pairs of ribs, which are attached at joints to the vertebrae. The ribs are divided into three groups, called true ribs, false ribs, and floating ribs. The top seven pairs of ribs are true ribs. They are attached by cartilage directly to the sternum. The next three pairs of ribs are false ribs. They are attached by cartilage to the ribs above them, rather than directly to the sternum. The lowest two pairs of ribs are floating ribs. They are attached by cartilage to muscles in the abdominal wall. The attachments of false and floating ribs let the lower part of the rib cage expand to accommodate the internal movements of breathing.

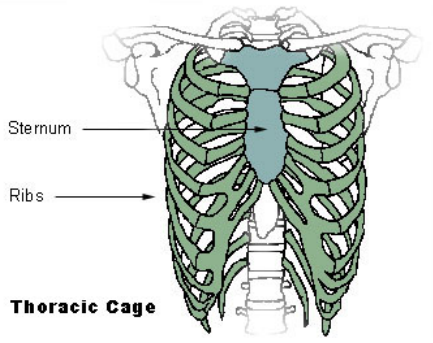



Figure **5.3.6**: The rib cage encloses and protects the thoracic cavity

## APPENDICULAR SKELETON

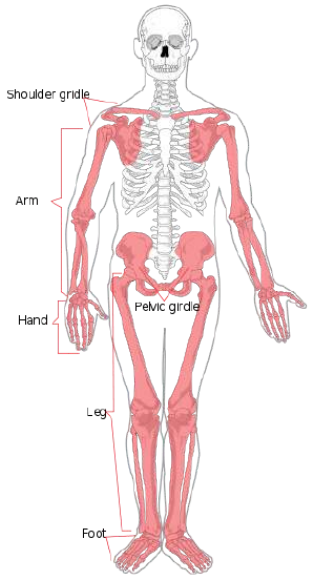



Figure **5.3.7**. The appendicular skeleton (in red) includes the upper and lower appendages and girdles.

The appendicular skeleton, shown in red in Figure **5.3.7**, consists of a total of 126 bones. It includes all the bones of the limbs (arms, legs, hands, and feet) as well as the bones of the shoulder (shoulder girdle) and pelvis (pelvic girdle).

### UPPER LIMBS

Each upper limb consists of 30 bones. As shown in Figure **5.3.8**, there is one bone, called the humerus, in each of the upper arms, and there are two bones, called the ulna and radius, in each of the lower arms.

The remaining bones of the upper limb are shown in Figure **5.3.9**. Each wrist contains eight carpal bones, which are arranged in two rows of four bones each; and each hand contains five metacarpal bones. The bones in the fingers of each hand include 14 phalanges (three in each finger except the thumb, which has two phalanges). The thumb has the unique ability to move into opposition with the palm of the hand and with each of the fingers when they are slightly

bent. This allows the hand to handle and manipulate objects such as tools.

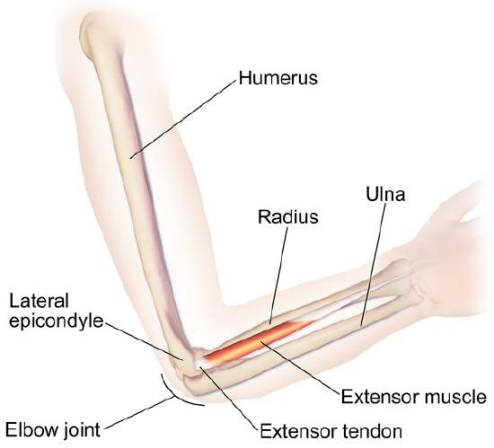



Figure **5.3.8**: In the upper limb, the upper arm contains one bone, Humerus, and the lower arm contains two bone, Ulna and Radius.

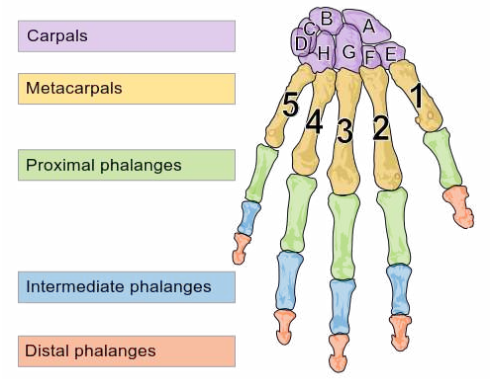



Figure **5.3.9**: Bones of the wrist (carpals A-E) and hand (metacarpals 1-5 and phalanges).

## LOWER LIMBS

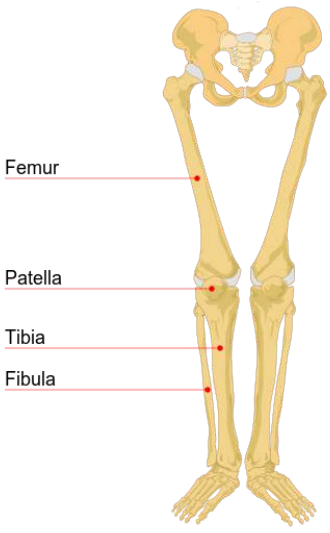



Figure **5.3.10**: Bones of the legs.

Each lower limb consists of 30 bones. As shown in Figure **5.3.10**, there is one bone, called the femur, in each of the upper legs, and there are two bones, called the tibia and fibula, in each of the lower legs. The knee cap, or patella, is an additional leg bone at the front of each knee, which is the largest joint in the human body.

The remaining bones of the lower limbs are shown in Figure **5.3.11**. Each ankle contains seven tarsal bones (including the talus and calcaneus), and each foot contains five metatarsal bones. The tarsals and metatarsals form the ankle, heel, and arch of the foot. They give the foot strength while allowing flexibility. The bones in the toes of each foot consist of 14 phalanges (three in each toe except the big toe, which has two phalanges)




Figure **5.3.11**: Bones of the lower leg (fibula and tibia), ankle (talus), heel (calcaneus), foot (metatarsals), and toes (phalanges).

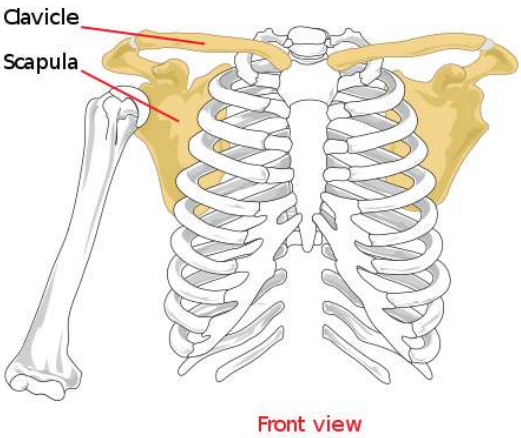



Figure **5.3.12**: Bones of the shoulder girdle are clavicle and scapula.

The pectoral girdle (also called shoulder girdle) attaches the upper limbs to the trunk of the body. Its connection with the axial skeleton is by muscles alone. This allows a considerable range of motion in the upper limbs. The shoulder girdle consists of just two pairs of bones, with one of each pair on opposite sides of the body (Figure **5.3.12**). There is a right and left clavicles (collarbone) and right and left scapulae (shoulder blade). The scapula is a pear-shaped flat bone that helps to form the shoulder joint. The clavicle is a long bone that serves as a strut between the shoulder blade and the sternum.

## PELVIC GIRDLE

The **pelvic girdle** attaches the legs to the trunk of the body and also provides a basin to contain and support the organs of the abdomen. It is connected to the vertebral column of the axial skeleton by ligaments. The pelvic girdle consists of two halves, one half for each leg, but the halves are fused with each other in adults at a joint called the pubic symphysis. Each half of the pelvic girdle includes three bones, as shown in the figure below: the ilium (flaring upper part of the pelvic girdle), pubis (lower front), and ischium (lower back). Each of these bones helps form the acetabulum, which is a depression into which the top of the femur (thigh bone) fits. When the body is in a seated position, it rests on protrusions (called tuberosities) of the two ischial bones.

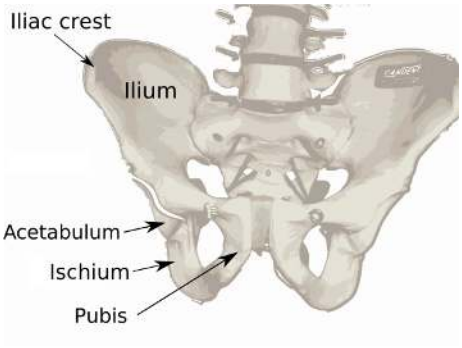



Figure **5.3.13**: Bones of the pelvic girdle.

## REVIEW

1. What bones are included in the axial skeleton?
2. Identify the two main parts of the skull. How many bones does each part contain?
3. Describe the vertebral column.
4. What are the advantages of an S-shaped vertebral column?
5. What is the rib cage, and what is its function?
6. What bones are included in the appendicular skeleton?
7. How many bones are found in each upper limb? What are they?
8. Identify the bones in each of the lower limbs.
9. What is the shoulder girdle, and why does it allow considerable upper limb mobility?
10. Describe the pelvic girdle and the bones it contains.
11. *True or False.* False ribs are made of cartilage and are not true rib bones.
12. *True or False.* The jaw contains two maxillae and one mandible.
13. Describe some of the similarities between the upper limbs and the lower limbs.
14. Explain the advantage of having some ribs that are not attached directly to the sternum.
15. Put the following vertebral regions in order, from the closest to the head to the farthest from the head:

    sacral; lumbar; cervical; coccygeal; thoracic

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# 5.4: STRUCTURE OF BONE

## ROASTED BONE MARROW

Do you recognize the food item in the top left of this photo in Figure **5.4.1**? It's roasted bone marrow, still inside the bones. It's considered a delicacy in some cuisines. Marrow is a type of tissue found inside many animal bones, including our own. It's a soft tissue that in adults may be mostly fat. You'll learn more about bone marrow and other tissues that make up bones when you read this concept.



Figure **5.4.1**:Roasted Bone Marrow

Bones are organs that consist primarily of bone tissue, also called osseous tissue. **Bone tissue** is a type of connective tissue consisting mainly of a collagen matrix that is mineralized with calcium and phosphorus crystals. The combination of flexible collagen and hard mineral crystals makes bone tissue hard without making it brittle.

## BONE ANATOMY

There are several different types of tissues in bones, including two types of osseous tissues.

### TYPES OF OSSEOUS TISSUE

The two different types of osseous tissue are compact bone tissue (also called hard or cortical bone) tissue and spongy bone tissue (also called cancellous or trabecular bone).

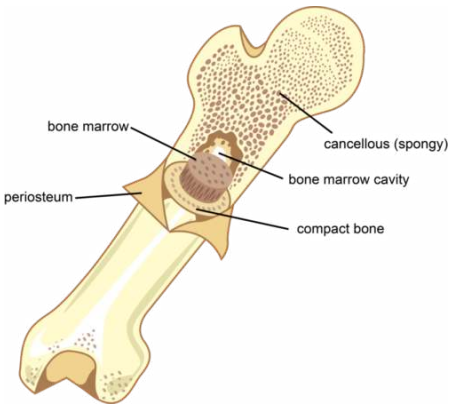



Figure **5.4.2**: Bones are more complex on the inside than you would expect from their outer appearance. There is bone marrow in the hollow part of the long bone. The outer boundary of bone is composed of compact bone tissue, and from the ends, and the rest of the bone interior is composed of cancellous or spongy bone tissue. The bone is covered in connecting tissue called the periosteum.

**Compact bone tissue** forms the extremely hard outside layer of bones. Cortical bone tissue gives bone its smooth, dense, solid appearance. It accounts for about 80 percent of the total bone mass of the adult skeleton. **Spongy bone tissue** fills part or all of the interior of many bones. As its name suggests, spongy bone is porous like a sponge, containing an irregular network of spaces. This makes spongy bone much less dense than compact bone. Spongy bone has a greater surface area than cortical bone but makes up only 20 percent of bone mass.

Both compact and spongy bone tissues have the same types of cells, but they differ in how the cells are arranged. The cells in the compact bone are arranged in multiple microscopic columns, whereas the cells in the spongy bone are arranged in a looser, more open network. These cellular differences explain why cortical and spongy bone tissues have such different structures.

### OTHER TISSUES IN BONES

Besides cortical and spongy bone tissues, bones contain several other tissues, including blood vessels and nerves. In addition, bones contain bone marrow and periosteum. You can see these tissues in Figure **5.4.2**.

- **Bone marrow** is a soft connective tissue that is found inside a cavity, called the marrow cavity. There are two types of marrow in adults, yellow bone marrow, which consists mostly of fat, and red bone marrow. All marrow is red in newborns, but by adulthood, much of the red marrow has changed to yellow marrow. In adults, red marrow is found mainly in the femur, ribs, vertebrae, and pelvic bones. Red bone marrow contains hematopoietic stem cells that give rise to red blood cells, white blood cells, and platelets in the process of hematopoiesis.
- **Periosteum** is a tough, fibrous membrane that covers the outer surface of bones. It provides a protective covering for cortical bone tissue. It is also the source of new bone cells.

### BONE CELLS

As shown in Figure **5.4.3**, bone tissues are composed of four different types of bone cells: osteoblasts, osteocytes, osteoclasts, and osteogenic cells.

- **Osteoblasts** are bone cells with a single nucleus that make and mineralize bone matrix. They make a protein mixture that is composed primarily of collagen and creates the organic part of the matrix. They also release calcium and phosphate ions that form mineral crystals within the matrix. In addition, they produce hormones that also play a role in the mineralization of the matrix.
- **Osteocytes** are mainly inactive bone cells that form from osteoblasts that have become entrapped within their own bone matrix. Osteocytes help regulate the formation and breakdown of bone tissue. They have multiple cell projections that are thought to be involved in communication with other bone cells.
- **Osteoclasts** are bone cells with multiple nuclei that resorb bone tissue and break down bone. They dissolve the minerals in bone and release them into the blood.

- **Osteogenic cells** are undifferentiated stem cells. They are the only bone cells that can divide. When they do, they differentiate and develop into osteoblasts.

Bone is a very active tissue. It is constantly remodeled by the work of osteoblasts and osteoclasts. Osteoblasts continuously make new bone, and osteoclasts keep breaking down bone. This allows for minor repair of bones as well as homeostasis of mineral ions in the blood.

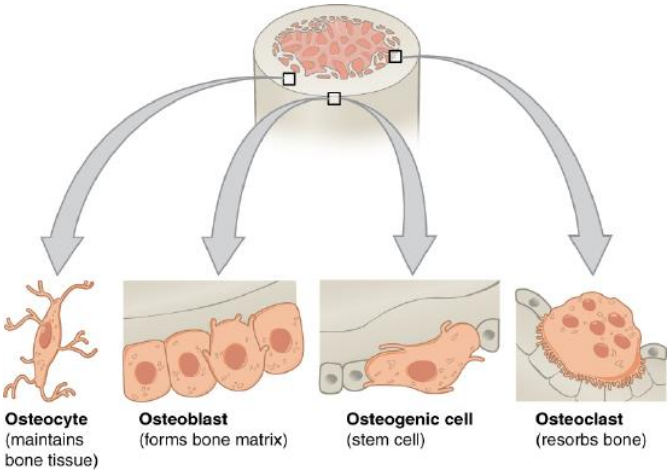



Figure **5.4.3**: Different types of bones cells have different functions.

## MICROSCOPIC ANATOMY OF THE COMPACT BONE

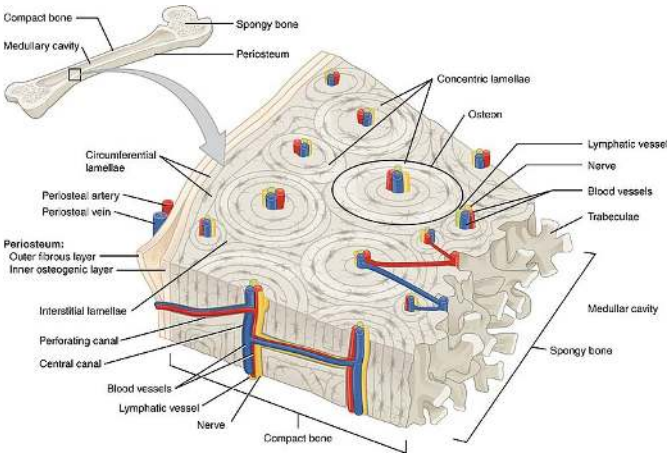



Figure **5.4.4**: Macroscopic and microscopic structures of the compact bone tissue.

The basic microscopic unit of bone is an osteon (or Haversian system). Osteons are roughly cylindrical structures that can measure several millimeters long and around 0.2 mm in diameter. Each osteon consists of lamellae of compact bone tissue that surround a central canal (Haversian canal). The Haversian canal contains the bone's blood supplies. The boundary of an osteon is called the cement line. Osteons can be arranged into woven bone or lamellar bone. Osteoblasts make the matrix of bone which calcifies hardens. This entraps the mature bone cells, osteocytes, in a little chamber called lacunae. The osteocytes receive their nutrition from the central (Haversian) canal via little canals called canaliculi. All of these structures plus more are visible in Figure **5.4.4**.

## TYPES OF BONES

There are six types of bones in the human body based on their shape or location: long, short, flat, sesamoid, sutural, and irregular bones. You can see an example of each type of bone in Figure **5.4.5**.

- Long bones are characterized by a shaft that is much longer than it is wide and by a rounded head at each end of the shaft. Long bones are made mostly of compact bone, with lesser amounts of spongy bone and marrow. Most bones of the limbs, including those of the fingers and toes, are long bones.
- Short bones are roughly cube-shaped and have only a thin layer of cortical bone surrounding a spongy bone interior. The bones of the wrists and ankles are short bones.
- Flat bones are thin and generally curved, with two parallel layers of compact bone sandwiching a layer of spongy bone. Most of the bones of the skull are flat bones, as is the sternum (breast bone).
- Sesamoid bones are embedded in tendons, the connective tissues that bind muscles to bones. Sesamoid bones hold tendons farther away from joints so the angle of the tendons is increased, thus increasing the leverage of muscles. The patella (knee cap) is an example of a sesamoid bone.
- Sutural bones are very small bones that are located between the major bones of the skull, within the joints (sutures) between the larger bones. They are not always present.
- Irregular bones are those that do not fit into any of the above categories. They generally consist of thin layers of cortical bone surrounding a spongy bone interior. Their shapes are irregular and complicated. Examples of irregular bones include the vertebrae and the bones of the pelvis.

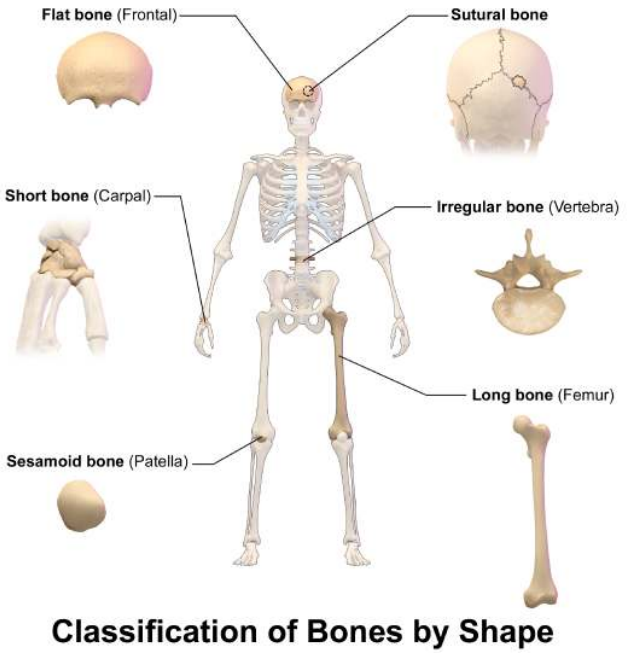



Figure **5.4.5**: six types of bones classified by shape or location.

## FEATURE: RELIABLE SOURCES

Diseased or damaged bone marrow can be replaced by donated bone marrow cells, which help treat and often cure many life-threatening conditions, including leukemia, lymphoma, sickle cell anemia, and thalassemia. If a bone marrow transplant is successful, the new bone marrow will start making healthy blood cells and improve the patient's condition.

Learn more about bone marrow donation, and consider whether you might want to do it yourself. Find reliable sources to answer the following questions:

1. How does one become a potential bone marrow donor?
2. Who can and who cannot donate bone marrow?
3. How is a bone marrow donation made?
4. What risks are there in donating bone marrow?

## REVIEW

1. Describe osseous tissue.
2. Why are bones hard but not brittle?
3. Compare and contrast the two main types of osseous tissue.
4. What non-osseous tissues are found in bones?
5. List four types of bone cells and their functions.
6. Identify six types of bones, and give an example of each type.
7. *True or False.* Spongy bone tissue is another name for bone marrow.
8. *True or False.* Periosteum covers osseous tissue.
9. Compare and contrast yellow bone marrow and red bone marrow.
10. Which bone is mostly made of cortical bone tissue?

    A. Pelvis

    B. Vertebrae

    C. Femur

    D. Carpal
11. a. Which type of bone cell divides to produce new bone cells?

    b. Where is this cell type located?
12. Where do osteoblasts and osteocytes come from, and how are they related to each other?
13. Which type of bone is embedded in tendons?
14. *True or False.* Calcium is the only mineral in bones.

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# 5.5: BONE GROWTH, REMODELING, AND REPAIR

## BREAK A LEG

Did you ever break a leg or other bone, like the man looking longingly at the water in this swimming pool? Having a broken bone can really restrict your activity. Bones are very hard, but they will break, or fracture if enough force is applied to them. Fortunately, bones are highly active organs that can repair themselves if they break. Bones can also remodel themselves and grow. You'll learn how bones can do all of these things in this concept.



Figure 5.5.1: Broken leg

## BONE GROWTH

Early in the development of a human fetus, the skeleton is made almost entirely of cartilage. The relatively soft cartilage gradually turns into hard bone through ossification. **Ossification** is a process in which bone tissue is created from cartilage. The steps in which bones of the skeleton form from cartilage are illustrated in Figure 5.5.2. The steps include the following:

1. Cartilage "model" of bone forms; this model continues to grow as ossification takes place.
2. Ossification begins at a primary ossification center in the middle of the bone.
3. Ossification then starts to occur at secondary ossification centers at the ends of the bone.
4. The medullary cavity forms and will contain red bone marrow.
5. Areas of ossification meet at epiphyseal plates, and articular cartilage forms. Bone growth ends.

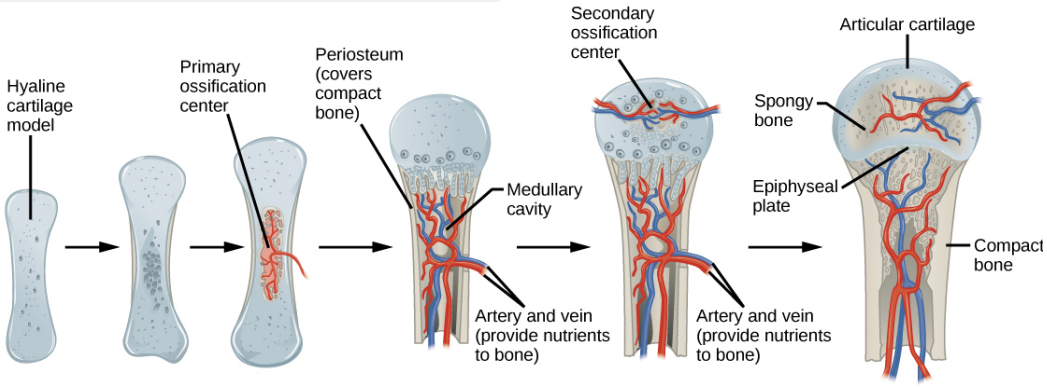



Figure 5.5.2: The ossification of cartilage in the human skeleton is a process that lasts throughout childhood in some bones.

### PRIMARY AND SECONDARY OSSIFICATION CENTERS

When bone forms from cartilage, ossification begins with a point in the cartilage called the primary ossification center. This generally appears during fetal development, although a few short bones begin their primary ossification after birth. Ossification occurs toward both ends of the bone from the primary ossification center, and it eventually forms the shaft of the bone in the case of long bones.

Secondary ossification centers form after birth. Ossification from secondary centers eventually forms the ends of the bones. The shaft and ends of the bone are separated by a growing zone of cartilage until the individual reaches skeletal maturity.

### SKELETAL MATURITY

Throughout childhood, the cartilage remaining in the skeleton keeps growing and allows for bones to grow in size. However, once all of the cartilage has been replaced by bone and fusion has taken place at epiphyseal plates, bones can no longer keep growing in length. This is the point at which skeletal maturity has been reached. It generally takes place by age 18 to 25.

The use of anabolic steroids by teens can speed up the process of skeletal maturity, resulting in a shorter period of cartilage growth before fusion takes place. This means that teens who use steroids are likely to end up shorter as adults than they would otherwise have been.

## BONE REMODELING

Even after skeletal maturity has been attained, bone is constantly being resorbed and replaced with new bone in a process known as **bone remodeling**. In this lifelong process, mature bone tissue is continually turned over, with about 10 percent of the skeletal mass of an adult being remodeled each year. Bone remodeling is carried

out through the work of osteoclasts, which are bone cells that resorb bone and dissolve its minerals; and osteoblasts, which are bone cells that make the new bone matrix.

Bones remodeling serves several functions. It shapes the bones of the skeleton as a child grows, and it repairs tiny flaws in the bone that result from everyday movements. Remodeling also makes bones thicker at points where muscles place the most stress on them. In addition, remodeling helps regulate mineral homeostasis because it either releases minerals from bones into the blood or absorbs minerals from the blood into bones. The figure below shows how osteoclasts in bones are involved in calcium regulation.

The action of osteoblasts and osteoclasts in bone remodeling and calcium homeostasis is controlled by a number of enzymes, hormones, and other substances that either promote or inhibit the activity of the cells. In this way, these substances control the rate at which bone is made, destroyed, and changed in shape. For example, the rate at which osteoclasts resorb bone and release calcium into the blood is promoted by parathyroid hormone (PTH) and inhibited by calcitonin, which is produced by the thyroid gland (Figure **5.5.3**). The rate at which osteoblasts create new bone is stimulated by growth hormone, which is produced by the anterior lobe of the pituitary gland. Thyroid hormone and sex hormones (estrogens and androgens) also stimulate osteoblasts to create new bone.

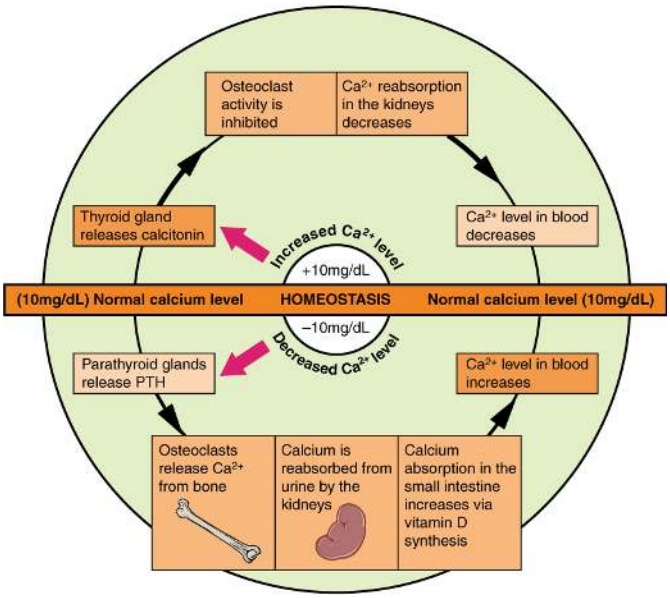



Figure **5.5.3**: Keeping the calcium level in homeostasis includes the work of osteoclasts, the bone cells that resorb bone and release calcium into the blood. If calcium levels increase, the thyroid releases calcitonin which inhibits osteoclast activity. This results in less calcium be reabsorbed in the kidneys which results in the lowering of calcium in the blood. If calcium levels decrease below homeostasis, the parathyroid gland releases PTH. This causes osteoclasts to release calcium from bones and increases calcium absorption in the kidney and small intestines. This brings calcium back to homeostasis.

## BONE REPAIR

**Bone repair**, or healing, is the process in which a bone repairs itself following a bone fracture. You can see an X-ray of bone fracture in Figure **5.5.4**. In this fracture, the humerus in the upper arm has been completely broken through its shaft. Before this fracture heals, a physician must push the displaced bone parts back into their correct positions. Then the bone must be stabilized — for example, with a cast and/or pins surgically inserted into the bone — until the bone's natural healing process is completed. This process may take several weeks.

The process of bone repair is mainly determined by the periosteum, which is the connective tissue membrane covering the bone. The periosteum is the primary source of precursor cells that develop into osteoblasts, which are essential to the healing process. Bones heal as osteoblasts form new bone tissue.

Although bone repair is a natural physiological process, it may be promoted or inhibited by several factors. For example, fracture repair is likely to be more successful with adequate nutrient intake. Age, bone type, drug therapy, and pre-existing bone disease are additional factors that may affect healing. Bones that are weakened by diseases, such as osteoporosis or bone cancer, are not only likely to heal more slowly but are also more likely to fracture in the first place.



Figure **5.5.4**: A bone fracture does not always involve a complete break in the bone, as in this X-ray. Sometimes a fracture is just a crack in the bone. In other cases, the bone not only breaks all the way through, as here but also breaks through the soft tissues around it so it protrudes from the skin. This is called an open fracture.

### FEATURE: MYTH VS. REALITY

Bone fractures are fairly common, and there are many myths about them. Knowing the facts is important because fractures generally require emergency medical treatment.

**Myth:** A bone fracture is a milder injury than a broken bone.

**Reality:** A bone fracture is the same thing as a broken bone.

**Myth:** If you still have a full range of motion in a limb, then it must not be fractured.

**Reality:** Even if a bone is fractured, the muscles and tendons attached to it may still be able to move the bone normally. This

is especially likely if the bone is cracked but not broken into two pieces. Even if a bone is broken all the way through, the range of motion may not be much affected if the bones on either side of the fracture remain properly aligned.

**Myth:** A fracture always produces a bruise.

**Reality:** Many but not all fractures produce a bruise. If a fracture does produce a bruise, it may take several hours or even a day or more for the bruise to appear.

**Myth:** Fractures are so painful that you will immediately know if you break a bone.

**Reality:** Ligament sprains and muscle strains are also very painful, sometimes more painful than fractures. Additionally, every person has a different pain tolerance. People with high pain tolerance may continue using a broken bone in spite of the pain.

**Myth:** You can tell when a bone is fractured because there will be very localized pain over the break.

**Reality:** A broken bone is often accompanied by injuries to surrounding muscles or ligaments. As a result, the pain may extend far beyond the location of the fracture. The pain may be greater directly over the fracture, but the intensity of the pain may make it difficult to pinpoint exactly where the pain originates.

## REVIEW

1. Outline how bone develops from early in the fetal stage through the age of skeletal maturity.
2. Describe the process of bone remodeling. When does it occur?
3. What purposes does bone remodeling serve?
4. Define bone repair. How long does this process take?
5. Explain how bone repair occurs.
6. Identify factors that may affect bone repair.
7. Parts of bone that have not yet become ossified are made of _____.
8. If there is a large region between the primary and secondary ossification centers in a bone, is the person young or old? Explain your answer.
9. The region where the primary and secondary ossification centers meet is called the _____.
10. *True or False.* Most bones are made entirely of cartilage at birth.
11. *True or False.* A broken bone is the same as a bone fracture.
12. If bones can repair themselves, why are casts and pins sometimes needed?
13. Which bone cell type causes the release of calcium to the bloodstream when calcium levels are low?
14. Which tissue and bone cell type are mainly involved in bone repair after a fracture?
15. Describe one way in which hormones are involved in bone remodeling.

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# 5.6: JOINTS

## DOUBLE JOINTED?

Is this person double jointed? No; there is no such thing, at least as far as humans are concerned. However, some people, like the individual pictured here, are much more flexible than others, generally because they have looser ligaments. Physicians call the condition joint hypermobility. Regardless of what it's called, the feats of people with highly mobile joints can be quite impressive.



Figure **5.6.1**: Yoga

## WHAT ARE JOINTS?

**Joints** are locations at which bones of the skeleton connect with one another. A joint is also called an articulation. The majority of joints are structured in such a way that they allow movement. However, not all joints allow movement. Of joints that do allow movement, the extent, and direction of the movements they allow also vary.

## CLASSIFICATION OF JOINTS

Joints can be classified as structurally or functionally. The structural classification of joints depends on the manner in which the bones connect to each other. The functional classification of joints depends on the nature of the movement the joints allow. There is significant overlap between the two types of classifications because function depends largely on the structure.

### STRUCTURAL CLASSIFICATION OF JOINTS

The structural classification of joints is based on the type of tissue that binds the bones to each other at the joint. There are three types of joints in the structural classification: fibrous, cartilaginous, and synovial joints.

1. **Fibrous joints** are joints in which bones are joined by dense connective tissue that is rich in collagen fibers. These joints are also called sutures. The joints between bones of the cranium are fibrous joints.
2. **Cartilaginous joints** are joints in which bones are joined by cartilage. The joints between most of the vertebrae in the spine are cartilaginous joints.
3. **Synovial joints** are characterized by a fluid-filled space, called a synovial cavity, between the bones of the joints. You can see a drawing of a typical synovial joint in Figure **5.6.2**. The cavity is enclosed by a membrane and filled with a fluid, called the synovial fluid, which provides extra cushioning to the ends of the bones. Cartilage covers the articulating surfaces of the two bones, but the bones are actually held together by ligaments. The knee is a synovial joint.

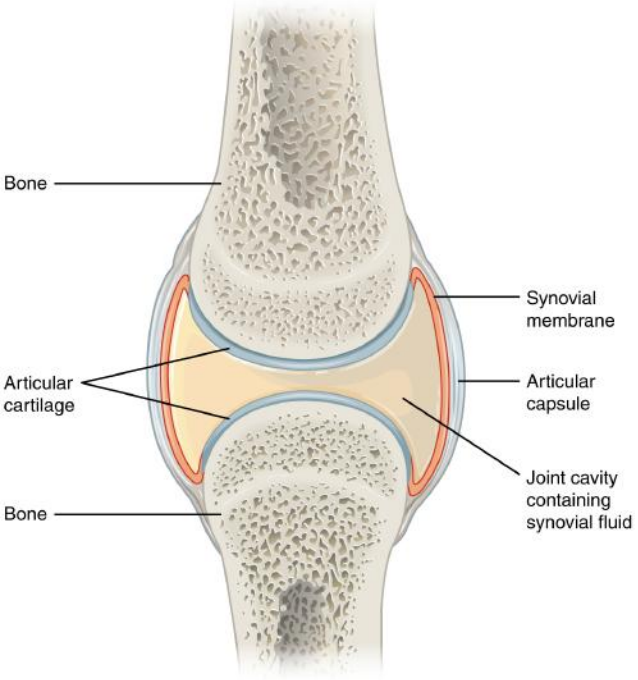



Figure **5.6.2**: The synovial membrane, articular capsule, joint cavity with synovial fluid, articular cartilage, and bone ends are the main components of a typical synovial joint.

### FUNCTIONAL CLASSIFICATION OF JOINTS

The functional classification of joints is based on the type and degree of movement that they allow. There are three types of joints in the functional classification: immovable, partly movable, and movable joints.

1. Immovable joints allow little or no movement at the joint. Most immovable joints are fibrous joints. Besides the bones of the cranium, immovable joints include joints between the tibia and fibula in the lower leg and between the radius and ulna in the lower arm.
2. Partly movable joints permit slight movement. Most partly movable joints are cartilaginous joints. Besides the joints between vertebrae, they include the joints between the ribs and sternum (breast bone).
3. Movable joints allow bones to move freely. All movable joints are synovial joints. Besides the knee, they include the shoulder, hip, and elbow. Movable joints are the most common type of joints in the body.

### TYPES OF MOVABLE JOINTS

Movable joints can be classified further according to the type of movement they allow. There are six classes of movable joints: pivot, hinge, saddle, plane, condyloid, and ball-and-socket joints. An example of each class, as well as the type of movement it allows, is shown in Figure **5.6.3**.

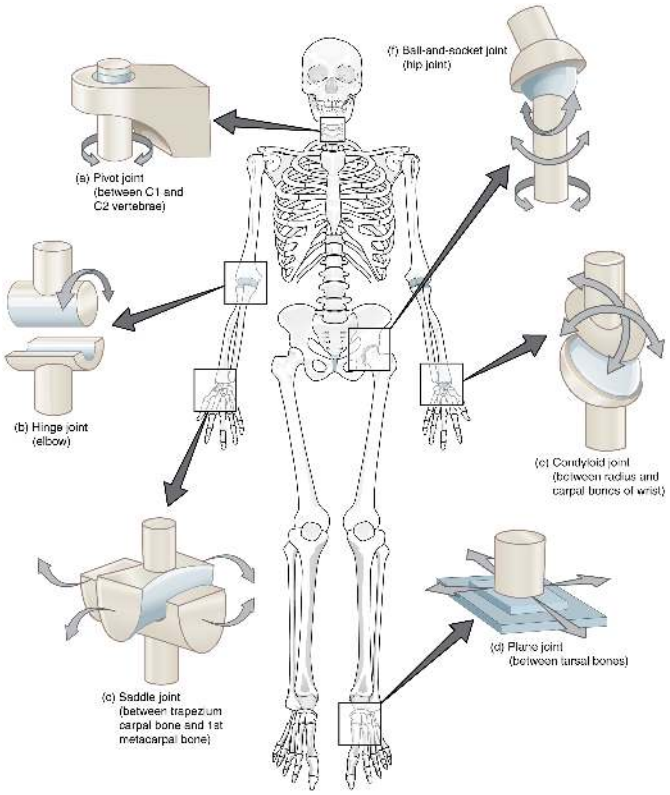



Figure **5.6.3**: This diagram shows the six classes of movable joints in the human body. All of these joints are synovial joints.

- A pivot joint allows one bone to rotate around another. An example of a pivot joint is the joint between the first two vertebrae in the spine. This joint allows the head to rotate from left to right and back again.
- A hinge joint allows back and forth movement like the hinge of a door. An example of a hinge joint is the elbow. This joint allows the arm to bend back and forth.
- A saddle joint allows two different types of movement. An example of a saddle joint is the joint between the first metacarpal bone in the hand and one of the carpal bones in the wrist. This joint allows the thumb to move toward and away from the index finger and also to cross over the palm toward the little finger.
- A plane joint also called a gliding joint, allows two bones that glide over one another. The joints between the tarsals in the ankles and between the carpals in the wrists are mainly gliding joints. In the wrist, this type of joint allows the hand to bend upward at the wrist and also to wave from side to side while the lower arm is held steady.
- A condyloid joint is one in which an oval-shaped head on one bone moves in an elliptical cavity in another bone, allowing movement in all directions except rotation around an axis. The joint between the radius in the lower arm and carpal bones of the wrist is a condyloid joint as is the joint at the base of the index finger.
- A ball-and-socket joint allows the greatest range of movement of any movable joint. It allows forward and backward as well as upward and downward motions. It also allows rotation in a circle. The hip and shoulder are the only two ball-and-socket joints in the human body.

## FEATURE: MY HUMAN BODY

Of all the parts of the skeletal system, the joints are generally the most fragile and subject to damage. If the cartilage that cushions bones at joints wears away, it does not grow back. Eventually, all of the cartilage may wear away. This is the cause of osteoarthritis, which can be both painful and debilitating. In serious cases, people may lose the ability to climb stairs, walk long distances, perform routine daily activities, or participate in activities they love such as gardening or playing sports. If you protect your joints, you can reduce your chances of joint damage, pain, and disability. If you already have joint damage, it is equally important to protect your joints and limit further damage. Follow these five tips:

1. Maintain a normal, healthy weight. The higher your weight is, the more force you exert on your joints. When you walk, each knee has to bear a force equal to as much as six times your body weight. If a person weighs 200 pounds, each knee bears more than half a ton of weight with every step. Seven in ten knee replacement surgeries for osteoarthritis can be attributed to obesity.
2. Avoid too much high-impact exercise. Examples of high-impact activities include volleyball, basketball, and tennis. These activities generally involve running or jumping on hard surfaces, which puts tremendous stress on weight-bearing joints, especially the knees. Replace some or all of your high-impact activities with low-impact activities, such as biking, swimming, yoga, or lifting light weights.
3. Reduce your risk of injury. Don't be a weekend warrior, sitting at a desk all week and then crowding all your physical activity into two days. Get involved in a regular, daily exercise routine that keeps your body fit and your muscles toned. Building up muscles will make your joints more stable and spread stress across them. Be sure to do some stretching every day to keep the muscles around joints flexible and less prone to injury.
4. Distribute work over your body, and use your largest, strongest joints. Use your shoulder, elbow, and wrist to lift heavy objects, not just your fingers. Hold small items in the palm of your hand, rather than by the fingers. Carry heavy items in a backpack rather than in your hands. Hold weighty objects close to your body rather than at arms' length. Lift with your hips and knees, not your back.
5. Respect pain. If it hurts, stop doing it. Take a break from the activity at least until the pain stops. Try to use joints only to the point of mild fatigue, not pain.

## REVIEW

1. What are the joints?
2. What are the two ways that joints are commonly classified?

3. How are joints classified structurally?
4. Describe the functional classification of joints.
5. How are movable joints classified?
6. Name the six classes of movable joints, and describe how they move.
7. Give an example of a joint in each of the classes of movable joints.
8. *True or False.* The skull is one smooth bone and has no joints.
9. *True or False.* A plane joint is a type of synovial joint.
10. Which specific type of moveable joint do you think your knee joint is? Explain your reasoning.
11. Explain the difference between cartilage in a cartilaginous joint and cartilage in a synovial joint.
12. Why are fibrous joints immovable?
13. Which type of joint has ligaments?

    A. Ball-and-socket
    B. Fibrous
    C. Cartilaginous
    D. None of the above

14. Which type of joint allows for the greatest range of motion?
15. What is the function of synovial fluid?

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# 5.7: DISORDERS OF THE SKELETAL SYSTEM

## DOWAGER'S HUMP

The individual on the right in Figure **5.7.1** has a deformity in her back commonly called dowager's hump because it occurs most often in elderly women. Its medical name is kyphosis, and it is defined as excessive curvature of the spinal column in the thoracic region. The curvature generally results from fractures of thoracic vertebrae. As the inset drawings suggest, these fractures may occur due to a significant decrease in bone mass, which is called osteoporosis. Osteoporosis is one of the most prevalent disorders of the skeletal system.



Figure **5.7.1**: Kyphosis

## COMMON SKELETAL SYSTEM DISORDERS

A number of disorders affect the skeletal system, including bone fractures and bone cancers. However, the two most common disorders of the skeletal system are osteoporosis and osteoarthritis. At least ten million people in the United States have osteoporosis, and more than 8 million of them are women. Osteoarthritis is even more common, affecting almost 30 million people in the United States. Because osteoporosis and osteoarthritis are so common, they are the focus of this concept. These two disorders are also good examples to illustrate the structure and function of the skeletal system.

## OSTEOPOROSIS

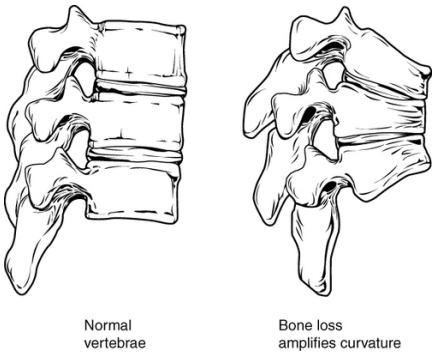



Figure **5.7.2**: Compression fractures of thoracic vertebrae are relatively common in people with osteoporosis.

**Osteoporosis** is an age-related disorder in which bones lose mass, weaken, and break more easily than normal bones. Bones may weaken so much that a fracture can occur with minor stress — or even spontaneously, without any stress at all. Osteoporosis is the most common cause of broken bones in the elderly, but until a bone fracture occurs, it typically causes no symptoms. The bones that break most often include those in the wrist, hip, shoulder, and spine. When the thoracic vertebrae are affected, there can be a gradual collapse of the vertebrae due to compression fractures, as shown in Figure **5.7.2**. This is what causes kyphosis, as pictured in Figure **5.7.1**.

### CHANGES IN BONE MASS WITH AGE

As shown in the graph below, bone mass in both males and females generally peaks when people are in their thirties. Bone mass usually decreases after that, and this tends to occur more rapidly in individuals with XX chromosomes, especially after menopause. This is generally attributable to low levels of estrogen in the post-menopausal years.

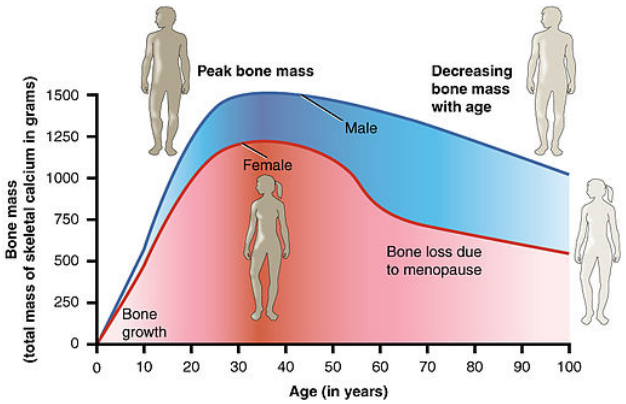



Figure **5.7.3**: Bone mass is a measure of the total mass of calcium in the bones of the skeleton. The chart shows that the bone mass peaks around age 30 in males and females. Then it starts to decrease.

### WHAT CAUSES OSTEOPOROSIS?

Osteoporosis is due to an imbalance between bone formation by osteoblasts and bone resorption by osteoclasts. Normally, bones are constantly being remodeled by these two processes, with up to ten percent of all bone mass undergoing remodeling at any point in time. If these two processes are in balance, no net loss of bone occurs. There are three main ways that an imbalance between bone formation and bone resorption can occur and lead to a net loss of bone.

1. **An individual never develops normal peak bone mass during the young adult years:** If the peak level is lower than normal, then there is less bone mass, to begin with, making osteoporosis more likely to develop.
2. **There is greater than normal bone resorption:** Bone resorption normally increases after peak bone mass is reached, but age-related bone resorption may be greater than normal for a variety of reasons. One possible reason is calcium or vitamin D

deficiency, which causes the parathyroid gland to release PTH, the hormone that promotes resorption by osteoclasts.

3. **There is the inadequate formation of new bone by osteoblasts during remodeling:** Lack of estrogen may decrease the normal deposition of new bone. Inadequate levels of calcium and vitamin D also lead to the impaired bone formation by osteoblasts.

An imbalance between bone building and bone destruction leading to bone loss may also occur as a side effect of other disorders. For example, people with alcoholism, anorexia nervosa, or hyperthyroidism have an increased rate of bone loss. Some medications — including anti-seizure medications, chemotherapy drugs, steroid medications, and some antidepressants — also increase the rate of bone loss.

## OSTEOPOROTIC FRACTURES

Fractures are the most dangerous aspect of osteoporosis, and osteoporosis is responsible for millions of fractures annually. Debilitating pain among the elderly is often caused by fractures from osteoporosis, and it can lead to further disability and early mortality. Fractures of the long bones (such as the femur) can impair mobility and may require surgery. A hip fracture usually requires immediate surgery, as well. The immobility associated with fractures — especially of the hip — increases the risk of deep vein thrombosis, pulmonary embolism, and pneumonia. Osteoporosis is rarely fatal, but these complications of fractures often are. Older people tend to have more falls than younger people, due to such factors as poor eyesight and balance problems, increasing their risk of fractures even more. The likelihood of falls can be reduced by removing obstacles and loose carpets or rugs in the living environment.

## RISK FACTORS FOR OSTEOPOROSIS

There are a number of factors that increase the risk of osteoporosis. Eleven of them are listed below. The first five factors cannot be controlled, but the remaining factors generally can be controlled by changing behaviors.

1. older age
2. XX chromosome
3. European or Asian ancestry
4. family history of osteoporosis
5. short stature and small bones
6. smoking
7. alcohol consumption
8. lack of exercise
9. vitamin D deficiency
10. poor nutrition
11. consumption of soft drinks

## TREATMENT AND PREVENTION OF OSTEOPOROSIS

Osteoporosis is often treated with medications that may slow or even reverse bone loss. Medications called bisphosphonates, for example, are commonly prescribed. Bisphosphonates slow down the breakdown of bone, allowing bone rebuilding during remodeling to keep pace. This helps maintain bone density and decreases the risk of fractures. The medications may be more effective in patients who have already broken bones than in those who have not, significantly reducing their risk of another fracture. Generally, patients are not recommended to stay on bisphosphonates for more than three or four years. There is no evidence for continued benefit after this time — in fact, there is a potential for adverse side effects.



Figure **5.7.4**: Hiking is an enjoyable way to help keep bones strong and reduce the risk of osteoporosis.

Preventing osteoporosis includes eliminating any risk factors that can be controlled through changes of behavior. If you smoke, stop. If you drink, reduce your alcohol consumption — or cut it out altogether. Eat a nutritious diet and make sure you are getting adequate amounts of vitamin D. You should also avoid drinking carbonated beverages.

If you're a couch potato, get involved in regular exercise. Aerobic, weight-bearing and resistance exercises can all help maintain or increase bone mineral density. Exercise puts stress on bones, which stimulates bone building. Good weight-bearing exercises for bone-building include weight training, dancing, stair climbing, running, and hiking (Figure **5.7.4**). Biking and swimming are less beneficial because they don't stress the bones. Ideally, you should exercise for at least 30 minutes a day on most days of the week.

## OSTEOARTHRITIS

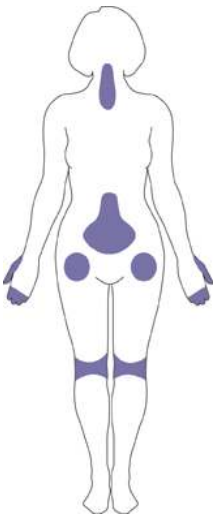


Figure **5.7.5**: The areas shaded in blue indicate the joints most commonly affected by OA.

**Osteoarthritis (OA)** is a joint disease that results from the breakdown of joint cartilage and bone. The most common symptoms are joint pain and stiffness. Other symptoms may include joint swelling and decreased range of motion. Initially, symptoms may

occur only after exercise or prolonged activity, but over time, they may become constant, negatively affecting work and normal daily activities. As shown in Figure 5.7.5, the most commonly involved joints are those near the ends of the fingers, at the bases of the thumbs, and in the neck, lower back, hips, and knees. Often, joints on one side of the body are affected more than those on the other side.

## WHAT CAUSES OSTEOARTHRITIS?

OA is thought to be caused by mechanical stress on the joints with insufficient self-repair of cartilage. The stress may be exacerbated by low-grade inflammation of the joints, as cells lining the joint attempt to remove breakdown products from cartilage in the synovial space. OA develops over decades as stress and inflammation cause an increasing loss of articular cartilage. Eventually, bones may have no cartilage to separate them, so bones rub against one another at joints. This damages the articular surfaces of the bones and contributes to the pain and other symptoms of OA. Because of the pain, movement may be curtailed, leading to loss of muscle, as well.

## DIAGNOSING OSTEOARTHRITIS

Diagnosis of OA is typically made on the basis of signs and symptoms. Signs include joint deformities, such as bony nodules on the finger joints or bunions on the feet (Figure 5.7.6). Symptoms include joint pain and stiffness. The pain is usually described as a sharp ache or burning sensation, which may be in the muscles and tendons around the affected joints, as well as in the joints themselves. The pain is usually made worse by prolonged activity, and it typically improves with rest. Stiffness is most common when first arising in the morning, and it usually improves quickly as daily activities are undertaken.



Figure 5.7.6. A bunion is a common sign of osteoarthritis. It is typically located at the base of the big toe.

X-rays or other tests are sometimes used to either support the diagnosis of OA or to rule out other disorders. Blood tests might be done, for example, to look for factors that indicate rheumatoid arthritis (RA), an autoimmune disease in which the immune system attacks the body's joints. If these factors are not present in the blood, then RA is unlikely, and a diagnosis of OA is more likely to be correct.

## RISK FACTORS FOR OSTEOARTHRITIS

Age is the chief risk factor for osteoarthritis. By age 65, as many as 80 percent of all people have evidence of osteoarthritis. However, people are more likely to develop OA — especially at younger ages — if they have had a joint injury. A high school football player might have a bad knee injury that damages the joint, leading to OA in the knee by the time he is in his thirties. If people have joints that are misaligned due to congenital malformations or disease, they are also more likely to develop OA. Excess body weight is another factor that increases the risk of OA, because of the added stress it places on weight-bearing joints.

Researchers have found that people with a family history of OA have a heightened risk of developing the disorder, which suggests that genetic factors are also involved in OA. It is likely that many different genes are needed for normal cartilage and cartilage repair. If such genes are defective and cartilage is abnormal or not normally repaired, OA is more likely to result.

## TREATMENT AND PREVENTION OF OSTEOARTHRITIS

OA cannot be cured, but the symptoms — especially the pain — can often be treated successfully to maintain a good quality of life for people with OA. Treatments include exercise, efforts to decrease stress on joints, pain medications, and surgery.

### *DESTRESSING JOINTS*

Efforts to decrease stress on joints include resting and using mobility devices such as canes, which reduce the weight placed on weight-bearing joints and also improve stability. In people who are overweight, losing weight may also reduce joint stress.

### *EXERCISE*

Exercise helps maintain joint mobility and also increases muscle strength. Stronger muscles may help keep the bones in joints correctly aligned, and this can reduce joint stress. Good exercises for OA include swimming, water aerobics (see Figure 5.7.7), and biking. These activities are recommended for OA because they put relatively little stress on the joints.



Figure 5.7.7: Exercising in water provides buoyancy that places less stress on joints than the same exercises would on the ground or other hard surfaces.

### *PAIN MEDICATIONS*

The first type of pain medication likely to be prescribed for OA is acetaminophen (e.g., Tylenol). When taken as prescribed, it has a relatively low risk of serious side effects. If this medication is inadequate to relieve the pain, non-steroidal anti-inflammatory drugs (NSAIDs, such as ibuprofen) may be prescribed. NSAIDs, however, are more likely to cause serious side effects, such as gastrointestinal bleeding, elevated blood pressure, and increased risk of stroke. Opioids usually are reserved for patients who have suffered serious side effects or for whom other medications have failed to relieve pain. Due to the risk of addiction, the short-term use of opioids is generally recommended.

### SURGERY

Joint replacement surgery is the most common treatment for serious OA in the knee or hip. In fact, knee and hip replacement surgeries are among the most common of all surgeries. Although they require a long period of healing and physical rehabilitation, the results are usually worth it. The replacement "parts" are usually pain-free and fully functional for at least a couple of decades. Quality, durability, and customization of artificial joints are constantly improving.

## FEATURE: MYTH VS. REALITY

About one out of every two Americans will develop osteoarthritis in his or her lifetime. The more you know about this disease, the more you can do to avoid it or slow its progression. That means knowing the facts, rather than believing the myths about osteoarthritis.

**Myth:** Cracking my knuckles will cause osteoarthritis.

**Reality:** Cracking your knuckles may lead to inflammation of your tendons, but it will not cause osteoarthritis.

**Myth:** My diet has no effect on my joints.

**Reality:** What and how much you eat *does* affect your body weight, and every pound you gain translates into an additional four pounds (or more!) of stress on your knees. Being overweight, therefore, increases the chances of developing osteoarthritis — and also the rate at which it progresses.

**Myth:** Exercise causes osteoarthritis or makes it worse, so I should avoid it.

**Reality:** This is one of the biggest myths about osteoarthritis. Low-impact exercise can actually lessen the pain and improve other symptoms of osteoarthritis. If you don't have osteoarthritis, exercise can reduce your risk of developing it. Low-impact exercise helps keep the muscles around joints strong and flexible, so they can help stabilize and protect the joints.

**Myth:** If my mom or dad has osteoarthritis, I will also develop it.

**Reality:** It is true that you are more likely to develop osteoarthritis if a parent has it, but it isn't a sure thing. There are several things you can do to decrease your risk, such as getting regular exercise and maintaining a healthy weight.

**Myth:** Bad weather causes osteoarthritis.

**Reality:** Weather conditions do not cause osteoarthritis, although, in some people who already have osteoarthritis, bad weather seems to make the symptoms worse. It is primarily low barometric pressure that increases osteoarthritis pain, probably because it leads to greater pressure inside the joints relative to the outside air pressure. Some people think their osteoarthritis pain is worse in cold weather, but systematic studies have not found convincing evidence for this.

**Myth:** Joint pain is unavoidable as you get older, so there is no need to see a doctor for it.

**Reality:** Many people with osteoarthritis think there is nothing that can be done for the pain of osteoarthritis, or that surgery is the only treatment option. In reality, osteoarthritis symptoms often can be improved with a combination of exercise, weight loss, pain management techniques, and pain medications. If osteoarthritis pain interferes with daily life and lasts more than a few days, you should see your doctor.

**Myth:** Osteoarthritis is inevitable in seniors.

**Reality:** Although many people over 65 develop osteoarthritis, there are many people who never develop it, no matter how old they live to be. You can reduce your risk of developing osteoarthritis in later life by protecting your joints throughout life.

## REVIEW

1. Name the two most common disorders of the skeletal system.
2. What is osteoporosis? What causes it?
3. How is osteoporosis diagnosed?
4. Why is osteoporosis dangerous?
5. Identify risk factors for osteoporosis.
6. How is osteoporosis treated? What can be done to prevent it?
7. What is OA? What are its chief symptoms?
8. What causes OA?
9. Describe how OA is diagnosed.
10. Identify risk factors for OA.
11. How is OA treated?
12. Why is it important to build sufficient bone mass in your young adult years?
13. Explain the difference in the cause of rheumatoid arthritis and osteoarthritis.
14. *True or False:* Osteoarthritis is caused by physical activity, so people who are equally active are equally susceptible to it.
15. *True or False:* Estrogen generally promotes the production of new bone.

## EXPLORE MORE

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## ATTRIBUTIONS


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# 5.8: CASE STUDY CONCLUSION- HEELS AND CHAPTER SUMMARY

## CASE STUDY CONCLUSION: A PAIN IN THE FOOT

You may have seen signs such as the one in Figure 5.8.1 indicating that high-heeled shoes are not allowed on certain walking surfaces because of the risk of injury. High heels affect a person's balance, and wearers can easily twist their ankle on uneven or slippery surfaces, causing a sprain or even a fracture. Besides twisting an ankle, wearing high heels on a regular basis can cause a variety of other negative health consequences—some of which may be long-lasting.



Figure 5.8.1: No heels

As Amari discovered at the beginning of the chapter, wearing high heels can result in a condition called metatarsalgia. Metatarsalgia is named for the metatarsal bones, which are the five bones that run through the ball of the foot just behind the toes (highlighted in Figure 5.8.2 ) Wearing high heels causes excessive pressure on the ball of the foot, as described at the beginning of this chapter. Additionally, the toes are forced to pull upwards in high heels, which moves the fleshy padding away from the ball of the foot, adding to the overall pressure placed on this region. Over time, this can cause inflammation and direct stress on the bones, resulting in pain in the ball of the foot known as metatarsalgia. The pain particularly occurs in weight-bearing positions such as standing, walking, or running—which is what Amari was experiencing. There may also be pain, numbness, or tingling in the toes associated with metatarsalgia.

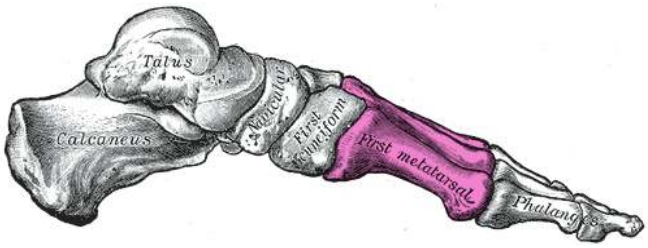



Figure 5.8.2: Illustration of the bones of the foot, with the metatarsal bones highlighted in pink.

Wearing high heels can also cause stress fractures in the feet, which are tiny breaks in the bone that occur due to repeated mechanical stress. This is due to the excessive pressure that high heels put on some of the bones of the feet. These fractures are somewhat similar to what occurs in osteoporosis when the bone mass decreases to the point where bones can fracture easily as people go about their daily activities. In both cases, a major, noticeable injury is not necessary to create tiny fractures. As you have learned, tiny fractures that accrue over time are the cause of dowager's hump, or kyphosis, which is often seen in women with osteoporosis.

Don't think you are immune to stress fractures just because you don't wear high heels! This injury also commonly occurs in people who participate in sports that involve repetitive striking of the foot on the ground, such as running, tennis, basketball, or gymnastics. Stress fractures may be avoided by taking preventative measures such as ramping up any increase in activity slowly, cross-training by engaging in a variety of different sports or activities, resting if you experience pain, and wearing well-cushioned and supportive running shoes.

Amari learned through their online research that wearing high heels can also lead to foot deformities such as bunions and hammertoes. As you saw in the section *Disorders of the Skeletal System*, a bunion is a protrusion on the side of the foot, most often at the base of the big toe. It can be caused by wearing shoes with a narrow, pointed toe box — a common shape for high heels (see Figure 5.8.3). The pressure of the shoes on the side of the foot causes an enlargement of bone or inflammation of other tissues in the region, which pushes the big toe towards the other toes.



Figure 5.8.3: High heels with a narrow, pointed toe box and thin stiletto heels.

Hammertoes are abnormal bend in the middle joint of the second, third, or fourth toe (with the big toe being the first toe), causing the toe to be shaped similar to a hammer as seen in Figure 5.8.4. The narrow, pointed toe box of many high heels, combined with the way the toes are squished into the front of the shoe as a result of the height of the heel, can cause the toes to become deformed in this manner. Treatments for bunions and hammertoe include wearing shoes with a roomy toe box, padding or taping the toes, and toe exercises and stretches. If the bunion or hammertoe does not respond to these treatments, surgery may be necessary to correct the deformity.



Figure **5.8.4**: X-ray of a hammer toe.

Because the bones of the skeleton are connected and work together with other systems to support the body, wearing high heels can also cause physical problems in areas other than the feet. Wearing high heels shifts a person's posture and alignment and can put a strain on tendons, muscles, and other joints in the body. For instance, research from a team at Stanford University published in 2014 suggests that wearing high heels, particularly if the person is overweight or the heels are very high, may increase the risk of osteoarthritis (OA) in the knee due to added stress on the knee joint as the person walks. As you have learned, OA results from the breakdown of cartilage and bone at the joint. Because it can only be treated to minimize symptoms, not cured, OA could be an unfortunate long-term consequence of wearing high heels.

Amari has decided that wearing high heels regularly is not worth the pain and potential long-term damage to their body. After consulting with their doctor, who confirmed they have metatarsalgia, Amari was able to successfully treat it with ice, rest, and wearing comfortable, supportive shoes instead of heels.

High heels are not the only kind of shoes that can cause problems. Flip-flops, worn-out sneakers, and shoes that are too tight can all cause foot issues. To prevent future problems from shoe choices, Amari is following guidelines recommended by medical experts, which include:

- Wearing shoes that fit well, have plenty of room in the toe box, are supportive, and are comfortable right away. There should be no "break-in" period needed for shoes.
- Avoiding shoes that have high heels, especially ones over two inches in height; narrow, pointed toe boxes; or very thin heels. The shoes in Figure **5.8.3** are an example of a type that should be avoided!
- If high heels must be worn, they should be worn for only a limited period of time.

As you have learned in this chapter, your skeletal system carries out a variety of important functions in your body, including physical support. But even though it is strong, your skeletal system can become damaged and deformed—even through such a seemingly innocuous act as wearing a certain type of shoe. Taking good care of your skeletal system is necessary to help it continue to take good care of the rest of you.

## CHAPTER SUMMARY

In this chapter, you learned about the skeletal system. Specifically, you learned that:

- The skeletal system is the organ system that provides an internal framework for the human body. In adults, the skeletal system contains 206 bones.
- Bones are organs made of dense connective tissues, mainly the tough protein collagen. Bones also contain blood vessels, nerves, and other tissues. Bones are hard and rigid due to deposits of calcium and other mineral salts within their living tissues. Besides bones, the skeletal system includes cartilage and ligaments.
- The skeletal system has many different functions, including supporting the body and giving it shape, protecting internal organs, providing attachment surfaces for skeletal muscles, allowing body movements, producing blood cells, storing minerals, helping to maintain mineral homeostasis, and producing endocrine hormones.
- The skeleton is traditionally divided into two major parts: the axial skeleton and the appendicular skeleton.
- The axial skeleton consists of a total of 80 bones. It includes the skull, vertebral column, and rib cage. It also includes the three tiny ossicles in the middle ear and the hyoid bone in the throat.
    - The skull provides a bony framework for the head. It consists of 22 different bones: eight in the cranium, which encloses the brain, and 14 in the face, which includes the upper and lower jaw.
    - The vertebral column is a flexible, S-shaped column of 33 vertebrae that connects the trunk with the skull and encloses the spinal cord. The vertebrae are divided into five regions: cervical, thoracic, lumbar, sacral, and coccygeal regions. The S shape of the vertebral column allows it to absorb shocks and distribute the weight of the body.
    - The rib cage holds and protects the organs of the upper part of the trunk, including the heart and lungs. It includes the 12 thoracic vertebrae, the sternum, and 12 pairs of ribs.
- The appendicular skeleton consists of a total of 126 bones. It includes the bones of the four limbs, shoulder girdle, and pelvic girdle. The girdles attach the appendages to the axial skeleton.
    - Each upper limb consists of 30 bones. There is one bone, called the humerus, in the upper arm, and two bones, called the ulna and radius, in the lower arm. The wrist contains eight carpal bones, the hand contains five metacarpals, and the fingers consist of 14 phalanges. The thumb is opposable to the palm and fingers of the same hand.
    - Each lower limb also consists of 30 bones. There is one bone, called the femur, in the upper leg, and two bones, called the tibia and fibula, in the lower leg. The patella covers the knee joint. The ankle contains seven tarsal bones, and the foot contains five metatarsals. The tarsals and metatarsals form the heel and arch of the foot. The bones in the toes consist of 14 phalanges.

  - The shoulder girdle attaches the upper limbs to the trunk of the body. It is connected to the axial skeleton only by muscles, allowing mobility of the upper limbs. Bones of the shoulder girdle include a right and left clavicle and a right and left scapula.
  - The pelvic girdle attaches the legs to the trunk of the body and supports the organs of the abdomen. It is connected to the axial skeleton by ligaments. The pelvic girdle consists of two halves that are fused together in adults. Each half consists of three bones: the ilium, pubis, and ischium.
- Bones are organs that consist mainly of bone, or osseous, tissue. Osseous tissue is a type of connective tissue consisting of a collagen matrix that is mineralized with calcium and phosphorus crystals. The combination of flexible collagen and minerals makes bone hard without making it brittle.
  - There are two types of osseous tissues: cortical bone tissue and spongy bone tissue. Cortical bone tissue is smooth and dense. It forms the outer layer of bones. Spongy bone tissue is porous and light. It is found inside many bones.
- Besides osseous tissues, bones also contain nerves, blood vessels, bone marrow, and periosteum.
- Bone tissue is composed of four different types of bone cells: osteoblasts, osteocytes, osteoclasts, and osteogenic cells. Osteoblasts form new collagen matrix and mineralize it, osteoclasts break down bone, osteocytes regulate the formation and breakdown of bone, and osteogenic cells divide and differentiate to form new osteoblasts. Bone is a very active tissue, constantly being remodeled by the work of osteoblasts and osteoclasts.
- There are six types of bones in the human body: long bones such as the limb bones, short bones such as the wrist bones, sesamoid bones such as the patella, sutural bones in the skull, and irregular bones such as the vertebrae.
- Early in the development of a human fetus, the skeleton is made almost entirely of cartilage. The relatively soft cartilage gradually turns into hard bone. This is called ossification. It begins at a primary ossification center in the middle of the bone and later also occurs at secondary ossification centers in the ends of the bone. The bone can no longer grow in length after the areas of ossification meet and fuse at the time of skeletal maturity.
- Throughout life, bone is constantly being replaced in the process of bone remodeling. In this process, osteoclasts resorb bone and osteoblasts make new bone to replace it. Bone remodeling shapes the skeleton, repairs tiny flaws in bones, and helps maintain mineral homeostasis in the blood.
- Bone repair is the natural process in which a bone repairs itself following a bone fracture. This process may take several weeks. In the process, periosteum produces cells that develop into osteoblasts, and the osteoblasts form a new bone matrix to heal the fracture. Bone repair may be affected by diet, age, pre-existing bone disease, or other factors.
- Joints are locations at which bones of the skeleton connect with one another.
- Joints can be classified structurally or functionally, and there is significant overlap between the two types of classifications.
- The structural classification of joints depends on the type of tissue that binds the bones to each other at the joint. There are three types of joints in the structural classification: fibrous, cartilaginous, and synovial joints.
- The functional classification of joints is based on the type and degree of movement that they allow. There are three types of joints in the functional classification: immovable, partly movable, and movable joints.
  - Movable joints can be classified further according to the type of movement they allow. There are six classes of movable joints: pivot, hinge, saddle, plane, condyloid, and ball-and-socket joints.
- A number of disorders affect the skeletal system, including bone fractures and bone cancers. The two most common disorders of the skeletal system are osteoporosis and osteoarthritis.
- Osteoporosis is an age-related disorder in which bones lose mass, weaken, and break more easily than normal bones. The underlying mechanism in all cases of osteoporosis is an imbalance between bone formation and bone resorption in bone remodeling. Osteoporosis may also occur as a side effect of other disorders or certain medications.
  - Osteoporosis is diagnosed by measuring a patient's bone density and comparing it with the normal level of peak bone density. Fractures are the most dangerous aspect of osteoporosis. Osteoporosis is rarely fatal, but complications of fractures often are.
  - Risk factors for osteoporosis include older age, female sex, European or Asian ancestry, family history of osteoporosis, short stature and small bones, smoking, alcohol consumption, lack of exercise, vitamin D deficiency, poor nutrition, and consumption of soft drinks.
  - Osteoporosis is often treated with medications such as bisphosphonates that may slow or even reverse bone loss. Preventing osteoporosis includes eliminating any risk factors that can be controlled through changes of behavior, such as undertaking weight-bearing exercise.
- Osteoarthritis (OA) is a joint disease that results from the breakdown of joint cartilage and bone. The most common symptoms are joint pain and stiffness. OA is thought to be caused by mechanical stress on the joints with insufficient self-repair of cartilage, coupled with low-grade inflammation of the joints.
  - Diagnosis of OA is typically made on the basis of signs and symptoms, such as joint deformities, pain, and stiffness. X-rays or other tests are sometimes used to either support the diagnosis or rule out other disorders. Age is the chief risk factor for OA. Other risk factors include joint injury, excess body weight, and a family history of OA.

- OA cannot be cured, but the symptoms can often be treated successfully. Treatments may include exercise, efforts to decrease stress on joints, pain medications, and surgery to replace affected hip or knee joints.

As you have learned in this chapter, one of the important functions of the skeletal system is to allow movement of the body. But it doesn't do it alone. Movement is caused by the contraction of muscles, which pull on the bones, causing them to move. Read the next chapter to learn about this and other important functions of the muscular system.

## CHAPTER SUMMARY REVIEW

1. Hematopoiesis is carried out by:
   A. spongy bone tissue
   B. periosteum
   C. yellow bone marrow
   D. red bone marrow
2. *True or False.* Osteocalcin is a hormone produced by bone cells.
3. *True or False.* Vertebrae make up part of the rib cage.
4. For each of the following bones, indicate whether they are part of the axial or appendicular skeleton.
   A. The ossicles of the middle ear
   B. The femur
   C. The phalanges
   D. The bones of the cranium
   E. The ilium
5. Why does the rib cage need to be flexible and why is it able to be flexible?
6. In general, what do "girdles" in the skeletal system do?
7. Which protein does bone mainly consist of?
   A. Keratin
   B. Collagen
   C. Cellulose
   D. Elastin
8. For each of the descriptions below, identify which process best fits the description. Use each process only once. Processes: bone growth; bone repair; bone remodeling
   A. New osteoblasts form from the periosteum and produce new bone tissue.
   B. Cartilage grows, and the primary and secondary ossification centers move towards each other.
   C. Osteoclasts break down bone tissue and osteoblasts build new bone tissue.
9. For each of the following processes, describe when it occurs.
   A. Bone growth
   B. Bone repair
   C. Bone remodeling
10. Would swimming likely be more effective as an exercise for preventing osteoporosis or as a treatment for osteoarthritis? Explain your answer.
11. *True or False.* Use of anabolic steroids in the teenage years generally makes people taller.
12. *True or False.* The largest joint in the human body is the knee joint.
13. How much of an adult's skeletal mass is broken down and rebuilt each year?
    A. None
    B. 5 percent
    C. 10 percent
    D. 30 percent
14. Explain why some of the vertebrae become misshapen in the condition called dowager's hump, or kyphosis.
15. Explain why osteoarthritis often involves inflammation in the joints.
16. Osteoporosis can involve both excess bone resorption as well as insufficient production of new bone tissue. What are the two main bone cell types that carry out these processes, respectively?
17. *True or False.* Bone mass does not decrease as men age.
18. *True or False.* Ideally, a person's spine would be perfectly straight and rigid.
19. Compare and contrast a tendon and a ligament.
20. Describe two roles that calcium plays in the bones of the body.
21. How many bones are in the adult human skeleton?
    A. 80
    B. 126
    C. 206
    D. 270

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# CHAPTER OVERVIEW

## 6: THE MUSCULAR SYSTEM

This chapter describes the structure and functions of the muscular system. It compares and contrasts the three major types of muscle tissue and explains in detail how muscles contract according to the sliding filament theory. The chapter also relates physical exercise to fitness and health and describes several musculoskeletal and neuromuscular disorders.


6.1: Case Study- Muscles and Movement

6.2: Introduction to the Muscular System

6.3: Types of Muscle Tissue

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# 6.1: CASE STUDY- MUSCLES AND MOVEMENT

## CASE STUDY: NEEDING TO RELAX

The dog in Figure **6.1.3** is expressing his interest in something—perhaps a piece of food—by using the neck muscles to tilt its head in an adorable fashion. Humans also sometimes tilt their heads to express interest. But imagine how disturbing and painful it would be if your neck tilted involuntarily, without you being able to control it! Forty-three-year-old Nasir, unfortunately, knows just how debilitating this can be. Nasir uses they, them, and their pronouns.



Figure **6.1.1**: Curious dog

Nasir has a rare condition called cervical dystonia, which is also called spasmodic torticollis. In this condition, the muscles in the neck contract involuntarily, often causing the person's head to twist to one side. The illustration in Figure **6.1.2** shows one type of abnormal head positioning that can be caused by cervical dystonia. The muscles may contract in a sustained fashion, holding the head and neck in one position, or they may spasm repeatedly, causing jerky movements of the head and neck.

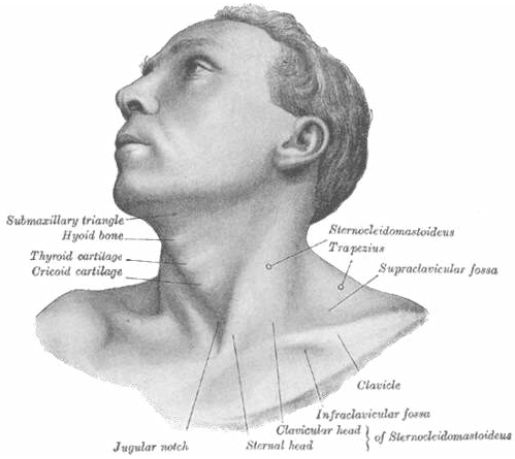



Figure **6.1.2**: Illustration from a medical book written around 1910, showing a person identified as having spasmodic torticollis. The person's neck is permanently tilted to the side.

Cervical dystonia is painful and can significantly interfere with individuals' ability to carry out their usual daily activities. In Nasir's case, they can no longer drive a car, because their uncontrollable head and neck movements and abnormal head positioning prevent them from navigating the road safely. Nasir also has severe neck and shoulder pain much of the time.

Although it can be caused by an injury, there is no known cause of cervical dystonia—and there is also no cure. Fortunately for Nasir and other cervical dystonia sufferers, though, there is a treatment that can significantly reduce symptoms in many people. You may be surprised to learn that this treatment is the same substance that, when injected into the face, is used for cosmetic purposes to reduce wrinkles!

The substance is botulinum toxin, one preparation of which may be familiar to you by its brand name: Botox. It is a neurotoxin produced by the bacterium *Clostridium botulinum*, and can cause a life-threatening illness called botulism. However, when injected in very small amounts by a skilled medical professional, botulinum toxins have some safe and effective uses. In addition to cervical dystonia, botulinum toxins can be used to treat other disorders involving the muscular system, such as strabismus (misalignment of the eyes), eye twitches, excessive muscle contraction due to neurological conditions like cerebral palsy; and even overactive bladder.

Botulinum toxin has its effect on the muscular system by inhibiting muscle contractions. When used to treat wrinkles, it relaxes the muscles of the face, lessening the appearance of wrinkles. When used to treat cervical dystonia and other disorders involving excessive muscle contraction, it reduces abnormal contractions.

In this chapter, you will learn about the muscles of the body, how they contract to produce movements and carry out their functions, and some disorders that affect the muscular system. At the end of the chapter, you will find out if botulinum toxin helped relieve Nasir's cervical dystonia, and how this toxin works to inhibit muscle contraction.

## CHAPTER OVERVIEW: MUSCULAR SYSTEM

In this chapter, you will learn about the muscular system, which carries out both voluntary body movements and involuntary contractions of internal organs and structures. Specifically, you will learn about:

- The different types of muscle tissue—skeletal, cardiac, and smooth muscle—and their different characteristics and functions
- How muscle cells are specialized to contract and cause voluntary and involuntary movements
- The ways in which muscle contraction is controlled
- How skeletal muscles can grow or shrink, causing changes in strength
- The structure and organization of skeletal muscles (including the different types of muscle fibers) and how actin and myosin

filaments move across each other, according to the sliding filament theory, to cause muscle contraction

- How cardiac muscle tissue in the heart contracts to pump blood through the body
- Smooth muscle tissue that makes up internal organs and structures, such as the digestive system, blood vessels, and uterus
- The physical and mental health benefits of aerobic and anaerobic exercise, such as running and weight lifting
- How individuals vary in their response to exercise
- Disorders of the muscular system, including musculoskeletal disorders (such as strains and carpal tunnel syndrome) and neuromuscular disorders (such as muscular dystrophy, myasthenia gravis, and Parkinson's disease)

As you read the chapter, think about the following questions:

1. How is the contraction of skeletal muscles controlled?
2. Botulinum toxin works on the cellular and molecular levels to inhibit muscle contraction. Based on what you learn about how muscle contraction works, can you think of some ways it could potentially be inhibited?
3. What is one disorder involving a lack of sufficient muscle contraction? Why does it occur?

## ATTRIBUTIONS


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# 6.2: INTRODUCTION TO THE MUSCULAR SYSTEM

## MARVELOUS MUSCLES

Does the word *muscle* make you think of the well-developed muscles of a weightlifter, like a woman in Figure **6.2.1**? Her name is Natalia Zabolotnaya, and she's a Russian Olympian. The muscles that are used to lift weights are easy to feel and see, but they aren't the only muscles in the human body. Many muscles are deep within the body, where they form the walls of internal organs and other structures. You can flex your biceps at will, but you can't control internal muscles like these. It's a good thing that these internal muscles work without any conscious effort on your part because the movement of these muscles is essential for survival. Muscles are the organs of the muscular system.



Figure **6.2.1**: weightlifter lifting weight over her head.

## WHAT IS THE MUSCULAR SYSTEM?



Figure **6.2.2**: Many of the skeletal muscles in the human muscular system are shown in this drawing of the human body.

The **muscular system** consists of all the muscles of the body. The largest percentage of muscles in the muscular system consists of skeletal muscles, which are attached to bones and enable voluntary body movements. There are almost 650 skeletal muscles in the human body, many of them shown in Figure **6.2.2**. Besides skeletal muscles, the muscular system also includes cardiac muscle — which makes up the walls of the heart — and smooth muscles, which control movement in other internal organs and structures.

## MUSCLE STRUCTURE AND FUNCTION

Muscles are organs composed mainly of muscle cells, which are also called **muscle fibers** (mainly in skeletal and cardiac muscle) or **myocytes** (mainly in smooth muscle). Muscle cells are long and thin cells that are specialized for the function of contracting. They contain protein filaments that slide over one another using energy in ATP. The sliding filaments increase the tension in — or shorten the length of — muscle cells, causing a contraction. Muscle contractions are responsible for virtually *all* the movements of the body, both inside and out.

Skeletal muscles are attached to the bones of the skeleton. When these muscles contract, they move the body. They allow us to use our limbs in a variety of ways, from walking to turning cartwheels. Skeletal muscles also maintain posture and help keep balance.

Smooth muscles in the walls of blood vessels contract to cause vasoconstriction, which may help conserve body heat. Relaxation of these muscles causes vasodilation, which may help the body lose heat. In the organs of the digestive system, smooth muscles squeeze food through the gastrointestinal tract by contracting in sequence to form a wave of muscle contractions called **peristalsis.** Think of squirting toothpaste through a tube by applying pressure in sequence from the bottom of the tube to the top, and you have a good idea of how food is moved by muscles through the digestive system. Peristalsis of smooth muscles also moves urine through the urinary tract.

Cardiac muscle tissue is found only in the walls of the heart. When cardiac muscle contracts, it makes the heartbeat. The pumping action of the beating heart keeps blood flowing through the cardiovascular system.

## MUSCLE HYPERTROPHY AND ATROPHY

Muscles can grow larger, or **hypertrophy.** This generally occurs through increased use, although hormonal or other influences can also play a role. The increase in testosterone during puberty, for example, causes a significant increase in muscle size. Physical exercise that involves weight-bearing or resistance training can increase the size of skeletal muscles in virtually everyone. Exercises (such as running) that increase the heart rate may also increase the size and strength of cardiac muscle. The size of a muscle, in turn, is the main determinant of muscle strength, which may be measured by the amount of force a muscle can exert.

Muscles can also grow smaller, or **atrophy**, which can occur through lack of physical activity or from starvation. People who are immobilized for any length of time — for example, because of a broken bone or surgery — lose muscle mass relatively quickly. People in concentration or famine camps may be so malnourished

that they lose much of their muscle mass, becoming almost literally just “skin and bones.” Astronauts on the International Space Station may also lose significant muscle mass because of weightlessness in space (Figure 6.2.3).

Many diseases, including cancer and AIDS, are often associated with muscle atrophy. Atrophy of muscles also happens with age. As people grow older, there is a gradual decrease in the ability to maintain skeletal muscle mass, known as **sarcopenia.** The exact cause of sarcopenia is not known, but one possible cause is a decrease in sensitivity to growth factors that are needed to maintain muscle mass. Because muscle size determines the strength, muscle atrophy causes a corresponding decline in muscle strength.

In both hypertrophy and atrophy, the number of muscle fibers does not change. What changes the size of the muscle fibers? When muscle hypertrophy happens, the individual fibers become wider. When muscle atrophy happens, the fibers become narrower.

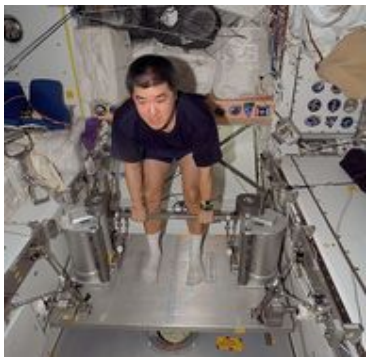


Figure 6.2.3: An astronaut exercising in space. It is important for astronauts to exercise onboard the International Space Station to help counter the loss of muscle mass that occurs because they are weightless without Earth’s gravity.

## INTERACTIONS WITH OTHER BODY SYSTEMS

Muscles cannot contract on their own. Skeletal muscles need stimulation from motor neurons in order to contract. The point where a motor neuron attaches to a muscle is called a **neuromuscular junction**. Let’s say you decide to raise your hand in class. Your brain sends electrical messages through motor neurons to your arm and shoulder. The motor neurons, in turn, stimulate muscle fibers in your arm and shoulder to contract, causing your arm to rise.

Involuntary contractions of smooth and cardiac muscles are also controlled by electrical impulses, but in the case of these muscles, the impulses come from the autonomic nervous system (smooth muscle) or specialized cells in the heart (cardiac muscle). Hormones and some other factors also influence involuntary contractions of cardiac and smooth muscles. For example, the fight-or-flight hormone adrenaline increases the rate at which cardiac muscle contracts, thereby speeding up the heartbeat.

Muscles cannot move the body on their own. They need the skeletal system to act upon. The two systems together are often referred to as the **musculoskeletal system**. Skeletal muscles are attached to the skeleton by tough connective tissues called **tendons**. Many skeletal muscles are attached to the ends of bones that meet at a joint. The muscles span the joint and connect the bones. When the muscles contract, they pull on the bones, causing them to move. The skeletal system provides a system of levers that allow body movement. The muscular system provides the force that moves the levers.

## REVIEW

1. What is the muscular system?
2. Describe muscle cells and their function.
3. Identify three types of muscle tissue and where each type is found.
4. Define muscle hypertrophy and muscle atrophy.
5. What are the possible causes of muscle hypertrophy?
6. Give three reasons that muscle atrophy may occur.
7. How do muscles change when they increase or decrease in size?
8. How do changes in muscle size affect strength?
9. Explain why astronauts can easily lose muscle mass in space.
10. Describe how the terms *muscle cells*, *muscle fibers*, and *myocytes* relate to each other.
11. Muscle tissue in the stomach is considered _____.

A. cardiac muscle

B. skeletal muscle

C. smooth muscle

D. voluntary muscle

12. Muscle contraction is the _____ of muscle fibers.

A. hypertrophy

B. atrophy

C. lengthening

D. shortening

13. *True or False:* Smooth muscle does not contract.
14. Name two systems in the body that work together with the muscular system to carry out movements.
15. Describe one way in which the muscular system is involved in regulating body temperature.

## EXPLORE MORE

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# 6.3: TYPES OF MUSCLE TISSUE

## WORK THOSE EYE MUSCLES!

Turn your eyes—a tiny movement, considering the conspicuously large and strong external eye muscles that control eyeball movements. These muscles have been called the strongest muscles in the human body relative to the work they do. However, the external eye muscles actually do a surprising amount of work. Eye movements occur almost constantly during waking hours, especially when we are scanning faces or reading. Eye muscles are also exercised nightly during the phase of sleep called rapid eye movement sleep. External eye muscles can move the eyes because they are made mainly of muscle tissue.



Figure **6.3.1**: Eyes

## WHAT IS MUSCLE TISSUE?

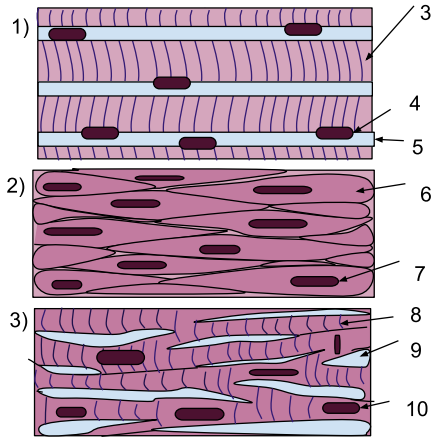



Figure **6.3.2**: Muscle type 1) Skeletal muscle cells are long tubular cells with striations (3) and multiple nuclei (4). The nuclei are embedded in the cell membrane (5) to be just inside the cell. This type of tissue occurs in the muscles that are attached to the skeleton. Skeletal muscles function for the voluntary movements of the body. Muscle type 2) Smooth muscle cells are spindle-shaped (6), and each cell has a single nucleus (7). Unlike skeletal muscle, there are no striations. The smooth muscle acts involuntarily and functions in the movement of substances in the lumens. They are primarily found in blood vessel walls and walls along the digestive tract. Muscle type 3) Cardiac muscle cells branch off from each other, rather than remaining, like the cells in the skeletal and smooth muscle tissues. Because of this, there are junctions between adjacent cells (9). The cells have striations (8), and each cell has a single nucleus (10). This type of tissue occurs in the heart wall, and its primary function is for pumping blood. This is an involuntary action.

**Muscle tissue** is a soft tissue that makes up most of the tissues in the muscles of the human muscular system. Other tissues in muscles are connective tissues, such as tendons that attach skeletal muscles to bones and sheaths of connective tissues that cover or line muscle tissues. Only muscle tissue per se, however, has cells with the ability to contract.

There are three major types of muscle tissues in the human body: skeletal, smooth, and cardiac muscle tissues. Figure **6.3.2** shows how the three types of muscle tissues appear under a microscope. When you read about each type below, you will learn why the three types appear as they do.

## SKELETAL MUSCLE TISSUE

**Skeletal muscle** is muscle tissue attached to bones by **tendons**, which are bundles of collagen fibers. Whether you are moving your eyes or running a marathon, you are using skeletal muscles. Contractions of skeletal muscles are voluntary or under the conscious control of the central nervous system via the somatic nervous system. Skeletal muscle tissue is the most common type of muscle tissue in the human body. By weight, an average adult male is about 42 percent skeletal muscles, and the average adult female is about 36 percent skeletal muscles. Some of the major skeletal muscles in the human body are labeled in Figures **6.3.3** and Figure **6.3.4** and listed in Table **6.3.1**.

Table **6.3.1**: Skeletal muscles. Some muscles are visible from both anterior and posterior views.

| Muscles visible in Figure **6.3.3** | Muscles visible in Figure **6.3.4** |
|---|---|
| rotator cuff (multiple muscles are part of this group) | levator scapulae |
| biceps brachii | rhomboids |
| brachialis | rotator cuff |
| pronator teres | triceps brachii |
| brachioradialis | gluteus maximus |
| adductor muscles | tibialis posterior |
| tibialis anterior | peroneus longus |
| deltoid | peroneus brevis |
| pectoralis major | trapezius |
| rectus abdominis | deltoid |
| abdominal external oblique | brachioradialis |
| iliopsoas | latissimus dorsi |
| quadriceps femoris | biceps femoris |
| peroneus longus | semitendinosus |
| peroneus bravis | semimembranousus |
| | gastrocnemius |
| | soleus |

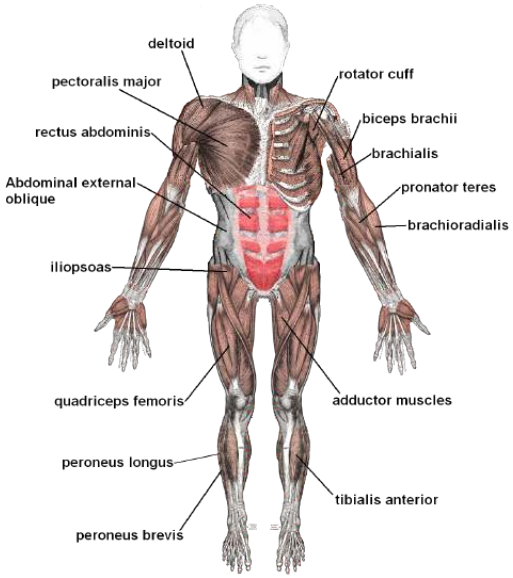



Figure **6.3.3**: This figure shows major skeletal muscles in the front (anterior) of the body.

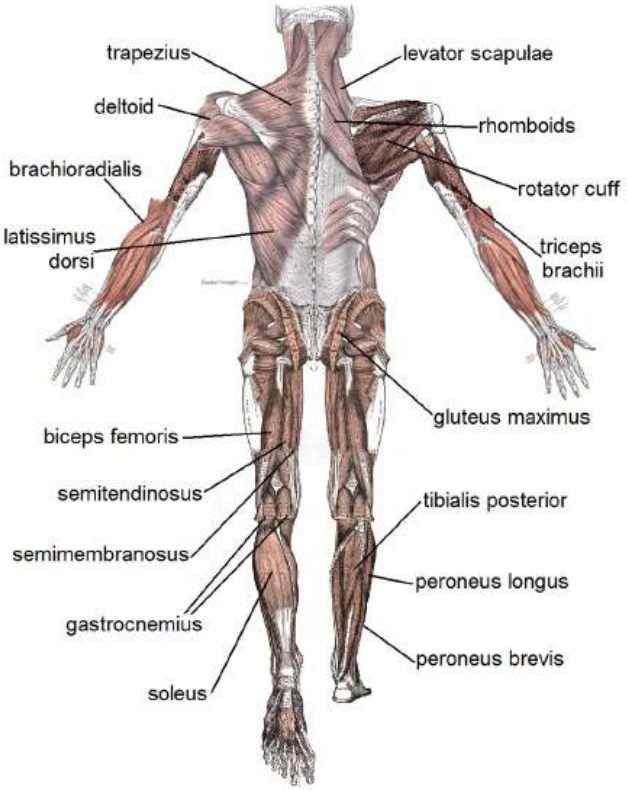



Figure **6.3.4**: This figure shows major skeletal muscles in the back (posterior) of the body.

## SKELETAL MUSCLE PAIRS

To move bones in opposite directions, skeletal muscles often consist of muscle pairs that work in opposition to one another. For example, when the biceps muscle (on the front of the upper arm) contracts, it can cause the elbow joint to flex or bend the arm, as shown in Figure **6.3.5**. When the triceps muscle (on the back of the upper arm) contracts, it can cause the elbow to extend or straighten the arm. The biceps and triceps muscles are examples of a muscle pair where the muscles work in opposition to each other.

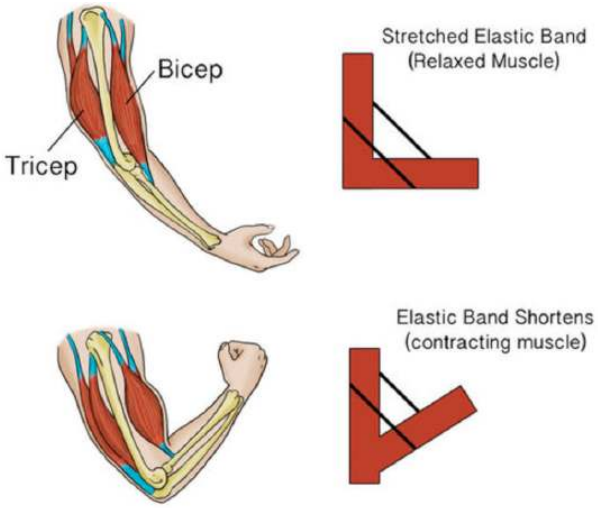



Figure **6.3.5**: Triceps and biceps muscles in the upper arm are opposing muscles that move the arm at the elbow in opposite directions.

## SKELETAL MUSCLE STRUCTURE

Each skeletal muscle consists of hundreds — or even *thousands* — of skeletal muscle fibers, which are long, string-like cells. As shown in Figure **6.3.6**, skeletal muscle fibers are individually wrapped in connective tissue called **endomysium**. The skeletal muscle fibers are bundled together in units called **muscle fascicles**, surrounded by sheaths of connective tissue called **perimysium**. Each fascicle contains between ten and 100 (or even more!) skeletal muscle fibers. Fascicles, in turn, are bundled together to form individual skeletal muscles, which are wrapped in connective tissue called **epimysium**. The connective tissues in skeletal muscles have a variety of functions. They support and protect muscle fibers, allowing them to withstand contraction forces by distributing the forces applied to the muscle. They also provide pathways for nerves and blood vessels to reach the muscles. Also, the epimysium anchors the muscles to tendons.

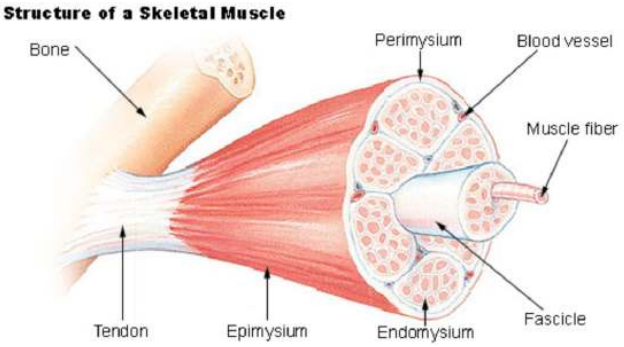



Figure **6.3.6**: Each skeletal muscle has a structure of bundles within bundles. Bundles of muscle fibers make up a muscle fascicle, and fascicles' bundles make up a skeletal muscle. At each level of bundling, a connective tissue membrane surrounds the bundle. The muscle cells, fascicle, and the whole muscle are surrounded by Endomysium, perimysium, and epimysium, respectively. All connective tissues merge together to make a tendon that attaches the muscle to bones.

The same bundles-within-bundles structure is replicated within each muscle fiber. As shown in Figure **6.3.7**, a muscle fiber consists of a bundle of myofibrils, which are themselves bundles of protein filaments. These protein filaments consist of thin filaments of the protein actin, anchored to structures called Z discs — and thick filaments of the protein myosin. The filaments are arranged together within a myofibril in repeating units called **sarcomeres,** which run from one Z disc to the next. The sarcomere is the basic functional unit of skeletal (and cardiac) muscles. It contracts as actin and myosin filaments slide over one another. Skeletal muscle tissue is said to be striated because it appears striped. It has this appearance because of the regular, alternating A (dark) and I (light) bands of filaments arranged in sarcomeres inside the muscle fibers. Other components of a skeletal muscle fiber include multiple nuclei and mitochondria.

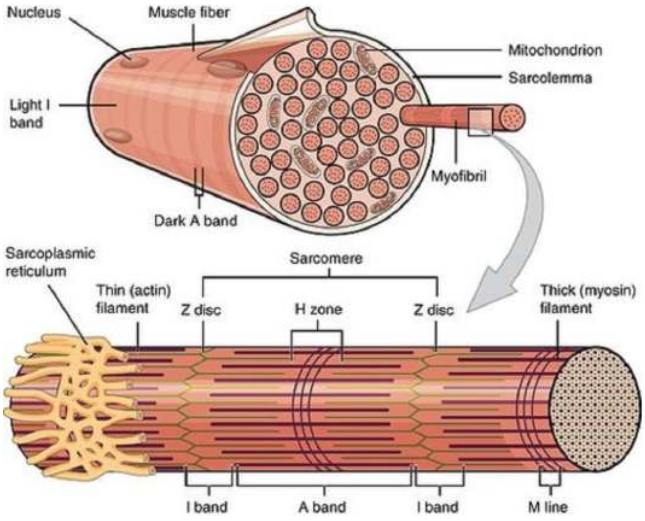



Figure **6.3.7**: Bundles of protein filaments form a myofibril, and bundles of myofibrils make up a single muscle fiber. I and A bands refer to the positioning of myosin and actin fibers in a myofibril. Sarcoplasmic reticulum is a specialized type of endoplasmic reticulum that forms a network around each myofibril. It serves as a reservoir for calcium ions, which are needed for muscle contractions. H zones and Z discs are also involved in muscle contractions, which you can read about in the concept of Muscle Contraction.

## SLOW- AND FAST-TWITCH SKELETAL MUSCLE FIBERS

Skeletal muscle fibers can be divided into two types, called slow-twitch (or type I) muscle fibers and fast-twitch (or type II) muscle fibers.

- **Slow-twitch muscle fibers** are dense with capillaries and rich in mitochondria and myoglobin, a protein that stores oxygen until needed for muscle activity. Relative to fast-twitch fibers, slow-twitch fibers can carry more oxygen and sustain aerobic (oxygen-using) activity. Slow-twitch fibers can contract for long periods of time, but not with very much force. They are relied upon primarily in endurance events, such as distance running or cycling.
- **Fast-twitch muscle fibers** contain fewer capillaries and mitochondria and less myoglobin. This type of muscle fiber can contract rapidly and powerfully, but it fatigues very quickly. Fast-twitch fibers can sustain only short, anaerobic (non-oxygen-using) bursts of activity. Relative to slow-twitch fibers, fast-twitch fibers contribute more to muscle strength and have a greater potential for increasing mass. They are relied upon primarily in short, strenuous events, such as sprinting or weight lifting.

Proportions of fiber types vary considerably from muscle to muscle and from person to person. Individuals may be genetically predisposed to have a larger percentage of one type of muscle fiber than the other. Generally, an individual who has more slow-twitch fibers is better suited for activities requiring endurance. In contrast, an individual who has more fast-twitch fibers is better suited for activities requiring short bursts of power.

## SMOOTH MUSCLE

**Smooth muscle** is muscle tissue in the walls of internal organs and other internal structures such as blood vessels. When smooth muscles contract, they help the organs and vessels carry out their functions. When smooth muscles in the stomach wall contract, they squeeze the food inside the stomach, helping to mix and churn the food and break it into smaller pieces. This is an important part of digestion. Contractions of smooth muscles are involuntary, so they are not under conscious control. Instead, they are controlled by the autonomic nervous system, hormones, neurotransmitters, and other physiological factors.

### STRUCTURE OF SMOOTH MUSCLE

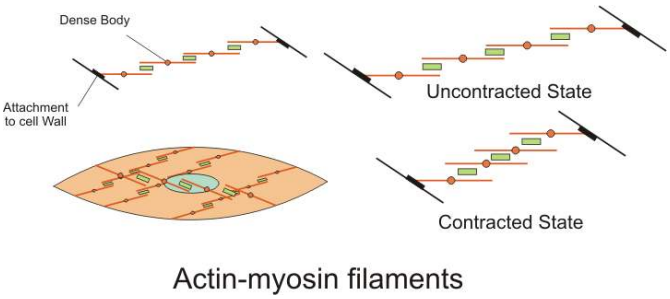



Figure **6.3.8**: The smooth muscle cell is composed of actin and myosin filaments, but they are not arranged in the sarcomere. The arrangement of these filaments is alternate and staggered.

The cells that make up smooth muscle are generally called **myocytes.** Unlike the muscle fibers of striated muscle tissue, the myocytes of smooth muscle tissue do not have their filaments arranged in sarcomeres. Therefore, smooth tissue is not striated. However, the myocytes of smooth muscle contain myofibrils, which contain bundles of myosin and actin filaments. The filaments cause contractions when they slide over each other, as shown in Figure **6.3.8**.

### FUNCTIONS OF SMOOTH MUSCLE

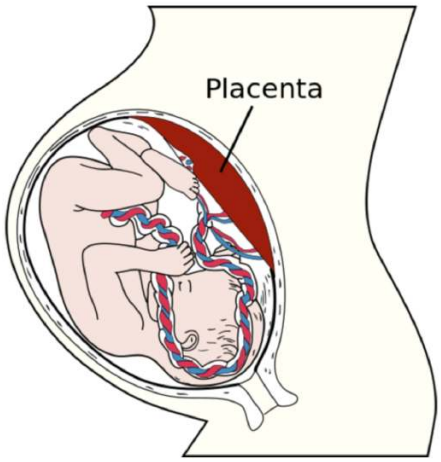



Figure **6.3.9**: The muscular uterine wall stretches to a great extent to accommodate a growing fetus, yet it can still contract with great force during the labor that precedes childbirth. At that time, it can exert up to 100 pounds of force.

Unlike striated muscle, smooth muscle can sustain very long-term contractions. Smooth muscle can also stretch and still maintain its contractile function, which striated muscle cannot. An extracellular matrix secreted by myocytes enhances the elasticity of smooth muscle. The matrix consists of elastin, collagen, and other stretchy fibers. The ability to stretch and still contract is an important attribute of smooth muscle in organs such as the stomach and uterus (Figure **6.3.9**), both of which must stretch considerably as they perform their normal functions.

The following list indicates where many smooth muscles are found, along with some of their specific functions.

- Walls of the gastrointestinal tract (such as the esophagus, stomach, and intestines), moving food through the tract by peristalsis.
- Walls of air passages of the respiratory tract (such as the bronchi), controlling the diameter of the passages and the volume of air that can pass through them
- Walls of organs of the male and female reproductive tracts; in the uterus, for example, pushing a baby out of the uterus and into the birth canal
- Walls of the urinary system structures, including the urinary bladder, allow the bladder to expand so it can hold more urine and then contract as urine is released.
- Walls of blood vessels, controlling the diameter of the vessels and thereby affecting blood flow and blood pressure
- Walls of lymphatic vessels, squeezing the fluid called lymph through the vessels.
- Iris of the eyes, controlling the size of the pupils and thereby the amount of light entering the eyes
- Arrector pili in the skin, raising hairs in hair follicles in the dermis.

## CARDIAC MUSCLE

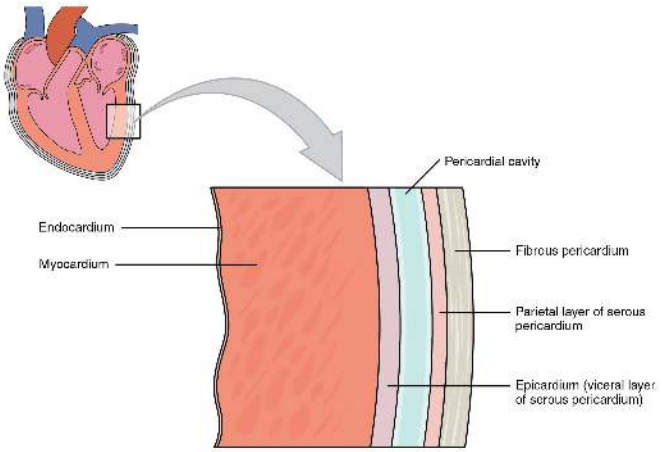



Figure **6.3.10**: The thick wall of the heart consists mainly of cardiac muscle tissue called myocardium. The thin epithelial tissue endocardium covers the chambers of the heart and the epicardium covers the myocardium. The heart is located in the pericardial cavity of the chest. The covering of the pericardial cavity is composed of fibrous and serous layers.

**Cardiac muscle** is found only in the wall of the heart. It is also called myocardium. As shown in Figure **6.3.10**, the myocardium is enclosed within connective tissues, including the endocardium on

the inside of the heart and pericardium on the outside of the heart. When cardiac muscle contracts, the heart beats and pumps blood. Contractions of cardiac muscle are involuntary, like those of smooth muscles. They are controlled by electrical impulses from specialized cardiac muscle cells in the heart muscle area called the sinoatrial node.

Like skeletal muscle, cardiac muscle is striated because its filaments are arranged in sarcomeres inside the muscle fibers. However, in cardiac muscle, the myofibrils are branched at irregular angles rather than arranged in parallel rows (as they are in skeletal muscle). This explains why cardiac and skeletal muscle tissues look different from one another.

The cells of cardiac muscle tissue are arranged in interconnected networks. This arrangement allows rapid transmission of electrical impulses, which stimulate virtually simultaneous contractions of the cells. This enables the cells to coordinate contractions of the heart muscle.

The heart is the muscle that performs the greatest amount of physical work in a lifetime. Although the heart's power output is much less than the maximum power output of some other muscles in the human body, the heart does its work continuously over an entire lifetime without rest. The cardiac muscle contains many mitochondria, which produce ATP for energy and help the heart resist fatigue.

## FEATURE: HUMAN BODY IN THE NEWS

The human heart develops in a sequence of events that are controlled by communication among different types of cells, including cells that will become myocardium (the cardiac muscle that forms the wall of the heart) and cells that will become endocardium (the connective tissue that covers the inside surface of the myocardium). If communication among the cells is abnormal, it can lead to various heart defects, such as cardiac hypertrophy or abnormal enlargement of the heart muscle. Cardiac hypertrophy causes the heart to thicken and weaken over time, so it is less able to pump blood. Eventually, heart failure may develop, causing fluid to build up in the lungs and extremities.

Abnormal cell communication is the mechanism by which a mutation called PTPN11 leads to cardiac hypertrophy in disorder referred to as NSML (Noonan Syndrome with Multiple Lentigines). New research by scientists at Beth Israel Deaconess Medical Center in Boston has determined which type of cell abnormalities occur that lead to NSML. In the research, the scientists engineered mouse models to express the PTPN11 mutation as they developed. The researchers manipulated the mouse models so that the mutation was expressed only in cells that would develop into the myocardium in some of the mice. In contrast, in other mice, the mutation was expressed only in cells that would develop into endocardium. Unexpectedly, the heart's hypertrophy occurred only in the mice that expressed the mutation in endocardial cells, not in myocardial cells, which had long been assumed to be the cells affected. The results of the research suggest potential targets for the treatment of NSML. They may also help scientists understand the causes of other cardiac disorders that are much more common than NSML.

## REVIEW

1. What is muscle tissue?
2. Where is the skeletal muscle found, and what is its general function?
3. Why do many skeletal muscles work in pairs?
4. Describe the structure of a skeletal muscle.
5. Relate muscle fiber structure to the functional units of muscles.
6. Why is skeletal muscle tissue striated?
7. Compare and contrast slow-twitch and fast-twitch skeletal muscle fibers.
8. Where is the smooth muscle found? What controls the contraction of smooth muscle?
9. Compare and contrast smooth muscle and striated muscle (such as skeletal muscle).
10. Where is the cardiac muscle found? What controls its contractions?
11. Both cardiac and skeletal muscle tissues are striated, but they look different from one another. Why?
12. The heart muscle is smaller and less powerful than some other muscles in the body. Why is the heart the muscle that performs the greatest amount of physical work in a lifetime? How does the heart resist fatigue?
13. Arrange the following units within a skeletal muscle in order, from smallest to largest: *fascicle; sarcomere; muscle fiber; myofibril*
14. Give one example of connective tissue that is found in muscles. Describe one of its functions.
15. *True or False:* skeletal muscle fibers are cells with multiple nuclei.

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# 6.4: MUSCLE CONTRACTION

## ARM WRESTLING

A sport like arm-wrestling depends on muscle contractions. Arm wrestlers must contract muscles in their hands and arms and *keep* them contracted to resist their opponent's opposing force. The wrestler whose muscles can contract with greater force wins the match.



Figure **6.4.1**: Arm wrestling

## MUSCLE CONTRACTION

### HOW A SKELETAL MUSCLE CONTRACTION BEGINS

Excluding reflexes, all skeletal muscle contractions occur as a result of conscious effort originating in the brain. The brain sends electrochemical signals through the somatic nervous system to motor neurons that innervate muscle fibers (to review how the brain and neurons function, see the chapter *Nervous System*). A single motor neuron with multiple axon terminals can innervate multiple muscle fibers, thereby causing them to contract at the same time. The connection between a motor neuron axon terminal and a muscle fiber occurs at a neuromuscular junction site**.** This is a chemical synapse where a motor neuron transmits a signal to muscle fiber to initiate a muscle contraction.

The process by which a signal is transmitted at a neuromuscular junction is illustrated in Figure **6.4.2**. The sequence of events begins when an action potential is initiated in the cell body of a motor neuron, and the action potential is propagated along the neuron's axon to the neuromuscular junction. Once the action potential reaches the end of the axon terminal, it causes the neurotransmitter acetylcholine (ACh) from synaptic vesicles in the axon terminal. The ACh molecules diffuse across the synaptic cleft and bind to the muscle fiber receptors, thereby initiating a muscle contraction. Muscle contraction is initiated with the depolarization of the sarcolemma caused by the sodium ions' entrance through the sodium channels associated with the ACh receptors.

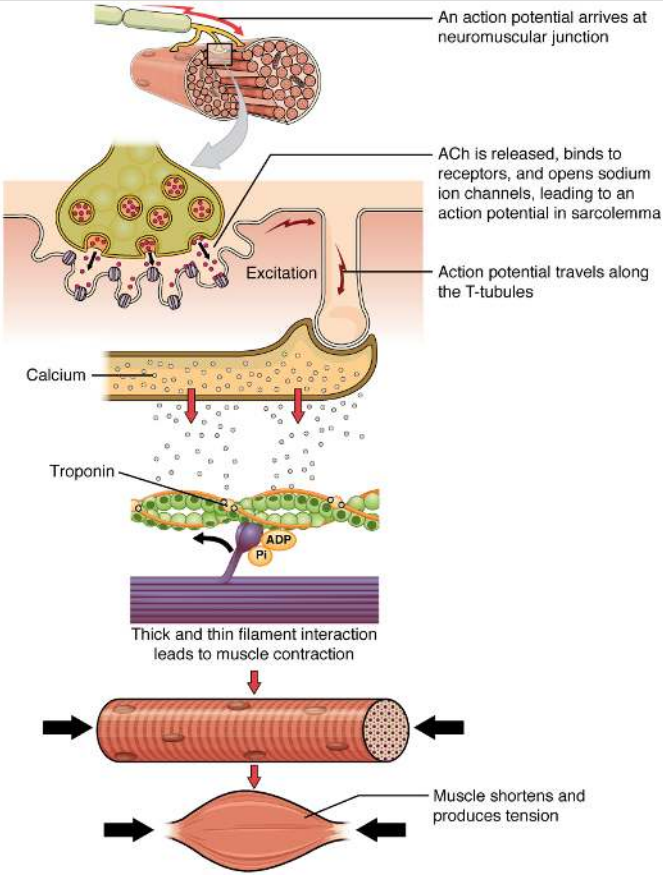



Figure **6.4.2**: This diagram represents the sequence of events that occurs when a motor neuron stimulates a muscle fiber to contract. The action potential travels down the t-tubules and excites the sarcoplasmic reticulum which releases calcium. Calcium when bound to troponin causes conformational changes in the sarcomere. Consequently, the interaction of thick and thin filaments of the sarcomere leads to muscle contraction.

Things happen very quickly in the world of excitable membranes (think about how quickly you can snap your fingers as soon as you decide to do it). Immediately following depolarization of the membrane, it repolarizes, re-establishing the negative membrane potential. Meanwhile, the ACh in the synaptic cleft is degraded by the enzyme acetylcholinesterase (AChE). The ACh cannot rebind to a receptor and reopen its channel, which would cause unwanted extended muscle excitation and contraction.

Propagation of an action potential along the sarcolemma enters the **T-tubules**. For the action potential to reach the membrane of the Sarcoplasmic Reticulum (SR), there are periodic invaginations in the sarcolemma, called **T-tubules** ("T" stands for "transverse"). The arrangement of a T-tubule with the membranes of SR on either side is called a **triad** (Figure **6.4.3**). The triad surrounds the cylindrical structure called a **myofibril**, which contains actin and myosin. The T-tubules carry the action potential into the interior of the cell, which triggers the opening of calcium channels in the membrane of the adjacent SR, causing $Ca^{++}$ to diffuse out of the SR and into the sarcoplasm. It is the arrival of $Ca^{++}$ in the sarcoplasm that initiates

contraction of the muscle fiber by its contractile units, or sarcomeres.

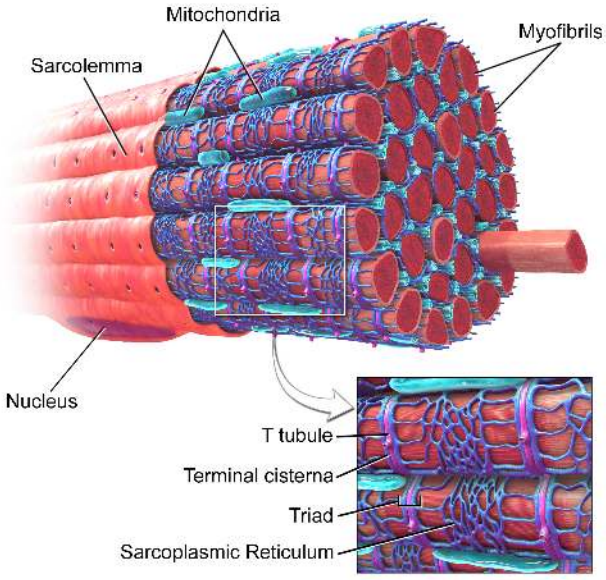



Figure **6.4.3**: Narrow T-tubules permit the conduction of electrical impulses. The SR functions to regulate intracellular levels of calcium. Two terminal cisternae (where enlarged SR connects to the T-tubule) and one T-tubule comprise a triad—a "threesome" of membranes, with those of SR on two sides and the T-tubule sandwiched between them.

## EXCITATION-CONTRACTION COUPLING

Although the term **excitation-contraction coupling** confuses or scares some students, it comes down to this: for a skeletal muscle fiber to contract, its membrane must first be "excited"—in other words, it must be stimulated to fire an action potential. The muscle fiber action potential, which sweeps along the sarcolemma as a wave, is "coupled" to the actual contraction through the release of calcium ions ($Ca^{++}$) from the SR. Once released, the $Ca^{++}$ interacts with the shielding proteins, troponin and tropomyosin complex, forcing them to move aside so that the actin-binding sites are available for attachment by myosin heads. The myosin then pulls the actin filaments toward the center, shortening the muscle fiber.

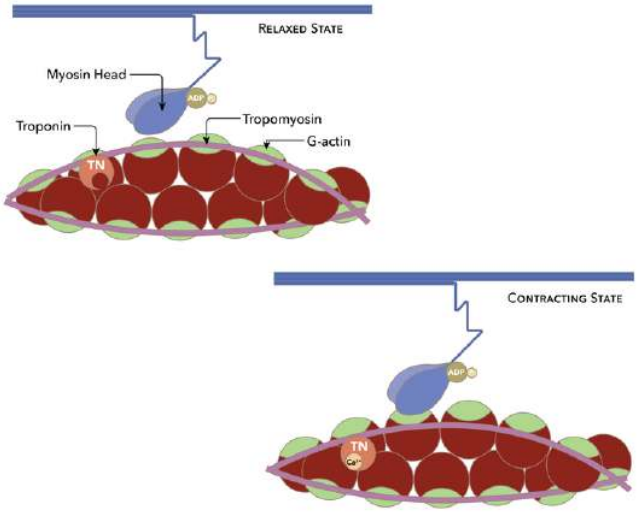



Figure **6.4.4**: Tropomyosin Troponin complex shields the cross-bridge sites on actin. Myosin can only bind with actin when this complex is removed with the help of Calcium ions.

In skeletal muscle, this sequence begins with signals from the somatic motor division of the nervous system. In other words, the "excitation" step in skeletal muscles is always triggered by signaling from the nervous system.

## SLIDING FILAMENT THEORY OF MUSCLE CONTRACTION

Once the muscle fiber is stimulated by the motor neuron, actin, and myosin protein filaments within the skeletal muscle fiber slide past each other to produce a contraction. The **sliding filament theory** is the most widely accepted explanation for how this occurs. According to this theory, muscle contraction is a cycle of molecular events in which thick myosin filaments repeatedly attach to and pull on thin actin filaments, so they slide over one another. The actin filaments are attached to Z discs, each of which marks the end of a sarcomere. The sliding of the filaments pulls the Z discs of a sarcomere closer together, thus shortening the sarcomere. As this occurs, the muscle contracts.

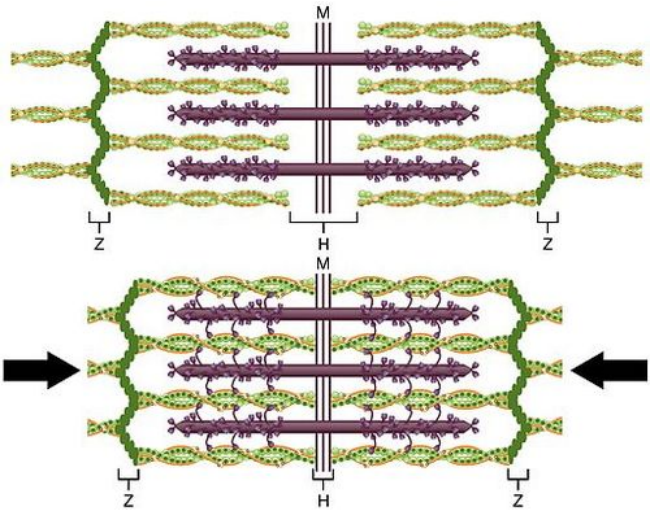



Figure **6.4.5**: The top diagram shows a relaxed sarcomere, and the bottom diagram shows a contracted sarcomere. Please note the z discs, h zone, and M line. In a contracted sarcomere the H zone reduces as compared to relaxed sarcomere because actin fibers (greenish-yellow double helix) move towards the M line.

## CROSSBRIDGE CYCLING

**Crossbridge cycling** is a sequence of molecular events that underlies the sliding filament theory. There are many projections from the thick myosin filaments, each of which consists of two myosin heads (you can see the projections and heads in Figures **6.4.5** and **6.4.3**). Each myosin head has binding sites for ATP (or ATP hydrolysis products: ADP and $P_i$) and actin. The thin actin filaments also have binding sites for the myosin heads—a cross-bridge forms when a myosin head binds with an actin filament.

The process of cross-bridge cycling is shown in Figure **6.4.6**. A cross-bridge cycle begins when the myosin head binds to an actin filament. ADP and $P_i$ are also bound to the myosin head at this stage. Next, a power stroke moves the actin filament inward toward the sarcomere center, thereby shortening the sarcomere. At the end of the power stroke, ADP and $P_i$ are released from the myosin head, leaving the myosin head attached to the thin filament until another ATP binds to the myosin head. When ATP binds to the myosin head, it causes the myosin head to detach from the actin filament. ATP is again split into ADP and $P_i$ and the energy released is used to move the myosin head into a "cocked" position. Once in this position, the myosin head can bind to the actin filament again, and another cross-bridge cycle begins.

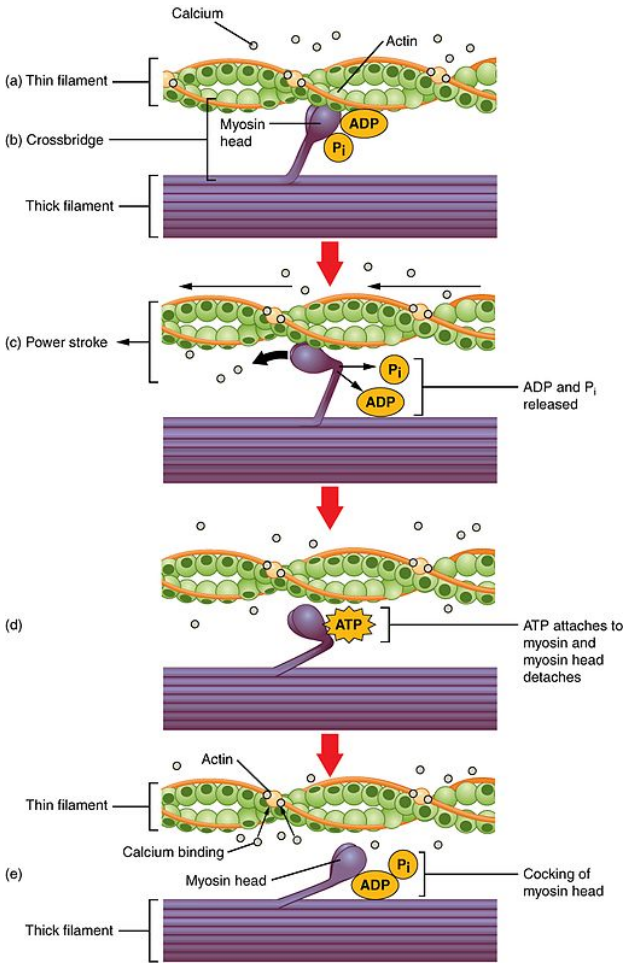



Figure **6.4.6**: Crossbridge cycling

## FEATURE: HUMAN BIOLOGY IN THE NEWS

Interesting and hopeful basic research on muscle contraction is often in the news because muscle contractions are involved in so many different body processes and disorders, including heart failure and stroke.

- **Heart failure** is a chronic condition in which cardiac muscle cells cannot contract forcefully enough to keep body cells adequately supplied with oxygen. In 2016, researchers at the University of Texas Southwestern Medical Center identified a potential new target for developing drugs to increase the strength of cardiac muscle contractions in patients with heart failure. The UT researchers found a previously unidentified protein involved in muscle contraction. The minimal protein turns off the “brake” on the heart, so it pumps blood more vigorously. At the molecular level, the protein affects the calcium-ion pump that controls muscle contraction. This result is likely to lead to searches for additional such proteins.
- A **stroke** occurs when a blood clot lodges in an artery in the brain and cuts off blood flow to part of the brain. Damage from the clot would be reduced if the smooth muscles lining brain arteries relaxed following a stroke because the arteries

would dilate and allow greater blood flow to the brain. In a recent study undertaken at the Yale University School of Medicine, researchers determined that the muscles lining blood vessels in the brain actually contract after a stroke. This constricts the vessels, reduces blood flow to the brain, and appears to contribute to permanent brain damage. The hopeful takeaway of this finding is that it suggests a new target for stroke therapy.

## REVIEW

1. What is skeletal muscle contraction?
2. Distinguish between isometric and isotonic contractions of skeletal muscle.
3. How does a motor neuron stimulate a skeletal muscle contraction?
4. What is the sliding filament theory?
5. Describe cross-bridge cycling.
6. Where does the ATP needed for a muscle contraction come from?
7. Explain why an action potential in a single motor neuron can cause multiple muscle fibers to contract.
8. The name of the synapse between a motor neuron and a muscle fiber is the _____ _____.
9. If a drug blocks the acetylcholine receptors on muscle fibers, what do you think this would do to muscle contraction? Explain your answer.
10. *True or False:* According to the sliding filament theory, actin filaments actively attach to and pull on myosin filaments.
11. *True or False:* When a motor neuron produces an action potential, the sarcomeres in the muscle fiber that it innervates become shorter as a result.
12. Explain how cross-bridge cycling and sliding filament theory are related to each other.
13. When does anaerobic respiration typically occur in human muscle cells?
14. If there were no ATP available in a muscle, how would this affect cross-bridge cycling? What would this do to muscle contraction?

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# 6.5: PHYSICAL EXERCISE

## STROLLERS

These caregivers are setting a great example for their children by engaging in physical exercise. Adopting a regular physical exercise habit is one of the most important ways to maintain fitness and good health. From higher self-esteem to a healthier heart, physical exercise can positively affect virtually all aspects of health, including physical, mental, and emotional health.



Figure **6.5.1**: Jogging with strollers

## WHAT IS PHYSICAL EXERCISE?

**Physical exercise** is any bodily activity that enhances or maintains physical fitness and overall health and wellness. We generally think of physical exercise as activities that are undertaken for the main purpose of improving physical fitness and health. However, physical activities that are undertaken for other purposes may also count as physical exercise. Scrubbing a floor, raking a lawn, or playing active games with young children or a dog are all activities that can have fitness and health benefits, even though they generally are not done mainly for this purpose.

How much physical exercise should people get? In the United States, both the Centers for Disease Control and Prevention and the Surgeon General have recommended that every adult participates in moderate exercise for a minimum of 30 minutes a day. This might include walking, swimming, and/or household or yard work.

## TYPES OF PHYSICAL EXERCISE

Physical exercise can be classified into three types, depending on the effects it has on the body: aerobic exercise, anaerobic exercise, and flexibility exercise. Many specific physical exercise examples (including playing soccer and rock climbing) can be classified as more than one type.

### AEROBIC EXERCISE

**Aerobic exercise** is any physical activity in which muscles are used below their maximum contraction strength, but for long periods of time. Aerobic exercise uses a relatively high percentage of slow-twitch muscle fibers that consume a large amount of oxygen. The main goal of aerobic exercise is to increase cardiovascular endurance, although it can have many other benefits, including muscle toning. Examples of aerobic exercise include cycling, swimming, brisk walking, jumping rope, rowing, hiking, and tennis.

### ANAEROBIC EXERCISE

**Anaerobic exercise** is any physical activity in which muscles are used close to their maximum contraction strength but for relatively short periods of time. Anaerobic exercise uses a relatively high percentage of fast-twitch muscle fibers that consume a small amount of oxygen. The goals of anaerobic exercise include building and strengthening muscles and improving bone strength, balance, and coordination. Examples of anaerobic exercise include push-ups, lunges, sprinting, interval training, resistance training, and weight training (such as biceps curls with a dumbbell, as pictured Figure **6.5.2**).



Figure **6.5.2**: Pitting the biceps muscle in the upper arm against a heavyweight helps build and strengthen this muscle.

### FLEXIBILITY EXERCISE

**Flexibility exercise** is any physical activity that stretches and lengthens muscles. The goals of flexibility exercise include increasing joint flexibility, keeping muscles limber, and improving the range of motion, all of which can reduce the risk of injury. Examples of flexibility exercises include stretching, yoga, and tai chi.

## HEALTH BENEFITS OF PHYSICAL EXERCISE

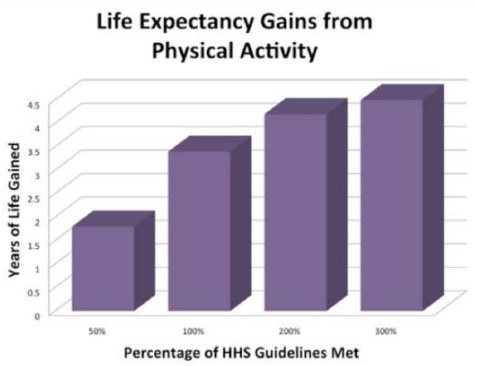



Figure 6.5.3: The U.S. Department of Health and Human Services (HHS) recommends that adults aged 18 to 64 engage in regular aerobic physical activity for 2.5 hours at moderate intensity (1.25 hours at vigorous intensity) each week. Moderate activities are those during which a person could talk but not sing. Vigorous activities are those during which a person could say only a few words without stopping to breathe. When people exercise at 50 percent of the HHS guidelines, they gain an average of 1.5 years of life. Exercising at 100 percent of the HHS guidelines results in a gain of almost four years of life. The gain in life expectancy starts to level off at about 300 percent of the HHS guidelines.

Many studies have shown that physical exercise is positively correlated with a diversity of health benefits. Some of these benefits include maintaining physical fitness, losing weight and maintaining a healthy weight, regulating digestive health, building and maintaining healthy bone density, increasing muscle strength, improving joint mobility, strengthening the immune system, boosting cognitive ability, and promoting psychological well-being. Some studies have also found a significant positive correlation between exercise and quality of life and life expectancy. People who participate in moderate to high levels of physical activity have been shown to have lower mortality rates than people of the same ages who are not physically active. The years of life gained with different amounts of physical activity are shown in the graph in Figure 6.5.3.

The underlying physiological mechanisms explaining why exercise has these positive health benefits are not completely understood. However, developing research suggests that many of the benefits of exercise may come about because of skeletal muscles' role as endocrine organs. Contracting muscles release hormones called **myokines**, which promote tissue repair and the growth of new tissue. Myokines also have anti-inflammatory effects, which, in turn, reduce the risk of developing inflammatory diseases. Exercise also reduces cortisol levels, the adrenal cortex stress hormone that may cause many health problems — both physical and mental — at sustained high levels.

## CARDIOVASCULAR BENEFITS OF PHYSICAL EXERCISE

The beneficial effects of exercise on the cardiovascular system are well documented. Physical inactivity has been identified as a risk factor for the development of coronary artery disease. There is also a direct correlation between physical inactivity and cardiovascular disease mortality. Physical exercise, in contrast, has been demonstrated to reduce several risk factors for cardiovascular disease, including hypertension (high blood pressure), "bad" cholesterol (low-density lipoproteins), high total cholesterol, and excess body weight. Physical exercise has also been shown to increase "good" cholesterol (high-density lipoproteins), insulin sensitivity, the mechanical efficiency of the heart, and exercise tolerance, which can perform physical activity without undue stress and fatigue.

## COGNITIVE BENEFITS OF PHYSICAL EXERCISE

Physical exercise has been shown to help protect people from developing neurodegenerative disorders, such as dementia. A 30-year study of almost 2,400 men found that those who exercised regularly had a 59 percent reduction in dementia when compared with those who did not exercise. Similarly, a review of cognitive enrichment therapies for the elderly found that physical activity — in particular, aerobic exercise — can enhance the cognitive function of older adults. Anecdotal evidence suggests that frequent exercise may even help reverse alcohol-induced brain damage. There are several possible reasons why exercise is so beneficial for the brain. Physical exercise:

- increases blood flow and oxygen availability to the brain
- increases growth factors that promote new brain cells and new neuronal pathways in the brain
- increases levels of neurotransmitters (such as serotonin), which increase memory retention, information processing, and cognition

## MENTAL HEALTH BENEFITS OF PHYSICAL EXERCISE

Numerous studies suggest that regular aerobic exercise works as well as pharmaceutical antidepressants in treating mild-to-moderate depression. A possible reason for this effect is that exercise increases the biosynthesis of at least three neurochemicals that may act as euphoriants. The euphoric effect of exercise is well known. Distance runners may refer to it as "runner's high," and people who participate in the crew (Figure 6.5.4) may refer to it as "rower's high." Because of these effects, health care providers often promote aerobic exercise as a treatment for depression.



Figure 6.5.4: This crew team is competing for the U.S. Army in the lightweight division of the world championships in 2003. They are clearly exerting themselves — and no doubt increasing their euphoriant neurochemicals in the process.

Additional mental health benefits of physical exercise include reducing stress, improving body image, and promoting positive self-esteem. Conversely, there is evidence to suggest that being sedentary is associated with an increased risk of anxiety.

### SLEEP BENEFITS OF PHYSICAL EXERCISE

A recent review of published scientific research suggests that exercise generally improves sleep for most people and helps sleep disorders, such as insomnia. Exercise is the most recommended alternative to sleeping pills for people with insomnia. For sleep benefits, the optimum time to exercise is four to eight hours before bedtime, although exercise at any time of day seems to be beneficial. The only possible exception is a heavy exercise undertaken shortly before bedtime, which may actually interfere with sleep.

### OTHER BENEFITS OF PHYSICAL EXERCISE

Some studies suggest that physical activity may benefit the immune system. For example, moderate excise is associated with a decreased incidence of upper respiratory tract infections. Evidence from many studies has found a correlation between physical exercise and reduced death rates from cancer, specifically breast cancer and colon cancer. Physical exercise has also been shown to reduce the risk of type 2 diabetes and obesity.

## VARIATION IN RESPONSES TO PHYSICAL EXERCISE

Not everyone benefits equally from physical exercise. When participating in aerobic exercise, most people will have a moderate increase in their endurance, but some will double their endurance. On the other hand, some people will show little or no increase in endurance from aerobic exercise. Genetic differences in slow-twitch and fast-twitch skeletal muscle fibers may play a role in these different results. People with more slow-twitch fibers may develop greater endurance because these muscle fibers have more capillaries, mitochondria, and myoglobin than fast-twitch fibers. As a result, slow-twitch fibers can carry more oxygen and sustain aerobic activity for a longer period of time than fast-twitch fibers. Studies show that endurance athletes (like the marathoner in Figure **6.5.5**) generally tend to have a higher proportion of slow-twitch fibers than other people.



Figure **6.5.5**: This winning marathoner is likely to have a relatively high proportion of slow-twitch muscle fibers that increase his endurance.

There is also great variation in individual responses to muscle building as a result of anaerobic exercise. Some people have a much greater capacity to increase muscle size and strength, whereas other people never develop large muscles, no matter how much they exercise them. People who have more fast-twitch than slow-twitch muscle fibers may develop bigger, stronger muscles because fast-twitch muscle fibers contribute more to muscle strength and have greater potential to increase in mass. Evidence suggests that athletes who excel at power activities (such as throwing and jumping) tend to have a higher proportion of fast-twitch fibers than endurance athletes.

## CAN YOU "OVERDOSE" ON PHYSICAL EXERCISE?



Figure **6.5.6**: New military recruits may suffer muscle damage from overexertion of unconditioned muscles. The drill instructor pictured here (in an orange shirt) is doing his best to encourage these marine recruits to expend their maximum effort.

Is it possible to exercise too much? Can too much exercise be harmful? Evidence suggests that some adverse effects may occur if exercise is extremely intense and the body is not given proper rest between exercise sessions. Athletes who train for multiple marathons have been shown to develop scarring of the heart and heart rhythm abnormalities. Doing too much exercise without prior conditioning also increases the risk of injuries to muscles and joints. Damage to muscles due to overexertion is often seen in new military recruits (Figure **6.5.6**). Too much exercise in females may cause amenorrhea, which is a cessation of menstrual periods. When this occurs, it generally indicates that a woman is pushing her body too hard.

Many people develop delayed onset muscle soreness (DOMS), which is pain or discomfort in muscles felt one to three days after exercising and generally subsides two or three days later. DOMS was once thought to be caused by the buildup of lactic acid in the muscles. Lactic acid is a product of anaerobic respiration in muscle tissues. However, lactic acid disperses fairly rapidly, so it is unlikely to explain pain experienced several days after exercise. The current theory is that DOMS is caused by tiny tears in muscle fibers, which occur when muscles are used at too high a level of intensity.

### FEATURE: MY HUMAN BODY

Most people know that exercise is important for good health, and it's easy to find endless advice about exercise programs and fitness plans. What is not so easy to find is the motivation to start exercising and stick with it. This is the main reason why so many people fail to get regular exercise. Practical concerns like a busy schedule and bad weather can certainly make exercising more of a challenge, but the biggest barriers to adopting a

regular exercise routine are mental. If you want to exercise but find yourself making excuses or getting discouraged and giving up, here are some tips that may help you get started and stay moving:

- **Avoid an all-or-nothing point of view.** Don't think you need to spend hours sweating at the gym or training for a marathon to get healthy. Even a little bit of exercise is better than nothing at all. Start with ten or 15 minutes of moderate activity each day. Taking a walk around your neighborhood is a great way to begin! From there, gradually increase the amount of time until you exercise to at least 30 minutes a day, five days a week.
- **Be kind to yourself, and reinforce positive behaviors with rewards.** Don't be down on yourself because you are overweight or out of shape. Don't beat yourself up because of a supposed lack of willpower. Instead, look at any past failures as opportunities to learn and do better. When you do achieve even small exercise goals, treat yourself to something special. Did you complete your first workout? Reward yourself with a relaxing bath or other treats.
- **Don't make excuses for not exercising.** Common complaints include being too busy or tired or not athletic enough. Such excuses are not valid reasons to avoid exercising, and they will sabotage any plans to improve your fitness. If you can't find a 30-minute period to work out, try to find ten minutes, three times a day. If you're feeling tired, know that exercise can actually reduce fatigue and boost your energy level. If you feel clumsy and uncoordinated, remind yourself that you don't need to be athletic to take a walk or engage in vigorous house or yard work.
- **Find an activity that you truly enjoy doing.** Don't think you have to lift weights or run on a treadmill to exercise your muscles. If you find such activities boring or unpleasant, you won't stick with them. Any activity that increases your heart rate and uses large muscles can provide a workout, especially if you're not in the habit of exercising, so find something you like to do. Do you like to dance? Put on some music and dance up a sweat! Do you enjoy gardening? Get out in the yard and dig up some dirt! Still not interested? Try an activity-based video game, such as Wii or Kinect. You may find it so much fun that it doesn't seem like exercise until you realize you've worked up a sweat.
- **Make yourself accountable.** Tell friends and family members that you're going to start exercising. You'll be letting them — as well as yourself — down if you don't follow through. Some people find that keeping an exercise log to track their progress is a good way to be accountable and stick to an exercise program. Perhaps the best way to keep at it is to find an exercise partner. If you've got someone waiting to exercise with you, you will be less likely to make excuses for not exercising.
- **Add more physical activity to your daily life.** You don't need to follow a structured exercise program to increase your activity level. Do your house or yard work briskly for a workout. Park your car further than necessary from work or the mall, and walk the extra distance. If you live close enough, leave the car at home and walk to and from your destination. Rather than taking elevators or escalators, walk up and downstairs. When you take breaks at work, take a walk instead of sitting. Every time a commercial comes on while you're watching TV, take a quick exercise break — run in place or do some curls with hand weights.

## REVIEW

1. How is physical exercise defined?
2. What are the current recommendations for physical exercise for adults?
3. Describe aerobic exercise, and give examples of aerobic exercises.
4. How does anaerobic exercise differ from aerobic exercise, and what are some examples of anaerobic exercises?
5. Define flexibility exercise, and state its benefits. What are two examples of flexibility exercises?
6. In general, how does physical exercise affect health, quality of life, and longevity?
7. What mechanism may underlie many of the general health benefits of physical exercise?
8. Relate physical exercise to cardiovascular disease risk.
9. What may explain the positive benefits of physical exercise on cognition?
10. How does physical exercise compare with antidepressant drugs in the treatment of depression?
11. Identify several other health benefits of physical exercise.
12. Explain how genetics may influence the way individuals respond to physical exercise.
13. Can too much physical exercise be harmful?
14. Lifting hefty weights for a short period of time is likely to:

    A. use a relatively high percentage of fast-twitch muscle fibers

    B. use a relatively high percentage of slow-twitch muscle fibers

    C. be an aerobic exercise

    D. use a large amount of oxygen

15. Walking quickly for an extended period of time is likely to:

    A. use a relatively high percentage of fast-twitch muscle fibers

    B. use a relatively high percentage of slow-twitch muscle fibers

    C. use muscles at close to their maximum contraction

    D. cause the muscles to use only a small amount of oxygen

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# 6.6: DISORDERS OF THE MUSCULAR SYSTEM

## PAIN IN THE NECK

Spending hours each day looking down at hand-held devices is a pain in the neck — literally. The weight of the head bending forward can put a lot of strain on neck muscles, and muscle injuries can be excruciating. Neck pain is one of the most common complaints that bring people to the doctor's office. In any given year, about one in five adults will suffer from neck pain. That's a lot of pain in the neck! Not all of them are due to muscular disorders, but many of them are. Muscular disorders, in turn, generally fall into two general categories: musculoskeletal disorders and neuromuscular disorders.



Figure **6.6.1**: On the phone

## MUSCULOSKELETAL DISORDERS

**Musculoskeletal disorders** are injuries in muscles or associated tissues (such as tendons) because of biomechanical stresses. They may be caused by sudden exertion, over-exertion, repetitive motions, or long periods of maintaining awkward positions. Musculoskeletal disorders often work- or sports-related, and generally, just one or a few muscles are affected. They can often be treated successfully, and full recovery can be very likely. The disorders include muscle strains, tendonitis, and carpal tunnel syndrome.

### MUSCLE STRAIN

A **muscle strain** is an injury in which muscle fibers tear as a result of overstretching. A muscle strain is also commonly called a pulled muscle or torn muscle. (Strains are often confused with sprains, which are similar injuries to ligaments.) Depending on the degree of injury to muscle fibers, a muscle strain can range from mildly to extremely painful. Besides pain, typical symptoms include stiffness and bruising in the area of the strained muscle. Figure **6.6.2** shows a large bruise caused by a hamstring muscle strain. Hamstring strains are prevalent in track and field athletes. In sprinters, for example, about one-third of injuries are hamstring injuries. Having a previous hamstring injury puts an athlete at increased risk of having another one.



Figure **6.6.2**: Bleeding in muscle tissue may cause a muscle strain to produce a bruise over the affected muscle, as in this hamstring bruise. The photos show two images of the same leg, both taken four days after the injury occurred.

Proper first aid for a muscle strain includes five steps, which are represented by the acronym PRICE. The PRICE steps should be followed for several days after the injury. The five steps are:

1. **Protection:** Apply soft padding to the strained muscle to minimize impact with objects that might cause further damage.
2. **Rest:** Rest the muscle to accelerate healing and reduce the potential for re-injury.
3. **Ice:** Apply ice for 20 minutes at a time every two hours to reduce swelling and pain.
4. **Compression:** Apply a stretchy bandage to the strained muscle to reduce swelling.
5. **Elevation:** Keep the strained muscle elevated to reduce the chance of blood pooling in the muscle.

Non-steroidal anti-inflammatory drugs (NSAIDs, such as ibuprofen) can help reduce inflammation and relieve pain. However, because such drugs interfere with blood clotting, they should be taken only after bleeding in the muscle has stopped — not immediately after the injury occurs. For severe muscle strains, professional medical care may be needed.

### TENDINITIS

**Tendinitis** is inflammation of a tendon that occurs when it is over-extended or worked too hard without rest. Tendons that are commonly affected include those in the ankle, knee, shoulder, and elbow. The affected tendon depends on the type of use that causes inflammation. Rock climbers tend to develop tendinitis in their fingers, while basketball players are more likely to develop tendonitis in the knees, to name a few examples.

Symptoms of tendinitis may include aching, sharp pain, a burning sensation, or joint stiffness. In some cases, swelling occurs around the inflamed tendon, and the area feels hot and looks red. Treatment includes the PRICE guidelines listed above and the use of NSAIDs to reduce inflammation and pain further. Although symptoms should show improvement within a few days of treatment, full recovery may take several months. A gradual return to exercise or other use of the affected tendon is recommended. Physical or occupational therapy may speed the return to normal activity levels.

## CARPAL TUNNEL SYNDROME

**Carpal tunnel syndrome** is a common biomechanical problem in the wrist when the median nerve becomes compressed between carpal bones (Figure **6.6.3**). This may occur due to repetitive use of the wrist, a tumor, or trauma to the wrist. Two-thirds of the cases are work-related. Computer work, work with vibrating tools and work requiring a strong grip all increase one's risk of developing this problem. Carpal tunnel syndrome occurs more often in women than in men. Other risk factors include obesity, pregnancy, and arthritis. Genetics may also play a role.

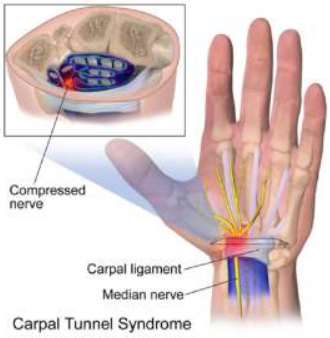



Figure **6.6.3**: Carpal tunnel syndrome occurs when the median nerve in the wrist becomes compressed.

Compression of the median nerve results in the muscles' inadequate nervous stimulation in the thumb and first two fingers of the hand. The main symptoms are pain, numbness, and tingling in these digits. Sometimes, symptoms can be improved by wearing a wrist splint or receiving corticosteroid injections. Surgery to cut the carpal ligament reduces pressure on the median nerve and is generally more effective than nonsurgical treatment. Recurrence of carpal tunnel syndrome after surgery is rare. On the other hand, without treatment, the lack of nervous stimulation by the median nerve may eventually cause the affected muscles of the hand to weaken and waste away.

## NEUROMUSCULAR DISORDERS

**Neuromuscular disorders** are systemic disorders that occur because of problems with the nervous control of muscle contractions or muscle cells themselves. These disorders are often due to faulty genes and not due to biomechanical stresses. Other system-wide problems, such as abnormal immune system responses, may also be involved in neuromuscular disorders.

Unlike musculoskeletal disorders, neuromuscular disorders generally affect most or all of the muscles in the body. The disorders also tend to be progressive and incurable. However, in most cases, treatment is available to slow the disease progression or lessen symptoms. Examples of neuromuscular disorders include muscular dystrophy, myasthenia gravis, and Parkinson's disease.

### MUSCULAR DYSTROPHY

**Muscular dystrophy** is a genetic disorder caused by defective proteins in muscle cells. It is characterized by progressive skeletal muscle weakness and death of muscle cells and tissues. Muscles become increasingly unable to contract in response to nervous stimulation.

There are at least nine major types of muscular dystrophy caused by different gene mutations. Some of the mutations cause autosomal recessive or autosomal dominant disorders, and some cause X-linked disorders. The most common type of childhood muscular dystrophy is Duchenne muscular dystrophy (DMD) due to a mutation in a recessive gene on the X chromosome. As an X-linked recessive disorder, Duchenne muscular dystrophy occurs almost exclusively in males.

Different types of muscular dystrophy affect different major muscle groups. In Duchenne muscular dystrophy, the lower limbs are affected. Signs of the disorder usually first become apparent when a child starts walking. Difficulty walking becomes progressively worse through childhood. By the time a child is ten, braces may be needed for walking — and walking may no longer even be possible by age 12. The lifespan of someone with muscular dystrophy is likely to be shorter than normal because of the disease, ranging from 15 to 45 years.

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.

In some cases, physical therapy, drug therapy, or orthopedic surgery may improve muscular dystrophy signs and symptoms. However, at present, there is no known cure for the disorder. Research is ongoing to find a cure, with financial support from such sources as the Muscular Dystrophy Association (MDA) (see photo below). MDA is a non-profit organization dedicated to curing muscular dystrophy by funding worldwide research.




Figure **6.6.4**: A firefighters from Camp Pendleton, California, who collected donations during their off hours for the Muscular Dystrophy Association (MDA) in 2010.

### MYASTHENIA GRAVIS

**Myasthenia gravis** is an autoimmune disorder in which circulating antibodies block the nicotinic acetylcholine receptors on the neuromuscular junction's motor endplate. This blockage of acetylcholine receptors causes muscle weakness, often first exhibiting drooping eyelids and expanding to include overall muscle

weakness and fatigue. It occurs more commonly in women and generally begins between the ages of 20 and 40. The initial symptom of myasthenia gravis is painless muscle weakness, generally in muscles around the eye (Figure 6.6.5). The disease then progresses to muscles elsewhere in the body, eventually involving most of the muscles. Swallowing and chewing may become difficult as the disease progresses, and speech may become slow and slur. In more advanced cases, myasthenia crises may occur, during which the muscles that control breathing may be affected. Emergency medical care to provide assisted ventilation is required to sustain life. A myasthenia gravis crisis may be triggered by various stressors, such as infection, fever, or stress. Treatment of myasthenia gravis may include medications to counter the mutant gene's effects or suppress the immune system.




Figure 6.6.5: The photograph on the left shows a myasthenia gravis patient with a drooping eyelid. The photo on the right shows the same patient after administering a drug that blocks the breakdown of acetylcholine.

## PARKINSON'S DISEASE



Figure 6.6.6: The awkward, stooped gait of this person is typical of people with advanced Parkinson's disease.

**Parkinson's disease** is a degenerative disorder of the central nervous system that mainly affects the muscular system and movement. Four motor signs and symptoms are considered defining Parkinson's disease: muscle tremor (shaking), muscle rigidity, slowness of movement, and postural instability. Tremor is the most common and obvious symptom, and it most often occurs in a limb at rest, so it disappears during sleep or when the patient moves the limb voluntarily. Difficulty walking eventually develops, and dementia is common in the advanced stages of the disease. Depression is common, as well.

Parkinson's disease is more common in older people, with most cases being diagnosed after 50. Often, the disease occurs for no known reason. Cases like this are called primary Parkinson's disease. Sometimes, the disease has a known or suspected cause, such as exposure to toxins in pesticides or repeated head trauma. In this case, it is called secondary Parkinson's disease. Regardless of the cause, the disease's motor symptoms result from the death of neurons in the midbrain. The cause of cell death is not fully understood, but it appears to involve the buildup in the brain of protein structures called Lewy bodies. Early in the course of the illness, medications can be prescribed to help reduce the motor disturbances. As the disease progresses, however, the medications become ineffective. They also cause a negative side effect of involuntary writhing movements.

### FEATURE: HUMAN BIOLOGY IN THE NEWS

On June 3, 2016, media worldwide exploded with news of the death of Muhammad Ali at the age of 74. The world champion boxer and Olympic gold medalist died that day of a respiratory infection complication, but the underlying cause was Parkinson's disease. Ali was diagnosed with Parkinson's in 1984 when he was only 42 years old. Doctors attributed his disease to repeated head trauma from boxing.

In the days following Ali's death, the news was full of stories and images from milestones in the athlete's life, both before and after his diagnosis with Parkinson's disease. Sadly, the news coverage also provided an overview of his gradual decline as the disease progressed. Ali was pictured in 1996, lighting the flame at the Summer Olympics in Atlanta. In 2012, Ali had to be helped to his feet by his wife to stand before the flag he was supposed to carry into the stadium. He was unable to carry it because of the ravages of Parkinson's disease.

Muhammad Ali retired from boxing in 1981 at 39, but he didn't retire from fighting. Until the final year of his life, Ali was a passionate activist for peace and justice and against war and racism. In 1998, he joined Michael J. Fox, who also has Parkinson's disease, to raise awareness and fund research on Parkinson's disease. In 2002, Fox and Ali made a joint appearance before Congress to present their case. In 2005, Ali received the Presidential Medal of Freedom from George W. Bush (Figure 6.6.7) for the many achievements and contributions he made throughout his amazing life, despite Parkinson's disease.



Figure 6.6.7: President George W. Bush gives a congratulatory hug to Muhammad Ali after awarding him a Presidential Medal of Freedom in 2005 as Ali's wife, Lonnie Ali, looks on.

## REVIEW

1. What are musculoskeletal disorders? What causes them?
2. How does a muscle strain occur?
3. Define tendinitis. Why does it occur?
4. Identify first-aid steps for treating musculoskeletal disorders such as muscle strains and tendinitis.
5. Describe carpal tunnel syndrome and how it may be treated.
6. Define neuromuscular disorders.
7. Identify the cause and symptoms of muscular dystrophy.

8. Outline the cause and progression of myasthenia gravis.
9. What is Parkinson's disease? List four characteristic signs of the disorder.
10. What are the main differences between musculoskeletal disorders and neuromuscular disorders?
11. Why is the padding of a strained muscle part of the typical treatment?
12. Which disorder would be the most likely to be caused by repeated use of a jackhammer?

    A. Parkinson's disease

    B. Muscular dystrophy

    C. Carpal tunnel syndrome

    D. A neuromuscular disorder

13. *True or False.* Participation in some sports may cause Parkinson's disease.
14. *True or False.* Myasthenia gravis occurs because the body stops making acetylcholine.
15. What are two tissues, other than muscle tissue, that can experience problems that result in muscular system disorders?

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# 6.7: CASE STUDY CONCLUSION- NEEDING TO RELAX AND CHAPTER SUMMARY

## CASE STUDY CONCLUSION: NEEDING TO RELAX

As you learned at the beginning of this chapter, botulinum toxin—one form sold under the brand name Botox—does much more than smooth out wrinkles. It can be used to treat several disorders involving excessive muscle contraction, including cervical dystonia. You also learned that cervical dystonia, from which Nasir suffers, causes abnormal, involuntary muscle contractions of the neck. This results in the head and neck's jerky movements and/or a sustained abnormal tilt to the head. It is often painful and can significantly interfere with a person's life.

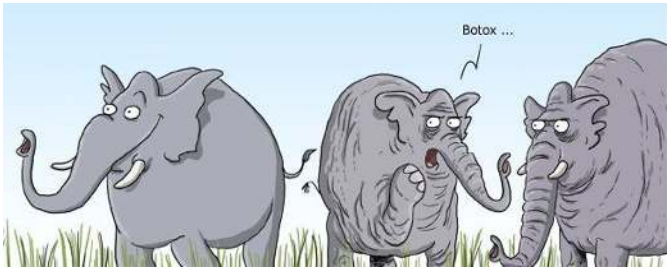



Figure **6.7.1**: Botox, he whispered.

How could a toxin actually *help* treat a muscular disorder? The soil bacterium *Clostridium botulinum* produces the botulinum toxin, and it is the cause of the potentially deadly disease called botulism. Botulism is often a foodborne illness, commonly caused by improperly canned foods. Other forms of botulism are caused by wound infections or occur when infants consume the bacteria's spores from soil or honey.

Botulism can be life-threatening because it paralyzes muscles throughout the body, including those involved in breathing. When a minimal amount of botulinum toxin is injected carefully into specific muscles by a trained medical professional, however, it can inhibit unwanted muscle contractions.




Figure **6.7.2**: These pickles are jokingly labeled "botulism," but actual botulism is really no joke.

For cosmetic purposes, botulinum toxin injected into the facial muscles relaxes them to reduce wrinkles' appearance. When used to treat cervical dystonia, it is injected into the neck muscles to inhibit excessive muscle contractions. For many patients, this helps relieve the abnormal positioning, movements, and pain associated with the disorder. The effect is temporary, so the injections must be repeated every three to four months to keep the symptoms under control.

How does botulinum toxin inhibit muscle contraction? First, recall how skeletal muscle contraction works. A motor neuron instructs skeletal muscle fibers to contract at a synapse between them called the neuromuscular junction. A nerve impulse called an action potential travels down to the motor neuron's axon terminal, where it causes the release of the neurotransmitter acetylcholine (ACh) from synaptic vesicles. The ACh travels across the synaptic cleft and binds to ACh receptors on the muscle fiber, signaling the muscle fiber to contract. According to the sliding filament theory, muscle fibers' contraction occurs due to the sliding of myosin and actin filaments across each other. This causes the Z discs of the sarcomeres to close together, shortening the sarcomeres and causing the muscle fiber to contract.

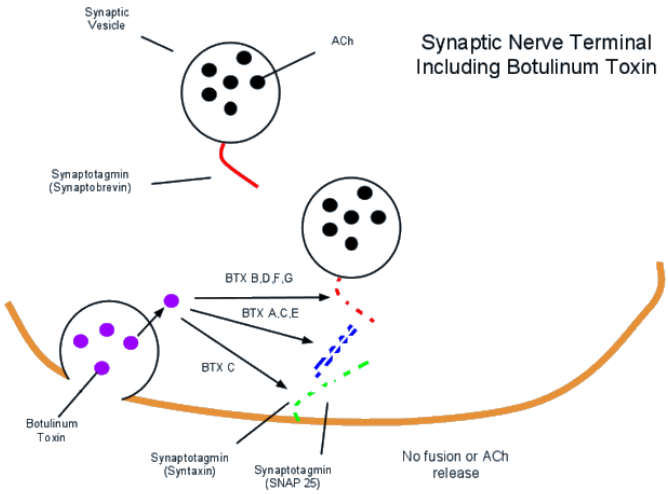



Figure **6.7.3**: Botulinum toxins cleave (break down) proteins (depicted here as red, blue, and green lines) that normally allow synaptic vesicles to bind to the membrane of the motor neuron's axon terminal to release the neurotransmitter ACh. Cleavage of these proteins prevents the synaptic vesicles from fusing to the membrane, and therefore ACh release is inhibited. In this illustration, BTX A-G refers to different subtypes of botulinum toxins.

If you wanted to inhibit muscle contraction, at what points could you theoretically interfere with this process? Inhibiting the action potential in the motor neuron, the release of ACh, the activity of ACh receptors, or the sliding filament process in the muscle fiber would all theoretically impair this process and inhibit muscle contraction. For example, in the disease myasthenia gravis, the ACh receptors' function is impaired, causing a lack of sufficient muscle contraction. As you have learned, this results in muscle weakness that can eventually become life-threatening. Botulinum toxin works by inhibiting the release of ACh from the motor neurons, thereby removing the signal instructing the muscles to contract (Figure **6.7.3**).

Fortunately, Nasir's excessive muscle contractions and associated pain improved significantly, thanks to botulinum toxin injections.

Although cervical dystonia cannot currently be cured, botulinum toxin injections have improved many patients' quality of life with this and other disorders involving excessive involuntary muscle contractions.

As you have learned in this chapter, our muscular system allows us to make voluntary movements, digest our food, and pump blood through our bodies. Whether in your arm, heart, stomach, or blood vessels, muscle tissue works by contracting. But as you have seen here, too much contraction can be a terrible thing. Fortunately, scientists and physicians have found a way to put a potentially deadly toxin—and wrinkle-reducing treatment—to excellent use as a medical treatment for some muscular system disorders.

## CHAPTER SUMMARY

In this chapter, you learned about the muscular system. Specifically, you learned that:

- The muscular system consists of all the muscles of the body. There are three types of muscle: skeletal muscle (which is attached to bones by tendons and enables voluntary body movements), cardiac muscle (which makes up the walls of the heart and makes it beat), and smooth muscle (which is found in the walls of internal organs and other internal structures and controls their movements).
- Muscles are organs composed mainly of muscle cells, which may also be called muscle fibers or myocytes. Muscle cells are specialized for contracting, which occurs when protein filaments inside the cells slide over one another using energy from ATP. Muscle tissue is the only type of tissue that has cells with the ability to contract.
- Muscles can grow larger or hypertrophy. This generally occurs through increased use, although hormonal or other influences can also play a role. Muscles can also grow smaller or atrophy. This may occur through lack of use, starvation, certain diseases, or aging. In both hypertrophy and atrophy, the size—but not the number—of muscle fibers changes. The size of the muscles is the main determinant of muscle strength.
- Skeletal muscles need the stimulus of motor neurons to contract and to move the body; they need the skeletal system to act upon.
- Skeletal muscle is the most common type of muscle tissue in the human body. To move bones in opposite directions, skeletal muscles often consist of pairs of muscles that work in opposition to move bones in different directions at joints.
- Skeletal muscle fibers are bundled together in muscle fascicles, which are bundled together to form individual skeletal muscles. Skeletal muscles also have connective tissue supporting and protecting the muscle tissue.
    - Each skeletal muscle fiber consists of a bundle of myofibrils, which are bundles of protein filaments. The filaments are arranged in repeating units called sarcomeres, which are the skeletal muscles' basic functional units. Skeletal muscle tissue is striated because of the pattern of sarcomeres in its fibers.
    - Skeletal muscle fibers can be divided into two types, called slow-twitch and fast-twitch fibers. Slow-twitch fibers are used mainly in aerobic endurance activities (such as long-distance running). Fast-twitch fibers are used mainly for non-aerobic, strenuous activities (such as sprinting). Proportions of the two types of fibers vary from muscle to muscle and person to person.
- Smooth muscle tissue is found in the walls of internal organs and vessels. When smooth muscles contract, they help the organs and vessels carry out their functions. Contractions of smooth muscles are involuntary and controlled by the autonomic nervous system, hormones, and other substances.
    - Cells of smooth muscle tissue are not striated because they lack sarcomeres, but the cells contract in the same basic way as striated muscle cells. Unlike striated muscle, smooth muscle can sustain very long-term contractions and maintain its contractile function, even when stretched.
- Cardiac muscle tissue is found only in the wall of the heart. When cardiac muscle contracts, the heart beats and pumps blood. Contractions of cardiac muscle are involuntary, like those of smooth muscles. Electrical impulses from specialized cardiac cells control them.
    - Like skeletal muscle, cardiac muscle is striated because its filaments are arranged in sarcomeres. However, the exact arrangement differs, making cardiac and skeletal muscle tissues look different from one another.
    - The heart is the muscle that performs the greatest amount of physical work in a lifetime. Its cells contain many mitochondria to produce ATP for energy and help the heart resist fatigue.
- A muscle contraction is an increase in tension or a decrease in the length of a muscle. A muscle contraction is isometric if muscle tension changes, but muscle length remains the same. It is isotonic if muscle length changes, but muscle tension remains the same.
    - A skeletal muscle contraction begins with the electrochemical stimulation of a muscle fiber by a motor neuron. This occurs at a chemical synapse called a neuromuscular junction. The neurotransmitter acetylcholine diffuses across the synaptic cleft and binds to receptors on the muscle fiber. This initiates a muscle contraction.
    - Once stimulated, the skeletal muscle fibers' protein filaments slide past each other to produce a contraction. The sliding filament theory is the most widely accepted explanation for how this occurs. According to this theory, thick myosin filaments repeatedly attach to and pull on thin actin filaments, thus shortening sarcomeres.
    - Crossbridge cycling is a cycle of molecular events that underlies the sliding filament theory. Using energy in ATP, myosin heads repeatedly bind with and pull on actin filaments. This moves the actin filaments toward the center of

a sarcomere, shortening the sarcomere and causing a muscle contraction.
    - The ATP needed for a muscle contraction comes first from ATP already available in the cell, and more is generated from creatine phosphate. These sources are quickly used up. Glucose and glycogen can be broken down to form ATP and pyruvate. Pyruvate can then be used to produce ATP in aerobic respiration if oxygen is available or used in anaerobic respiration if oxygen is not available.
- Physical exercise is defined as any bodily activity that enhances or maintains physical fitness and overall health. Activities such as household chores may even count as physical exercise! Current recommendations for adults are 30 minutes of moderate exercise a day.
- Aerobic exercise is any physical activity that uses muscles at less than their maximum contraction strength but for long periods of time. This type of exercise uses a relatively high percentage of slow-twitch muscle fibers that consume large amounts of oxygen. Aerobic exercises increase cardiovascular endurance and include cycling and brisk walking.
- Anaerobic exercise is any physical activity that uses muscles at close to their maximum contraction strength, but for short periods of time. This type of exercise uses a relatively high percentage of fast-twitch muscle fibers that consume small amounts of oxygen. Anaerobic exercises increase muscle and bone mass and strength, and they include push-ups and sprinting.
- Flexibility exercise is any physical activity that stretches and lengthens muscles, thereby improving the range of motion and reducing injury risk. Examples include stretching and yoga.
- Many studies have shown that physical exercise is positively correlated with a diversity of physical, mental, and emotional health benefits. Physical exercise also increases the quality of life and life expectancy.
    - Many of the exercise benefits may come about because contracting muscles release hormones called myokines, which promote tissue repair and growth and have anti-inflammatory effects.
    - Physical exercise can reduce risk factors for cardiovascular disease, including hypertension and excess body weight. Physical exercise can also increase cardiovascular health factors, such as the mechanical efficiency of the heart.
    - Physical exercise has been shown to offer protection from dementia and other cognitive problems, perhaps because it increases blood flow or neurotransmitters in the brain, among other potential effects.
    - Numerous studies suggest that regular aerobic exercise works and pharmaceutical antidepressants in treating mild-to-moderate depression, possibly because it increases the synthesis of natural euphoriants in the brain.
    - Research shows that physical exercise generally improves sleep for most people and helps sleep disorders, such as insomnia. Other health benefits of physical exercise include better immune system function and reduced risk of type 2 diabetes and obesity.
- There is great variation in individual responses to exercise, partly due to genetic differences in proportions of slow-twitch and fast-twitch muscle fibers. People with more slow-twitch fibers may be able to develop greater endurance from aerobic exercise. In contrast, people with more fast-twitch fibers may develop greater muscle size and strength from anaerobic exercise.
- Some adverse effects may occur if exercise is extremely intense, and the body is not given proper rest between exercise sessions. Many people who overwork their muscles develop delayed onset muscle soreness (DOMS), caused by tiny tears in muscle fibers.
- Musculoskeletal disorders are injuries in muscles or associated tissues (such as tendons) because of biomechanical stresses. The disorders may be caused by sudden exertion, over-exertion, repetitive motions, and similar stresses.
    - A muscle strain is an injury in which muscle fibers tear as a result of overstretching. First aid for a muscle strain includes the five steps represented by the acronym PRICE (protection, rest, ice, compression, and elevation). Medications for inflammation and pain (such as NSAIDs) may also be used.
    - Tendinitis is inflammation of a tendon that occurs when it is over-extended or worked too hard without rest. Tendinitis may also be treated with PRICE and NSAIDs.
    - Carpal tunnel syndrome is a biomechanical problem in the wrist when the median nerve becomes compressed between carpal bones. It may occur with repetitive use, a tumor, or trauma to the wrist. It may cause pain, numbness, and eventually—if untreated—muscle wasting in the thumb and first two fingers of the hand.
- Neuromuscular disorders are systemic disorders that occur because of problems with the nervous control of muscle contractions or muscle cells themselves.
    - Muscular dystrophy is a genetic disorder caused by defective proteins in muscle cells. It is characterized by progressive skeletal muscle weakness and death of muscle tissues.
    - Myasthenia gravis is a genetic neuromuscular disorder characterized by fluctuating muscle weakness and fatigue. More muscles are affected, and muscles become increasingly weakened, as the disorder progresses. Myasthenia gravis most often occurs because immune system antibodies block acetylcholine receptors on muscle cells because of the actual loss of acetylcholine receptors.
    - Parkinson's disease is a degenerative disorder of the central nervous system that mainly affects the muscular system and movement. It occurs because of the death of neurons in the midbrain. Characteristic signs of the disorder are muscle tremor, muscle rigidity, slowness of movement, and postural instability. Dementia and depression also often characterize advanced stages of the disease.

As you saw in this chapter, muscles need oxygen to provide enough ATP for most of their activities. In fact, all of the body's systems

require oxygen and remove waste products, such as carbon dioxide. In the next chapter, you will learn about how the respiratory system obtains and distributes oxygen throughout the body and how it removes wastes, such as carbon dioxide.

## CHAPTER SUMMARY REVIEW

1. *True or False.* Each motor neuron controls one muscle fiber.
2. *True or False.* Peristalsis is a pattern of muscle contraction in smooth muscle tissue.
3. When muscles atrophy:
   A. muscle fibers become narrower
   B. muscle fibers turn into fat cells
   C. muscle fibers are lost
   D. muscle fibers become shorter
4. What are tendons?
5. What is a muscular system disorder involving tendons?
6. Which of the main types of muscle tissue is used when you make a voluntary movement of one of your limbs?
7. Which main types of muscle tissue function independently of conscious control by the brain?
8. Describe the relationship between muscles, muscle fibers, and fascicles.
9. *Choose one.* The (autonomic; somatic) nervous system controls the skeletal muscles.
10. *True or False.* Sarcomeres are the cells of the muscular system.
11. *True or False.* Muscles contain connective tissue as well as muscle tissue.
12. The biceps and triceps muscles are shown in Figure **6.7.4**. Answer the following questions about these arm muscles.
    A. When the biceps contract and become shorter, as in the illustration, what kind of motion does this produce in the arm?
    B. Is the situation described in part more likely to be an isometric or isotonic contraction? Explain your answer.
    C. If the triceps were to then contract, which way would help the arm move?

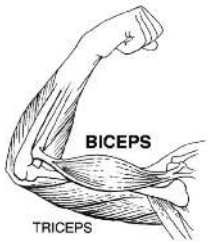



Figure **6.7.4**: biceps

13. Put the following events in order of when they occur during the process of skeletal muscle contraction, from earliest to latest:
    A. Acetylcholine binds to receptors on the muscle fiber
    B. Actin filaments slide, shortening the sarcomere
    C. An action potential is initiated in a motor neuron
    D. Acetylcholine is released from synaptic vesicles
14. What are Z discs, and what happens to them during muscle contraction?
15. *True or False.* Synapses only exist between neurons.
16. *True or False.* Muscles can produce hormones.
17. Which have been called the strongest muscles in the human body, relative to their work?
    A. The heart muscles
    B. The hamstring muscles
    C. The external eye muscles
    D. The stomach muscles
18. What is the function of mitochondria in muscle cells? Which type of muscle fiber has more mitochondria—slow-twitch or fast-twitch?
19. Fast-twitch and slow-twitch are types of which kind of muscle fibers?
    A. skeletal
    B. smooth
    C. cardiac
    D. B and C
20. Myoglobin:
    A. Stores oxygen for anaerobic respiration
    B. Stores oxygen for aerobic respiration
    C. Is present in higher amounts in fast-twitch fibers than slow-twitch fibers
    D. Is where ATP is produced
21. *True or False.* All people have the same proportion of slow-twitch to fast-twitch muscle fibers.
22. *True or False.* A sprain is a tear in the muscle fibers.
23. Which condition directly damages neurons, not muscles?
    A. Myasthenia gravis
    B. Muscular dystrophy
    C. Musculoskeletal disorder
    D. Parkinson's disease
24. What is the difference between primary and secondary Parkinson's disease?
25. Why can carpal tunnel syndrome cause muscle weakness in the hands?
26. *True or False.* The heart consists of smooth muscle tissue.
27. *True or False.* Sprinting is considered an anaerobic exercise

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# CHAPTER OVERVIEW

## 7: THE NERVOUS SYSTEM AND SENSES

This chapter describes neurons and other cells of the nervous system and compares and contrasts divisions of the nervous system, including central, peripheral, somatic, and autonomic divisions. The chapter explains how nerve impulses occur and how we sense stimuli. It also describes disorders of the nervous system and the effects of psychoactive drugs on the nervous system.


7.1: Case Study- The Control Center of Your Body

7.2: Introduction to the Nervous System

7.3: Neurons

7.4: Nerve Impulses

7.5: Central Nervous System

7.6: Peripheral Nervous System

7.7: Human Senses

7.8: Psychoactive Drugs

7.9: Case Study Conclusion- Memory and Chapter Summary


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# 7.1: CASE STUDY- THE CONTROL CENTER OF YOUR BODY

## CASE STUDY: FADING MEMORY

Each of these brightly colored sticky notes represents a piece of information that someone doesn't want to forget. Although we are all forgetful sometimes, most people do not have trouble remembering things that are important or routine to us, such as our friend's name or how to get to class. Our brain, the control center of the nervous system and the rest of the body, normally allows us to retain and recall information. But if the brain becomes damaged, a person may need to rely excessively on external reminders — like this wall of sticky notes — rather than being able to trust their own memory. That is if they are able to remember to write things down in the first place.

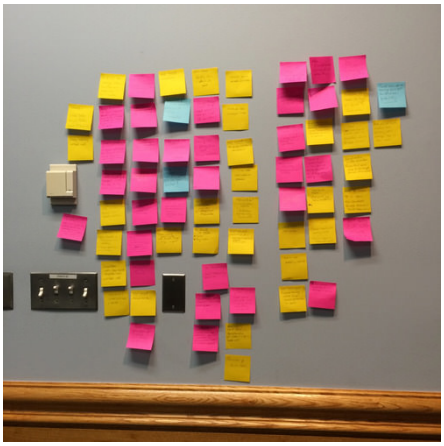


Figure **7.1.1**: Stickies

One person having trouble with their memory is Rosa, who is 68 years old. Rosa has been having difficulty remembering where she has set down objects in her house and forgot about a few doctor's appointments and lunches she planned with friends. Her family began to notice that she would sometimes not recall recent conversations, requiring them to repeat things to her. Rosa would also sometimes struggle to find the right word in a conversation and would put objects in unusual places, such as the milk in a cabinet instead of the refrigerator. While most people do things like this occasionally, it seemed to Rosa and her family that it was happening to her more often recently.

She also had some other symptoms that were impacting her life, such as having trouble paying her bills on time and managing her budget, which she had previously done well. Rosa ascribed these lapses in memory and mental functioning to the normal effects of aging, but her family was concerned. They noticed that she was also more irritable than usual and would sometimes verbally lash out at them, which was not like her. When she became disoriented on a walk around her neighborhood and a neighbor had to escort her home, her family convinced her to see a doctor.

Besides a complete physical exam and lab tests, Rosa's doctor interviewed Rosa and her family about her memory, ability to carry out daily tasks, and mood changes. He also administered a variety of tests to assess her memory and cognitive functioning, such as her ability to solve problems and use numbers and language correctly. Finally, he ordered a scan of her brain to investigate whether a tumor or some other observable cause was causing changes in the functioning of her brain.

Based on the results of these tests, Rosa's doctor came to the conclusion that she most likely has mild Alzheimer's disease (AD). AD results from abnormal changes in the molecules and cells of the brain, characterized by clumps of proteins called amyloid plaques between brain cells and tangled bundles of protein fibers called neurofibrillary tangles within certain brain cells. The affected brain cells stop functioning properly, lose their connections to other brain cells, and eventually will die. The picture below shows part of a cross-section of a brain from a patient who had severe AD compared to a similar section of a healthy brain. You can see how severely shrunken the brain with AD is, due to the death of many brain cells.

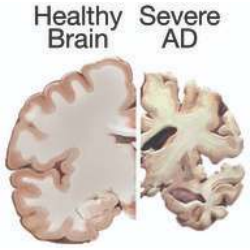



Figure **7.1.2**: The healthy brain is much larger than the brain with AD.

AD is a progressive disease, which means the damage and associated symptoms get worse over time. Clinicians have categorized the progression into three main stages — mild, moderate, and severe AD. Typically, AD cannot be definitively diagnosed until after death when the brain tissue can be directly examined for plaques and tangles. However, based on Rosa's symptoms and the results of her tests, her doctor thinks she most likely has mild AD, when the brain changes and resulting symptoms are not yet severe.

Although there is currently no cure for AD, and Rosa will eventually get worse, her doctor says that medications and behavioral therapies may improve and prolong her functioning and quality of life over the next few years. He prescribes a medication that improves communication between brain cells, which has been shown to help some people with AD.

As you read this chapter, you will learn much more about how the brain and the rest of the nervous system work, and the multitude of functions they control in the body. By the end of the chapter, you will have enough knowledge about the nervous system to learn more about why AD causes the symptoms that it does, how Rosa's medication works, and some promising new approaches that may help physicians diagnose and treat AD patients at earlier stages.

## CHAPTER OVERVIEW: NERVOUS SYSTEM

In this chapter, you will learn about the human nervous system, which includes the brain, spinal cord, and nerves. Specifically, you will learn about:

- The organization of the nervous system, including the central and peripheral nervous systems and their organs and subdivisions.
- The cells of the nervous system — neurons and glia — their parts, and their functions.
- How messages are sent by neurons through the nervous system and to and from the rest of the body.
- How these messages, or nerve impulses, are transmitted by electrical changes within neurons, and through chemical molecules to other cells.
- The structure and functions of different parts of the central nervous system, which includes the brain and spinal cord, and some of the things that can go wrong when they are damaged.
- The structure and functions of the peripheral nervous system, which includes the nerves that carry motor and sensory information to and from the body to control voluntary and involuntary activities.
- The human senses and how visual information, sounds, smells, tastes, touch, and balance are detected by sensory receptor cells and then sent to the brain for interpretation.
- How legal and illegal drugs can have psychoactive effects on the brain-altering mood, perceptions, thinking, and behavior — which can sometimes lead to addiction.

As you read the chapter, think about the following questions:

1. Based on Rosa's symptoms, which parts of her brain may have been affected by Alzheimer's disease?
2. How are messages sent between cells in the nervous system? What molecules are involved in this process? What are the ways in which drugs can alter this process?
3. Why can't Rosa's brain just grow new cells to replace the ones that have died?

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# 7.2: INTRODUCTION TO THE NERVOUS SYSTEM

## IN THE BLINK OF AN EYE

As you drive into a parking lot, a skateboarder suddenly flies in front of your car across your field of vision. You see the skateboarder in the nick of time and react immediately. You slam on the brakes and steer sharply to the right — all in the blink of an eye. You avoid a collision, but just barely. You're shaken up but thankful that no one was hurt. How did you respond so quickly? Such rapid responses are controlled by your nervous system.



Figure **7.2.1**: Skateboarder

## OVERVIEW OF THE NERVOUS SYSTEM

The **nervous system**, illustrated in Figure **7.2.2**, is the human organ system that coordinates all of the body's voluntary and involuntary actions by transmitting electrical signals to and from different parts of the body. Specifically, the nervous system extracts information from the internal and external environments using sensory receptors. It then usually sends signals encoding this information to the brain, which processes the information to determine an appropriate response. Finally, the brain sends signals to muscles, organs, or glands to bring about the response. In the example above, your eyes detected the skateboarder, the information traveled to your brain, and your brain instructed your body to act so as to avoid a collision.

## SIGNALS OF THE NERVOUS SYSTEM

The signals sent by the nervous system are electrical signals called nerve impulses, and they are transmitted by special nervous system cells named neurons, or nerve cells, like the one in Figure **7.2.3** (all the parts of a neuron are explained in the next section). Dendrites of a neuron receive nerve impulses from other cells. Long projection (called axons) from neurons carries nerve impulses directly to specific target cells. Schwann cells wrapped around the axon are called **glial cells**. They create a myelin sheath which allows the nerve impulse to travel very rapidly through the axons. A cell that receives nerve impulses from a neuron may be excited to perform a function, inhibited from carrying out an action, or otherwise controlled. In this way, the information transmitted by the nervous system is specific to particular cells and is transmitted very rapidly.

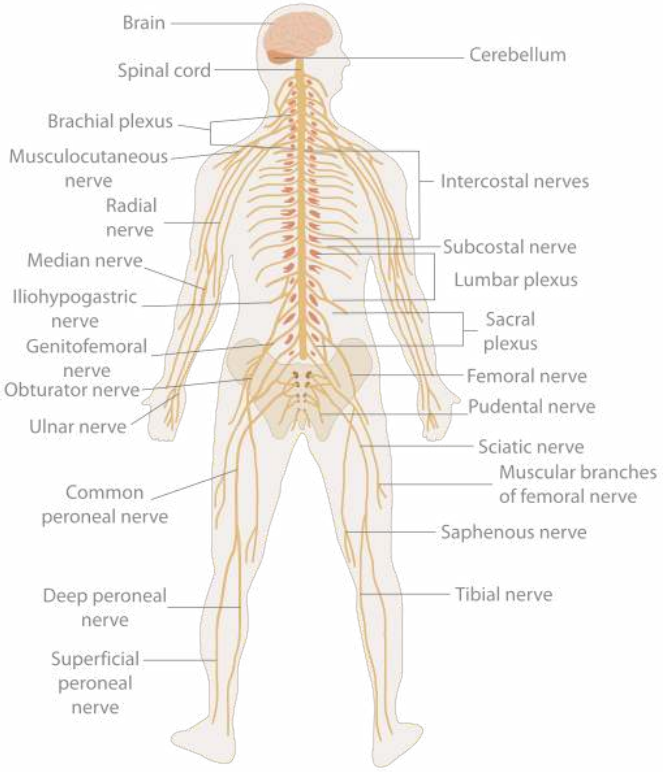



Figure **7.2.2**: The human nervous system consists of the brain and spinal cord (central nervous system) and a network of branching nerves that travel throughout the body (peripheral nervous system). Some of the major nerves in the peripheral system are identified in this drawing.

In fact, the fastest nerve impulses travel at speeds greater than 100 meters per second! Compare this to the chemical messages carried by the hormones that are secreted into the blood by endocrine glands. These hormonal messages are "broadcast" to all the cells of the body, and they can travel only as quickly as the blood flows through the cardiovascular system.

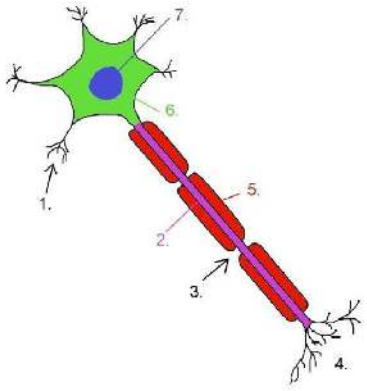



Figure **7.2.3**: This simple model of a neuron shows 1 Dendrite, 2 Axon, 3 Nodes of Ranvier, 4 Axon Terminals, 5 Schwann cell (Myelin Sheath), 6 Cell body, and 7 Nucleus

## ORGANIZATION OF THE NERVOUS SYSTEM

As you might predict, the human nervous system is very complex. It has multiple divisions, beginning with its two main parts, the central nervous system (CNS) and the peripheral nervous system (PNS), as shown in Figure **7.2.4**. The CNS includes the brain and spinal cord, and the PNS consists mainly of nerves, which are bundles of axons from neurons. The nerves of the PNS connect the CNS to the rest of the body. You can learn much more about the CNS by reading the concept *Central Nervous System*.

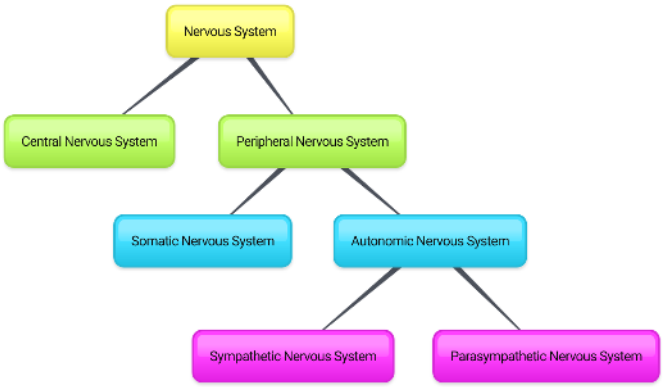



Figure **7.2.4**: The concept map illustrates that the nervous system is divided into the peripheral and central systems. The peripheral nervous system is divided into the autonomic and somatic systems. The autonomic nervous system is divided into the sympathetic and parasympathetic systems.

The PNS is divided into two major parts, called the autonomic and somatic nervous systems. The somatic nervous system controls activities that are under voluntary control, such as turning a steering wheel. The autonomic nervous system controls activities that are not under voluntary control, such as digesting a meal. The autonomic nervous system has two divisions: the sympathetic division, which controls the fight-or-flight response during emergencies, and the parasympathetic division, which controls the routine "housekeeping" functions of the body at other times. You can learn more about the PNS and its subdivisions by reading the concept *Peripheral Nervous System*.

## REVIEW

1. List the general steps by which the nervous system generates an appropriate response to information from the internal and external environments.
2. What are neurons?
3. Compare and contrast the central and peripheral nervous systems.
4. Which major division of the peripheral nervous system allows you to walk to class? Which major division of the peripheral nervous system controls your heart rate?
5. Identify the functions of the three divisions of the autonomic nervous system.
6. What is an axon and what is its function?
7. *True or False*. A nerve impulse always causes the target cell to perform an action.
8. *True or False*. The spinal cord is not considered part of the peripheral nervous system.
9. Define nerve impulses.
10. Explain why signals in the nervous system are generally more targeted and specific than signals in the endocrine system.
11. Explain generally how the brain and spinal cord can interact with and control the rest of the body.
12. _____ actions are performed without the person thinking about them.
13. The fight-or-flight response is controlled by the:
    A. autonomic nervous system
    B. somatic nervous system
    C. central nervous system
    D. parasympathetic nervous system
14. How are nerves and neurons related?
15. What type of information from the outside environment do you think is detected by sensory receptors in your ears?

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# 7.3: NEURONS

## LIFE AS ART

This colorful picture could be an abstract work of modern art. You might imagine it hanging in an art museum or art gallery. In fact, the picture illustrates real life rather than an artistic creation. It is a micrograph of human nervous tissue. The neon green structures in the picture are neurons. The neuron is one of two basic types of cells in the nervous system, the other type being the glial cell.

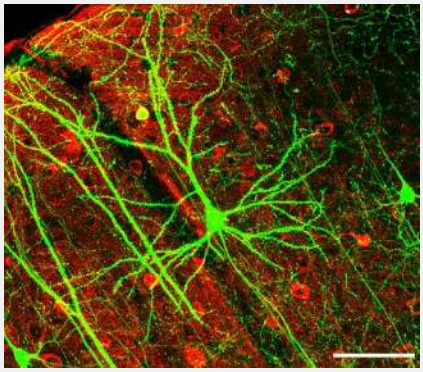


Figure **7.3.1**: Interneurons of Adult Visual Cortex

**Neurons,** also called nerve cells, are electrically excitable cells that are the main functional units of the nervous system. Their function is to transmit nerve impulses. They are the only type of human cells that can carry out this function.

### NEURON STRUCTURE

Figure **7.3.2** shows the structure of a typical neuron. The main parts of a neuron are labeled in the figure and described below.

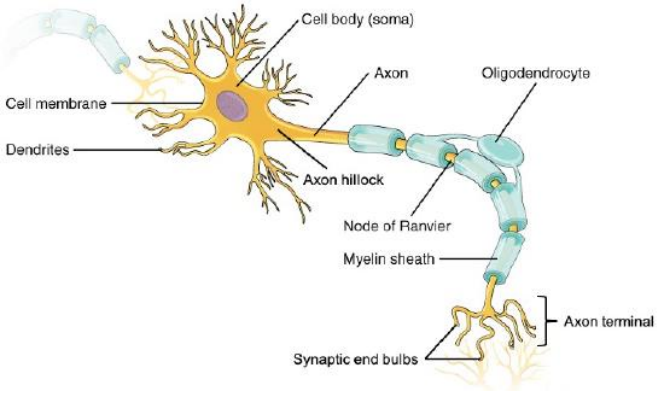



Figure **7.3.2**: Somatic Motor Neuron with cell body, axon, axon, myelin sheath, nodes of Ranvier, axon terminal, dendrites, synaptic end of the bulbs, and other associated structures.

- The **cell body** is the part of a neuron that contains the cell nucleus and other cell organelles. It is usually quite compact, and may not be much wider than the nucleus.
- **Dendrites** are thin structures that are extensions of the cell body. Their function is to receive nerve impulses from other cells and carry them to the cell body. A neuron may have many dendrites, and each dendrite may branch repeatedly to form a dendrite "tree" with more than 1,000 "branches." The end of each branch can receive nerve impulses from another cell, allowing a given neuron to communicate with tens of thousands of other cells.
- The **axon** is a long, thin extension of the cell body. It transmits nerve impulses away from the cell body and toward other cells. The axon branches at the end, forming multiple axon terminals. These are the points where nerve impulses are transmitted to other cells, often to the dendrites of other neurons. An area called a synapse occurs at each axon terminal. Synapses are complex membrane junctions that transmit signals to other cells. An axon may branch hundreds of times, but there is never more than one axon per neuron.
- Spread out along axons, especially the long axons of nerves, are many sections of the **myelin sheath.** These are lipid layers that cover sections of the axon. The myelin sheath is a very good electrical insulator, similar to the plastic or rubber that encases an electrical cord.
- Regularly spaced gaps between sections of myelin sheath occur along the axon. These gaps are called **nodes of Ranvier**, and they allow the transmission of nerve impulses along the axon. Nerve impulses skip from node to node, allowing nerve impulses to travel along the axon very rapidly.
- A Schwann cell (also on an axon) is a type of glial cell. Its function is to produce the myelin sheath that insulates axons in the peripheral nervous system. In the central nervous system, a different type of glial cell, called an oligodendrocyte, produces the myelin sheath.

### NEUROGENESIS

Fully differentiated neurons, with all their special structures, cannot divide and form new daughter neurons. Until recently, scientists thought that new neurons could no longer be formed after the brain developed prenatally. In other words, they thought that people were born with all the brain neurons they would ever have, and as neurons died, they would not be replaced. However, new evidence shows that additional neurons can form in the brain, even in adults, from the division of undifferentiated neural stem cells that are found throughout the brain. The production of new neurons is called **neurogenesis.** The extent to which it can occur is not known, but it is not likely to be very great in humans.

### NEURONS IN NERVOUS TISSUES

The nervous tissue in the brain and spinal cord consists of gray matter and white matter. Gray matter contains mainly the cell bodies of neurons. It is gray only in cadavers; living gray matter is actually more pink than gray (see image below). White matter consists mainly of axons covered with myelin sheath, which gives them their white color. White matter also makes up nerves of the peripheral nervous system. Nerves consist of long bundles of myelinated axons that extend to muscles, organs, or glands throughout the body. The axons in each nerve are bundled together like wires in a cable.

Axons in nerves may be more than a meter long in an adult. The longest nerve runs from the base of the spine to the toes.

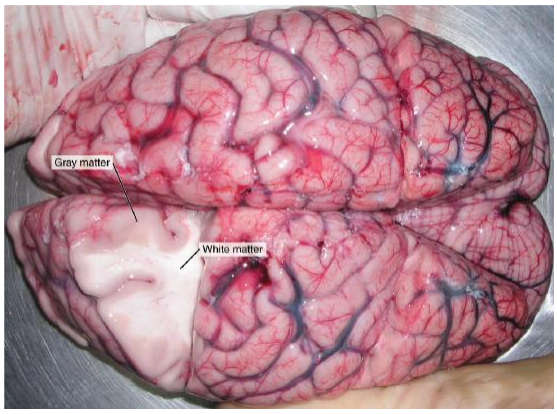



Figure **7.3.3**: You can see the layers of (pinkish) gray matter and white matter in this photo of a brain from a recently deceased human patient

## TYPES OF NEURONS

There are hundreds of different types of neurons in the human nervous system. These types exhibit a variety of structures and functions. Nonetheless, many neurons can be classified functionally based on the direction in which they carry nerve impulses.

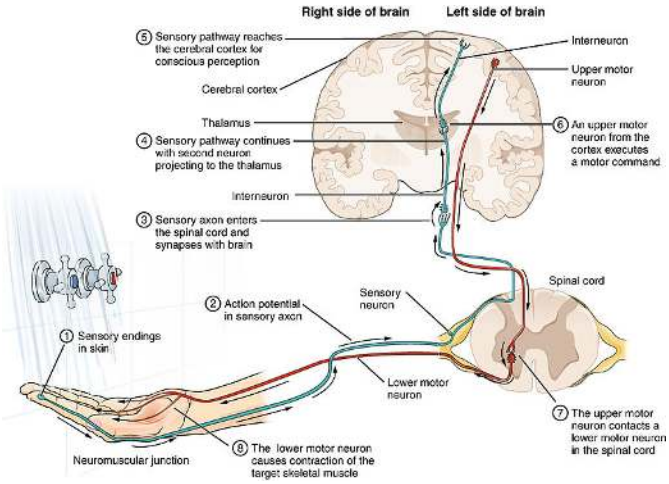



Figure **7.3.4**: Sensory neurons carry information towards the CNS. Motor neurons carry information from the CNS. Interneurons carry information between sensory and motor neurons.

- **Sensory** (also called afferent) **neurons** carry nerve impulses from sensory receptors in tissues and organs to the central nervous system. They change physical stimuli such as touch, light, and sound into nerve impulses.
- **Motor** (also called efferent) **neurons,** like the one in figure **7.3.2**, carry nerve impulses from the central nervous system to muscles and glands. They change nerve signals into the activation of these structures.
- **Interneurons** carry nerve impulses back and forth often between sensory and motor neurons within the spinal cord or brain.

## GLIAL CELLS

Besides neurons, nervous tissues also consist of **glial cells** (also called neuroglia). They are now known to play many vital roles in the nervous system. There are several different types of glial cells, each with a different function. Schwann cells and Oligodendrocytes are glial cells that produce myelin sheath.

### FEATURE: MY HUMAN BODY

Would you like your brain to make new neurons that could help you become a better learner? What college student wouldn't want a little more brainpower when it comes to learning new things? If research on rats applies to humans, then sustained aerobic exercise such as running can increase neurogenesis in the adult brain, and specifically in the hippocampus, a brain structure important for learning temporally and/or spatially complex tasks as well as memory. Although the research is still at the beginning stages, it suggests that exercise may actually lead to a "smarter" brain. However, even if the research results are not confirmed in the future for humans, it can't hurt to get more aerobic exercise, because it is certainly beneficial for your body if not for your brain.

## REVIEW

1. Identify the three main parts of a neuron and their functions.
2. Describe the myelin sheath and nodes of Ranvier. How does their arrangement allow nerve impulses to travel very rapidly along axons?
3. What is a synapse?
4. Define neurogenesis. What is the potential for neurogenesis in the human brain?
5. Relate neurons to different types of nervous tissues.
6. Compare and contrast sensory and motor neurons.
7. Identify the role of interneurons.
8. For each type of neuron below, identify whether it is a sensory neuron, motor neuron, or interneuron.
   A. A neuron in the spinal cord receives touch information and then transmits that information to another spinal cord neuron that controls the movement of an arm muscle.
   B. A neuron that takes taste information from your tongue and sends it to your brain.
   C. A spinal cord neuron stimulates a muscle to contract.
9. The myelin sheath is made by:
   A. Sensory neurons
   B. White neurons
   C. Peripheral nervous system neurons
   D. Glial cells
10. *True or False.* Synapses often exist where a dendrite and an axon terminal meet.
11. *True or False.* There is only one axon terminal per neuron.

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# 7.4: NERVE IMPULSES

## WHEN LIGHTNING STRIKES

This amazing cloud-to-surface lightning occurred when a difference in electrical charge built up in a cloud relative to the ground. When the buildup of charge was great enough, a sudden discharge of electricity occurred. A nerve impulse is similar to a lightning strike. Both a nerve impulse and a lightning strike occur because of differences in electrical charge, and both result in an electric current.



Figure **7.4.1**: Lightning

## GENERATING NERVE IMPULSES

A **nerve impulse**, like a lightning strike, is an electrical phenomenon. A nerve impulse occurs because of a difference in electrical charge across the plasma membrane of a neuron. How does this difference in electrical charge come about? The answer involves ions, which are electrically charged atoms or molecules.

### RESTING POTENTIAL

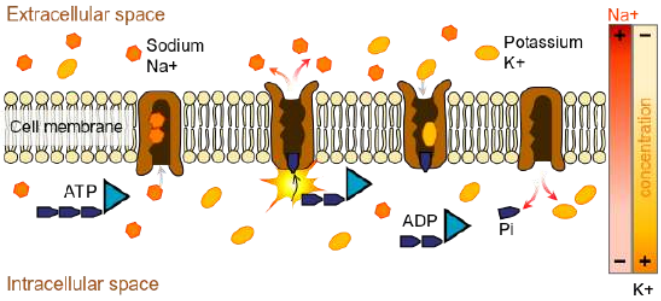



Figure **7.4.2**: The sodium-potassium pump maintains the resting potential of a neuron. There is more negative charge inside than outside the cell membrane. ATP is used to pump sodium out and potassium into the cell. There is more concentration of sodium outside the membrane and more concentration of potassium inside the cell due to the unequal movement of these ions by the pump

When a neuron is not actively transmitting a nerve impulse, it is in a resting state, ready to transmit a nerve impulse. During the resting state, the sodium-potassium pump maintains a difference in charge across the cell membrane of the neuron. The sodium-potassium pump is a mechanism of active transport that moves sodium ions out of cells and potassium ions into cells. The sodium-potassium pump moves both ions from areas of lower to higher concentration, using energy in ATP and carrier proteins in the cell membrane. Figure **7.4.3** shows in greater detail how the sodium-potassium pump works. Sodium is the principal ion in the fluid outside of cells, and potassium is the principal ion in the fluid inside of cells. These differences in concentration create an electrical gradient across the cell membrane, called **resting potential**. Tightly controlling membrane resting potential is critical for the transmission of nerve impulses.

## ACTION POTENTIAL

An **action potential**, also called a nerve impulse, is an electrical charge that travels along the membrane of a neuron. It can be generated when a neuron's membrane potential is changed by chemical signals from a nearby cell. In an action potential, the cell membrane potential changes quickly from negative to positive as sodium ions flow into the cell through ion channels, while potassium ions flow out of the cell, as shown in Figure **7.4.3**.

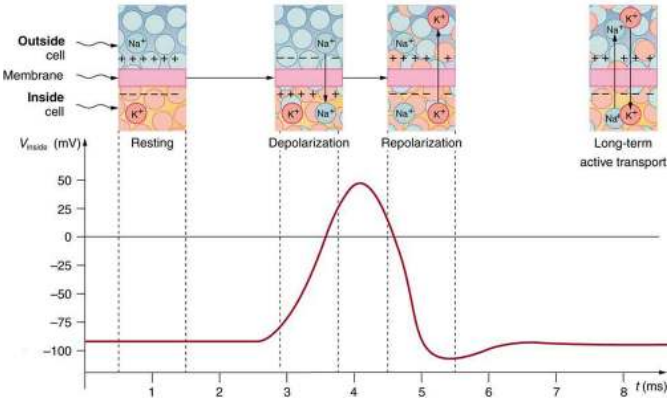



Figure **7.4.3**: An action potential speeds along an axon in milliseconds. Sodium ions flow in and cause the action potential, and then potassium ions flow out to reset the resting potential.


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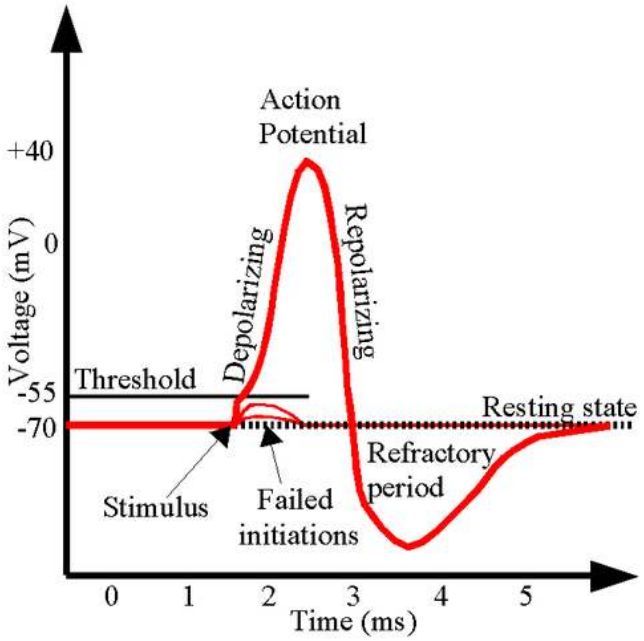



Figure **7.4.4**: An action potential graph of membrane potential over time. A neuron must reach a certain threshold in order to begin the depolarization step of reaching the action potential. The figure also shows the change in potential during the repolarization and refractory periods of the axon.

The change in membrane potential results in the cell becoming depolarized. An action potential works on an all-or-nothing basis. That is, the membrane potential has to reach a certain level of depolarization, called the threshold, otherwise, an action potential will not start. This threshold potential varies but is generally about 15 millivolts (mV) more positive than the cell's resting membrane potential. If a membrane depolarization does not reach the threshold level, an action potential will not happen. You can see in Figure **7.4.4** that two depolarizations did not reach the threshold level of -55mV.

The first channels to open are the sodium ion channels, which allow sodium ions to enter the cell. The resulting increase in positive charge inside the cell (up to about +40 mV) starts the action potential. This is called the depolarization of the membrane. Potassium ion channels then open, allowing potassium ions to flow out of the cell, which ends the action potential. The inside of the membrane becomes negative again. This is called repolarization of the membrane. Both of the ion channels then close, and the sodium-potassium pump restores the resting potential of -70 mV. The action potential will move down the axon toward the synapse like a wave would move along the surface of the water. Figure **7.4.4**shows the change in potential of the axon membrane during an action potential. The nerve goes through a brief refractory period before racing resting potential. During the refractory period, another action potential cannot be generated

In myelinated neurons, ion flows occur only at the nodes of Ranvier. As a result, the action potential signal "jumps" along the axon membrane from node to node rather than spreading smoothly along the membrane, as they do in axons that do not have a myelin sheath. This is due to a clustering of Na+ and K+ ion channels at the Nodes of Ranvier. Unmyelinated axons do not have nodes of Ranvier, and ion channels in these axons are spread over the entire membrane surface.

## TRANSMITTING NERVE IMPULSES

The place where an axon terminal meets another cell is called a **synapse.** This is where the transmission of a nerve impulse to another cell occurs. The cell that sends the nerve impulse is called the presynaptic cell, and the cell that receives the nerve impulse is called the postsynaptic cell.

Some synapses are purely electrical and make direct electrical connections between neurons. However, most synapses are chemical synapses. The transmission of nerve impulses across chemical synapses is more complex.

### CHEMICAL SYNAPSES

At a chemical synapse, both the presynaptic and postsynaptic areas of the cells are full of the molecular machinery that is involved in the transmission of nerve impulses. As shown in Figure **7.4.5**, the presynaptic area contains many tiny spherical vessels called synaptic vesicles that are packed with chemicals called **neurotransmitters**. When an action potential reaches the axon terminal of the presynaptic cell, it opens channels that allow calcium to enter the terminal. Calcium causes synaptic vesicles to fuse with the membrane, releasing their contents into the narrow space between the presynaptic and postsynaptic membranes. This area is called the synaptic cleft. The neurotransmitter molecules travel across the synaptic cleft and bind to **receptors**, which are proteins that are embedded in the membrane of the postsynaptic cell.

The effect of a neurotransmitter on a postsynaptic cell depends mainly on the type of receptors that it activates, making it possible for a particular neurotransmitter to have different effects on various target cells. A neurotransmitter might excite one set of target cells, inhibit others, and have complex modulatory effects on still others, depending on the type of receptors. However, some neurotransmitters have relatively consistent effects on other cells.

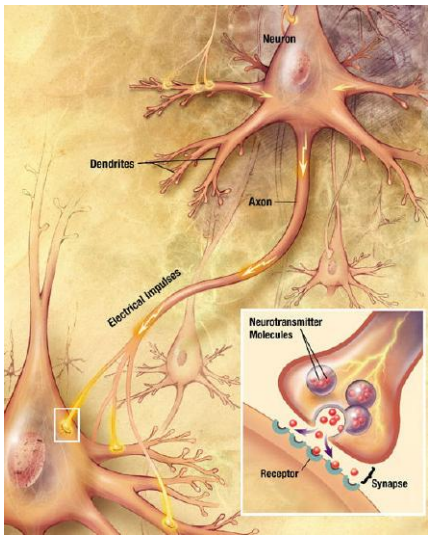



Figure 7.4.5: This diagram shows how an action potential transmits a signal across a synapse to another cell by neurotransmitter molecules. The inset diagram shows the axon terminal, synapse, and receptor of the postsynaptic cell. The neurotransmitters are released from the axon terminal, travel in the synaptic cleft, and attach to the receptors.

## REVIEW

1. Define nerve impulse.
2. What is the resting potential of a neuron, and how is it maintained?
3. Explain how and why an action potential occurs.
4. Outline how a signal is transmitted from a presynaptic cell to a postsynaptic cell at a chemical synapse.
5. What generally determines the effects of a neurotransmitter on a postsynaptic cell?
6. Identify three general types of effects neurotransmitters may have on postsynaptic cells.
7. Explain how an electrical signal in a presynaptic neuron causes the transmission of a chemical signal at the synapse.
8. The flow of which type of ion into the neuron results in an action potential?
   A. How do these ions get into the cell?
   B. What does this flow of ions do to the relative charge inside the neuron compared to the outside?
9. The sodium-potassium pump:
   A. is activated by an action potential
   B. requires energy
   C. does not require energy
   D. pumps potassium ions out of cells
10. *True or False.* Some action potentials are larger than others, depending on the amount of stimulation.
11. *True or False.* Synaptic vesicles from the presynaptic cell enter the postsynaptic cell.
12. *True or False.* An action potential in a presynaptic cell can ultimately cause the postsynaptic cell to become inhibited.
13. Name three neurotransmitters.

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# 7.5: CENTRAL NERVOUS SYSTEM

## HOMUNCULUS

Figure **7.5.1** is a very odd-looking drawing and is called a homunculus. The mass represents a cross-sectional wedge of the human brain. The drawing shows some areas of the brain associated with different parts of the body. As you can see, larger areas of the brain in this region are associated with the hands, face, and tongue than the legs and feet. Given the importance of speech, manual dexterity, and face-to-face social interactions in human beings, it is not surprising that relatively large areas of the brain are needed to control these body parts. The brain is the most complex organ in the human body and part of the central nervous system.

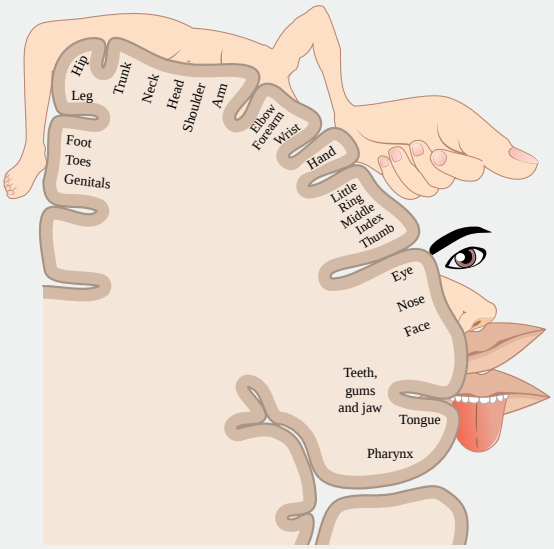



Figure **7.5.1**: Brain-Body Map. There's a map of your body on your brain's cortex, but the map is not proportional to actual space. Sensitive parts like the face and fingers are represented by more areas than less sensitive parts like the legs or back

## WHAT IS THE CENTRAL NERVOUS SYSTEM?

The central nervous system (CNS) is the part of the nervous system that includes the brain and spinal cord. Figure **7.5.2** shows the central nervous system as one of the two main divisions of the total nervous system. The other main division is the peripheral nervous system (PNS). The CNS and PNS work together to control virtually all body functions. You can read much more about the PNS in the concept *Peripheral Nervous System*.

The delicate nervous tissues of the central nervous system are protected by major physical and chemical barriers. Physically, the brain and spinal cord are surrounded by tough meninges, a three-layer protective sheath that also contains cushioning cerebrospinal fluid. The bones of the skull and spinal vertebrae also contribute to physically protecting the brain and spinal cord. Chemically, the brain and spinal cord are isolated from the circulation — and most toxins or pathogens in the blood — by the **blood-brain barrier.** The blood-brain barrier is a highly selective membrane formed of endothelial cells (a type of glial cells) that separates the circulating blood from the extracellular fluid in the CNS. The barrier allows water, certain gases, glucose, and some other molecules needed by the brain and spinal cord to cross from the blood into the CNS while keeping out potentially harmful substances. These physical and chemical barriers make the CNS less susceptible to injury. However, damage to the CNS is likely to have more serious consequences.

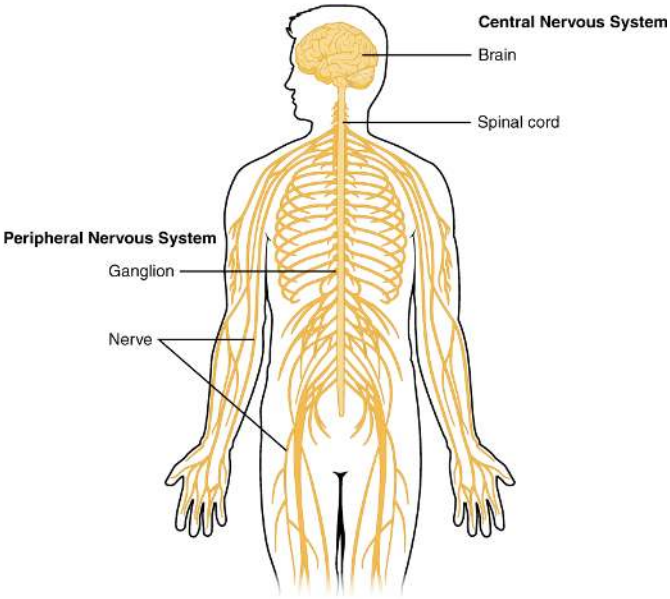



Figure **7.5.2**: The two main parts of the central nervous system are the brain and the spinal cord. Ganglions and nerves are part of the peripheral nerve system.

## THE BRAIN

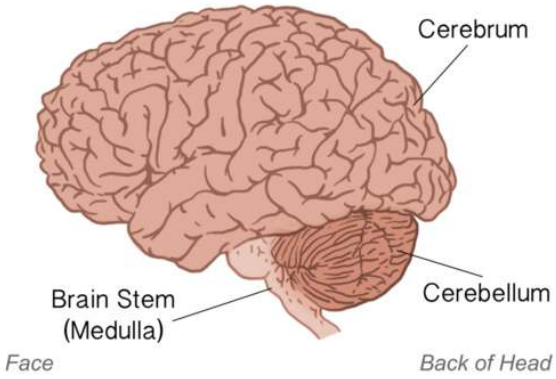



Figure **7.5.3**: Cerebrum, Cerebellum, and Brain Stem are the major parts of the brain. the medulla is part of the brain stem.

The **brain** is the control center not only of the rest of the nervous system but of the entire organism. The adult brain makes up only about 2 percent of the body's weight, but it uses about 20 percent of the body's total energy. The brain contains an estimated one hundred billion neurons, and each neuron has thousands of synaptic connections to other neurons. The brain also has about the same number of glial cells as neurons. No wonder the brain uses so much

energy! In addition, the brain uses mostly glucose for energy. As a result, if the brain is deprived of glucose, it can lead to unconsciousness. The brain is able to store some glucose in the form of glycogen, but in much smaller amounts than are found in the liver and skeletal muscles.

The brain controls such mental processes as reasoning, imagination, memory, and language. It also interprets information from the senses and commands the body how to respond. It controls basic physical processes such as breathing and heartbeat as well as voluntary activities such as walking and writing. The brain has three major parts: the cerebrum, cerebellum, and brain stem (Figure **7.5.3**). The figure shows the brain from the left side of the head. It shows how the brain would appear if the skull and meninges were removed. The brain stem via its medulla links to the spinal cord. The cerebellum is a small section at the back of the brain. The largest part of the brain is the cerebrum.

## CEREBRUM

The **cerebrum** is the largest part of the brain. It controls conscious, intellectual functions. For example, it controls reasoning, language, memory, sight, touch, and hearing. When you read a book, play a video game, or recognize a classmate, you are using your cerebrum.

### HEMISPHERES AND LATERALIZATION OF THE CEREBRUM

The cerebrum is divided from front to back into two halves called the left and right **hemispheres.** The two hemispheres are connected by a thick bundle of axons, known as the corpus callosum, which lies deep within the brain. The corpus callosum is the main avenue of communication between the two hemispheres. It connects each point in the cerebrum to the mirror-image point in the opposite hemisphere.

The right and left hemispheres of the cerebrum are similar in shape, and most areas of the cerebrum are found in both hemispheres. Some areas, however, show **lateralization,** or a concentration in one hemisphere or the other. For example, in most people, language functions are more concentrated in the left hemisphere, whereas abstract reasoning and visual-spatial abilities are more concentrated in the right hemisphere.

For reasons that are not yet clear, each hemisphere of the brain interacts primarily with the opposite side of the body. The left side of the brain receives messages from and sends commands to the right side of the body, and the right side of the brain receives messages from and sends commands to the left side of the body. Sensory nerves from the spinal cord to the brain and motor nerves from the brain to the spinal cord both cross the midline of the body at the level of the brain stem.

### CEREBRAL CORTEX

Most of the information processing in the brain actually takes place in the **cerebral cortex.** This is a rind of gray matter and other tissues just a few millimeters thick that makes up the outer surface of the cerebrum in both hemispheres of the brain. The cerebral cortex has many folds in it that greatly increase the amount of surface area of the brain that can fit within the skull. Because of all the folds in the human cerebral cortex, it has a surface area of about 2,500 $cm^2$(2.5 $ft^2$). The size and importance of the cerebral cortex are far greater in the human brain than the brains of any other vertebrates including nonhuman primates.

### LOBES OF THE CEREBRAL CORTEX

Each hemisphere of the cerebrum is further divided into the four lobes shown in Figure **7.5.4** and described below.

1. The **frontal lobes** are located at the front of the brain behind the forehead. The frontal lobes are associated with executive functions such as attention, self-control, planning, problem-solving, reasoning, abstract thought, language, and personality.

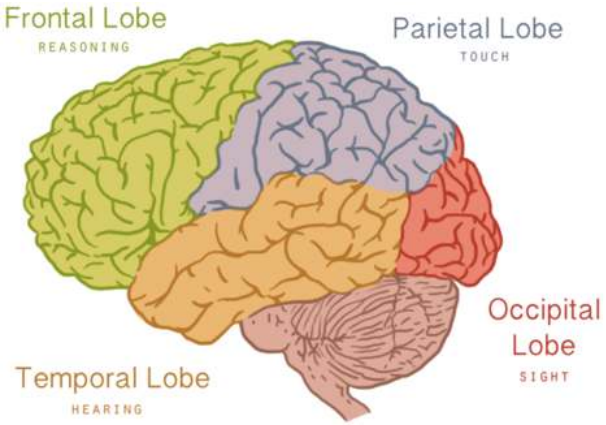



Figure **7.5.4**: Each hemisphere of the cerebrum consists of four parts, called lobes. The lobes are associated with multiple functions. The image shows one function of each lobe. Frontal, Parietal, Occipital, and Temporal lobes are associated with reasoning, touch, sight, and hearing, respectively.

2. The **parietal lobes** are located behind the frontal lobes at the top of the head. The parietal lobes are involved in sensation, including temperature, touch, and taste. Reading and arithmetic are also functions of the parietal lobes.

3. The **temporal lobes** are located at the sides of the head below the frontal and parietal lobes. The temporal lobes enable hearing, the formation and retrieval of memories, and the integration of memories and sensations.

4. The **occipital lobes** are located at the back of the head below the parietal lobes. The occipital lobes are the smallest of the four pairs of lobes. They are dedicated almost solely to vision.

## INNER STRUCTURES OF THE BRAIN

Several structures are located deep within the brain and are important for communication between the brain and spinal cord or the rest of the body. These structures include the hypothalamus and thalamus. Figure **7.5.5** shows where these structures are located in the brain. The cerebrum, hypothalamus, and thalamus exist in two halves, one in each hemisphere.

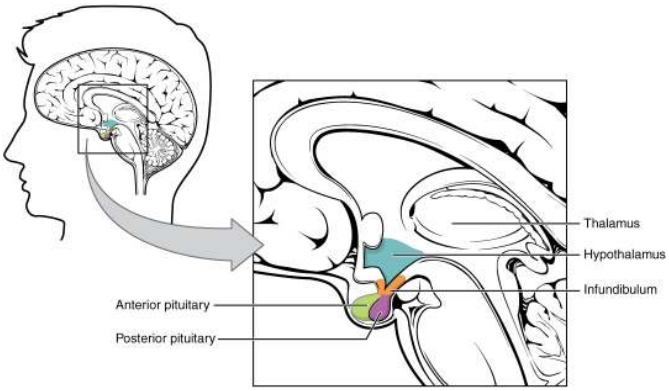



Figure **7.5.5**: Just below the cerebrum is the thalamus. Hypothalamus is located below the thalamus and a little to the anterior. The pituitary gland is attached to the hypothalamus via a tube called the infundibulum.

### HYPOTHALAMUS

The **hypothalamus** is located just above the brain stem and is about the size of an almond. The hypothalamus is responsible for certain metabolic processes and other activities of the autonomic nervous system, including body temperature, heart rate, hunger, thirst, fatigue, sleep, wakefulness, and circadian (24-hour) rhythms. The hypothalamus is also an important emotional center of the brain. The hypothalamus can regulate so many body functions because it responds to many different internal and external signals, including messages from the brain, light, steroid hormones, stress, and invading pathogens, among others.

One way the hypothalamus influences body functions is by synthesizing hormones that directly influence body processes. For example, it synthesizes the hormone oxytocin, which stimulates uterine contractions during childbirth and the letdown of milk during lactation. It also synthesizes the hormone vasopressin (also called antidiuretic hormone), which stimulates the kidneys to reabsorb more water and excrete more concentrated urine. These two hormones are sent from the hypothalamus via a stalk-like structure called the infundibulum (see diagram above) directly to the posterior (back) portion of the pituitary gland, which secretes them into the blood.

The main way the hypothalamus influences body functions is by controlling the pituitary gland, known as the master gland of the endocrine system. The hypothalamus synthesizes neurohormones called releasing factors that travel through the infundibulum directly to the anterior (front) part of the pituitary gland. The releasing factors generally either stimulate or inhibit the secretion of anterior pituitary hormones, most of which control other glands of the endocrine system.

### THALAMUS

The **thalamus,** which is located near the hypothalamus (Figure **7.5.5**), is a major hub for information traveling back and forth between the spinal cord and cerebrum. It filters sensory information traveling to the cerebrum. It relays sensory signals to the cerebral cortex and motor signals to the spinal cord. It is also involved in the regulation of consciousness, sleep, and alertness.

### CEREBELLUM

The **cerebellum** is just below the cerebrum and at the back of the brain behind the brain stem (Figure **7.5.3**). It coordinates body movements and is involved in movements that are learned with repeated practice. For example, when you hit a softball with a bat or touch type on a keyboard you are using the cerebellum. Many nerve pathways link the cerebellum with motor neurons throughout the body.

### BRAIN STEM

Sometimes called the “lower brain,” the **brain stem** is the lower part of the brain that is joined to the spinal cord. There are three parts to the brainstem: the midbrain, the pons, and the medulla oblongata, which are shown in Figure **7.5.6** below. The brain stem is primarily involved in the unconscious autonomic functions as well as several types of sensory information. It also helps coordinate large body movements such as walking and running. The **midbrain** deals with sight and sound information and translates these inputs before sending them to the forebrain. The **pons** relays messages to other parts of the brain (primarily the cerebrum and cerebellum) and helps regulate breathing. Some researchers have hypothesized that the pons plays a role in dreaming. Some of the functions of the Pons are shared by the **medulla oblongata,** also called the medulla. The medulla controls several subconscious homeostatic functions such as breathing, heart and blood vessel activity, swallowing, and digestion.

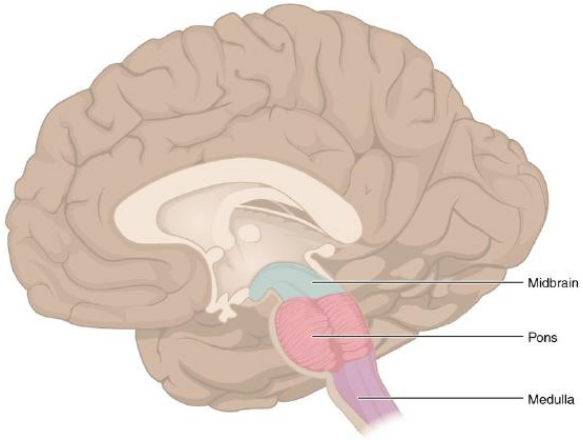



Figure **7.5.6**: Brain stem includes the midbrain, pons, and medulla oblongata

One of the brain stem’s most important roles is that of an “information highway.” That is, all of the information coming from the body to the brain and the information from the cerebrum to the body go through the brain stem. Sensory pathways for such things as pain, temperature, touch, and pressure sensation go upward to the cerebrum, and motor pathways for movement and other body processes go downward to the spinal cord. Most of the axons in the motor pathways cross from one side of the CNS to the other as they pass through the medulla oblongata. As a result, the right side of the brain controls much of the movement on the left side of the body,

and the left side of the brain controls much of the movement on the right side of the body.

## SPINAL CORD



Figure **7.5.7**: The spinal cord (yellow) runs from the bottom of the brain to the lower back

The **spinal cord** is a long, thin, tubular bundle of nervous tissues that extends from the brain stem and continues down the center of the back to the pelvis. It is highlighted in yellow in Figure **7.5.7**. The spinal cord is enclosed within but is shorter than, the vertebral column.

### STRUCTURE OF THE SPINAL CORD

The center of the spinal cord consists of gray matter, which is made up mainly of cell bodies of neurons, including interneurons and motor neurons. The gray matter is surrounded by white matter that consists mainly of myelinated axons of motor and sensory neurons. Spinal nerves, which connect the spinal cord to the PNS, exit from the spinal cord between vertebrae (Figure **7.5.8**).

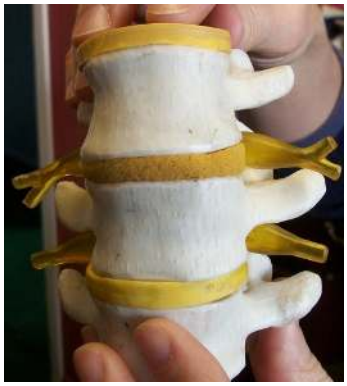


Figure **7.5.8**: This model shows three vertebrae (white) with branching spinal nerves (yellow) emerging from either side of the spinal cord between vertebrae

### FUNCTIONS OF THE SPINAL CORD

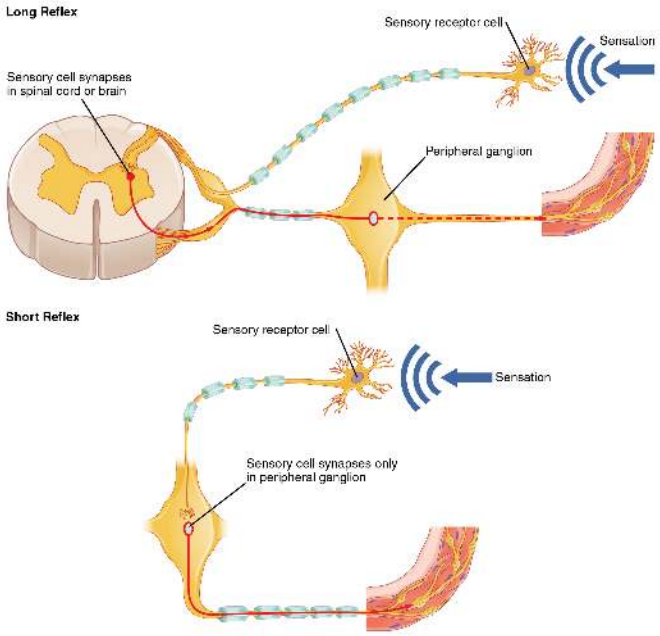



Figure **7.5.9**: This diagram shows what happens in a long reflex (top), in which sensory nerves carry the message all the way to the spinal cord; and in a short reflex (bottom), in which sensory nerves travel only to a ganglion outside the spinal cord. Note that interneurons are involved in reflexes, connecting sensory and motor neurons, but they are not actually shown in the diagram.

The spinal cord serves as an information superhighway. It passes messages from the body to the brain and from the brain to the body. Sensory (afferent) nerves carry nerve impulses to the brain from sensory receptor cells everywhere in and on the body. Motor (efferent) nerves carry nerve impulses away from the brain to glands, organs, or muscles throughout the body.

The spinal cord also independently controls certain rapid responses called **reflexes** without any input from the brain. You can see how this may happen in Figure **7.5.9**. A sensory receptor responds to a sensation and sends a nerve impulse along a sensory nerve to the spinal cord. In the spinal cord, the message passes to an interneuron and from the interneuron to a motor nerve, which carries the impulse to a muscle. The muscle contracts in response. These neuron connections form a reflex arc, which requires no input from the brain. No doubt you have experienced such reflex actions yourself. For example, you may have reached out to touch a pot on the stove, not realizing that it was very hot. Virtually at the same moment that you feel the burning heat, you jerk your arm back and remove your hand from the pot.

### INJURIES TO THE SPINAL CORD

Physical damage to the spinal cord may result in **paralysis,** which is a loss of sensation and movement in part of the body. Paralysis generally affects all the areas of the body below the level of the injury because nerve impulses are interrupted and can no longer travel back and forth between the brain and body beyond that point. If an injury to the spinal cord produces nothing more than swelling, the symptoms may be transient. However, if nerve fibers (axons) in

the spinal cord are badly damaged, the loss of function may be permanent. Experimental studies have shown that spinal nerve fibers attempt to regrow, but tissue destruction usually produces scar tissue that cannot be penetrated by the regrowing nerves, as well as other factors that inhibit nerve fiber regrowth in the central nervous system.

### FEATURE: MY HUMAN BODY

Each year, many millions of people have a stroke, and stroke is the second leading cause of death in adults. **Stroke,** also known as cerebrovascular accident, occurs when poor blood flow to the brain results in the death of brain cells. There are two main types of strokes:

- Ischemic strokes occur due to a lack of blood flow because of a blood clot in an artery going to the brain.
- Hemorrhagic strokes occur due to bleeding from a broken blood vessel in the brain.

Either type of stroke may result in paralysis, loss of the ability to speak or comprehend speech, loss of bladder control, personality changes, and many other potential effects, depending on the part of the brain that is injured. The effects of a stroke may be mild and transient or more severe and permanent. A stroke may even be fatal. It generally depends on the type of stroke and how extensive it is.

Are you at risk of stroke? The main risk factor for stroke is age: about two-thirds of strokes occur in people over the age of 65. There is nothing you can do about your age, but most other stroke risk factors can be reduced with lifestyle changes or medications. The risk factors include high blood pressure, tobacco smoking, obesity, high blood cholesterol, diabetes mellitus, and atrial fibrillation.

Chances are good that you or someone you know is at risk of a stroke, so it is important to recognize a stroke if one occurs. Stoke is a medical emergency, and the more quickly treatment is given, the better the outcome is likely to be. In the case of ischemic strokes, the use of clot-busting drugs may prevent permanent brain damage if administered within 3 or 4 hours of the stroke. Remembering the signs of a stroke is easy.

They are summed up by the acronym FAST, as explained in the chart below.




Figure **7.5.10**: The signs of stroke are abbreviated as FAST. Where F, A, S, and T stand for droopy face, arm weakness, slurry speech, and time to call 911, respectively.

## REVIEW

1. What is the central nervous system?
2. How is the central nervous system protected?
3. What is the overall function of the brain?
4. Identify the three main parts of the brain and one function of each part.
5. Describe the hemispheres of the brain.
6. Explain and give examples of lateralization of the brain.
7. Identify one function of each of the four lobes of the cerebrum.
8. Summarize the structure and function of the cerebral cortex.
9. Explain how the hypothalamus controls the endocrine system.
10. Describe the spinal cord.
11. What is the main function of the spinal cord?
12. Explain how reflex actions occur.
13. Why do severe spinal cord injuries usually cause paralysis?
14. What do you think are some possible consequences of severe damage to the brain stem? How might this compare to the consequences of severe damage to the frontal lobe? Explain your answer.
15. Information travels very quickly in the nervous system, but generally, the longer the path between areas, the longer it takes. Based on this, explain why you think reflexes often occur at the spinal cord level and do not require input from the brain.

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# 7.6: PERIPHERAL NERVOUS SYSTEM

## ONE PIANO, FOUR HANDS

Did you ever see two people play the same piano? How do they coordinate all the movements of their own fingers, let alone synchronize them with those of their partner? The peripheral nervous system plays an important part in this challenge.



Figure **7.6.1**: Two people playing piano together

## WHAT IS THE PERIPHERAL NERVOUS SYSTEM?

The *peripheral nervous system (PNS)* consists of all the nervous tissue that lies outside of the central nervous system (CNS). The main function of the PNS is to connect the CNS to the rest of the organism. It serves as a communication relay, going back and forth between the CNS and muscles, organs, and glands throughout the body.

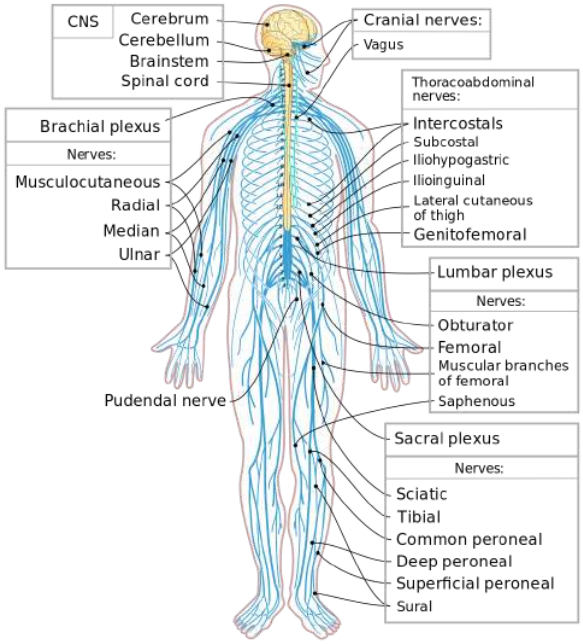



Figure **7.6.2**: The nerves of the peripheral nervous system are shown in blue in this figure.

## TISSUES OF THE PERIPHERAL NERVOUS SYSTEM

The tissues that make up the PNS are nerves and ganglia. Ganglia are nervous tissues that act as relay points for messages transmitted through nerves of the PNS. Nerves are cable-like bundles of axons that make up the majority of PNS tissues. Nerves are generally classified on the basis of the direction in which they carry nerve impulses as sensory, motor, or mixed nerves. See examples of sensory and motor never in Figure **7.6.3**.

- **Sensory nerves** transmit information from sensory receptors in the body to the CNS. Sensory nerves are also called afferent nerves.
- **Motor nerves** transmit information from the CNS to muscles, organs, and glands. Motor nerves are also called efferent nerves.
- **Mixed nerves** contain both sensory and motor neurons, so they can transmit information in both directions. They have both afferent and efferent functions.

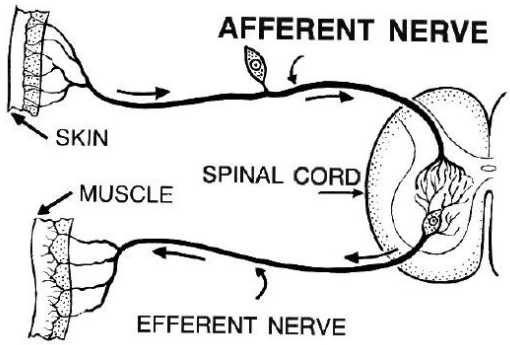



Figure **7.6.3**: An afferent nerve is a sensory nerve. The one pictured here sends nerve impulses from sensory cells in the skin to the CNS. An efferent nerve is a motor nerve. This one sends nerve impulses from the CNS to a muscle.

## DIVISIONS OF THE PERIPHERAL NERVOUS SYSTEM

The PNS is divided into two major systems, called the autonomic nervous system and the somatic (or sensory-somatic) nervous system. Both systems of the PNS interact with the CNS and include sensory and motor neurons, but they use different circuits of nerves and ganglia.

### SOMATIC NERVOUS SYSTEM

The **somatic nervous system** primarily senses the external environment and controls voluntary activities in which decisions and commands come from the cerebral cortex of the brain. For example, when you feel too warm, decide to turn on the air conditioner, and walk across the room to the thermostat, you are using your somatic nervous system. In general, the somatic nervous system is responsible for all of your conscious perceptions of the outside world and all of the voluntary motor activities you perform in response. Whether it's playing piano, driving a car, or playing basketball, you can thank your somatic nervous system for making it possible.

Structurally, the somatic nervous system consists of 12 pairs of cranial nerves and 31 pairs of spinal nerves (Figure **7.6.2**). Cranial nerves are in the head and neck and connect directly to the brain. Sensory cranial nerves sense smells, tastes, light, sounds, and body position. Motor cranial nerves control muscles of the face, tongue, eyeballs, throat, head, and shoulders. The motor nerves also control the salivary glands and swallowing. Four of the 12 cranial nerves participate in both sensory and motor functions as mixed nerves, having both sensory and motor neurons.

Spinal nerves of the somatic nervous system emanate from the spinal column between vertebrae. All of the spinal nerves are mixed nerves, containing both sensory and motor neurons. Spinal nerves also include motor nerves that stimulate skeletal muscle contraction, allowing for voluntary body movements.

### AUTONOMIC NERVOUS SYSTEM

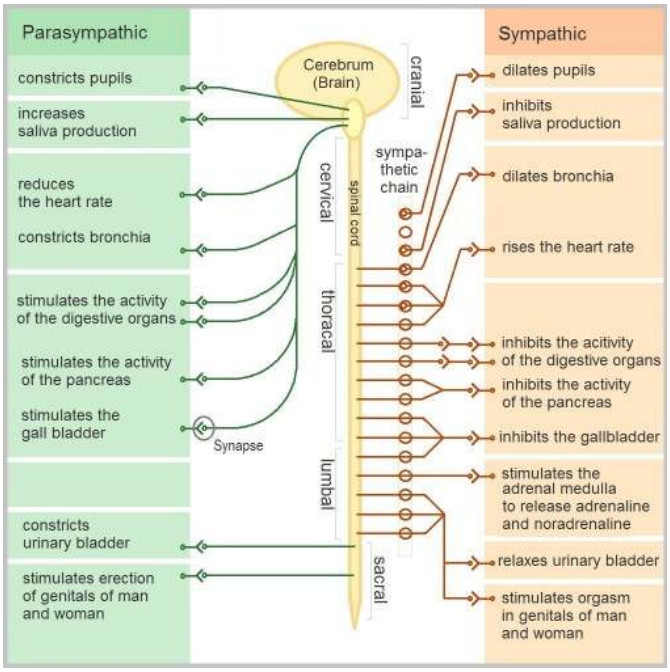



Figure **7.6.4**: This diagram summarizes the structures and functions controlled by the parasympathetic and sympathetic divisions of the autonomic nervous system. The images explained how eyes, salivary gland, bronchi, heart rate, digestive system, bladder, and genitalia are affected in opposite ways by the two systems.

The **autonomic nervous system** primarily senses the internal environment and controls involuntary activities. It is responsible for monitoring conditions in the internal environment and bringing about appropriate changes in them. In general, the autonomic nervous system is responsible for all the activities that go on inside your body without your conscious awareness or voluntary participation.

Structurally, the autonomic nervous system consists of sensory and motor nerves that run between the CNS (especially the hypothalamus in the brain) and internal organs (such as the heart, lungs, and digestive organs) and glands (such as the pancreas and sweat glands). Sensory neurons in the autonomic system detect internal body conditions and send messages to the brain. Motor nerves in the autonomic system function by controlling the contractions of smooth or cardiac muscle or glandular tissue. For example, when sensory nerves of the autonomic system detect a rise in body temperature, motor nerves signal smooth muscles in blood vessels near the body surface to undergo vasodilation, and the sweat glands in the skin secrete more sweat to cool the body.

The autonomic nervous system, in turn, has two subdivisions: the sympathetic division and parasympathetic division. The two subdivisions of the autonomic system are summarized in Figure **7.6.4**. Both affect the same organs and glands, but they generally do so in opposite ways.

- The **sympathetic division** controls the fight-or-flight response. Changes occur in organs and glands throughout the body that prepare the body to fight or flee in response to a perceived danger. For example, the heart rate speeds up, air passages in the

lungs become wider, more blood flows to the skeletal muscles, and the digestive system temporarily shuts down.

- The **parasympathetic division** returns the body to normal after the fight-or-flight response has occurred. For example, it slows down the heart rate, narrows air passages in the lungs, reduces blood flow to the skeletal muscles, and stimulates the digestive system to start working again. The parasympathetic division also maintains the internal homeostasis of the body at other times.

## DISORDERS OF THE PERIPHERAL NERVOUS SYSTEM

Unlike the CNS, which is protected by bones, meninges, and cerebrospinal fluid, the PNS has no such protections. The PNS also has no blood-brain barrier to protect it from toxins and pathogens in the blood. Therefore, the PNS is more subject to injury and disease than is the CNS. Causes of nerve injury include diabetes, infectious diseases such as shingles, and poisoning by toxins such as heavy metals. Disorders of the PNS often have symptoms such as loss of feeling, tingling, burning sensations, or muscle weakness. If a traumatic injury results in a nerve being transacted (cut all the way through), it may regenerate, but this is a very slow process and may take many months.

## REVIEW

1. Describe the general structure of the peripheral nervous system, and state its primary function.
2. What are ganglia?
3. Identify three types of nerves based on the direction in which they carry nerve impulses.
4. Outline all of the divisions of the peripheral nervous system.
5. Compare and contrast the somatic and autonomic nervous systems.
6. When and how does the sympathetic division of the autonomic nervous system affect the body?
7. What is the function of the parasympathetic division of the autonomic nervous system? What specific effects does it have on the body?
8. Name and describe two disorders of the peripheral nervous system.
9. Give one example of how the CNS interacts with the PNS to control a function in the body.
10. For each of the following types of information, identify whether the neuron carrying it is sensory or motor and whether it is most likely in the somatic or autonomic nervous system.
    A. Visual information
    B. Blood pressure information
    C. Information that causes muscle contraction in digestive organs after eating
    D. Information that causes muscle contraction in skeletal muscles based on the person's decision to make a movement
11. The cranial nerves:
    A. Carry sensory information
    B. Carry motor information
    C. Are part of the somatic nervous system
    D. All of the above
12. *True or False.* All of the spinal nerves carry both sensory and motor information.
13. *True or False.* The sympathetic nervous system enhances digestion to provide more energy for the body.

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# 7.7: HUMAN SENSES

## SEEING IS BELIEVING

Figure **7.7.1** appears at first glance to be just a pattern of colored leaves, but hidden within it is the three-dimensional shape of an ant. Can you see the ant among the leaves? This figure is an example of a stereogram, which is a two-dimensional picture that reveals a three-dimensional object when viewed correctly. If you can't see the hidden image, it doesn't mean that there is anything wrong with your eyes. It's all in how your brain interprets what your eyes are sensing. The eyes are special sensory organs, and vision is one of our special senses.

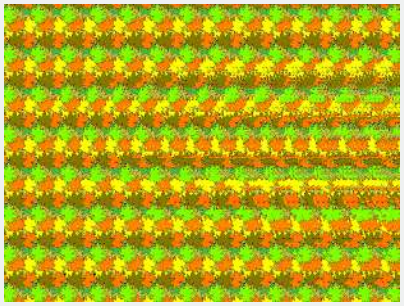


Figure **7.7.1**: Stereogram

## SPECIAL AND GENERAL SENSES

The human body has two basic types of senses, called special senses and general senses. **Special senses** have specialized sense organs that gather sensory information and change it into nerve impulses. Special senses include the vision for which the eyes are the specialized sense organs, hearing (ears), balance (ears), taste (tongue), and smell (nasal passages). **General senses,** in contrast, are all associated with the sense of touch and lack special sense organs. Instead, sensory information about touch is gathered by the skin and other body tissues, all of which have important functions besides gathering sensory information. Whether the senses are special or general, however, all of them depend on cells called sensory receptors.

## SENSORY RECEPTORS

A **sensory receptor** is a specialized nerve cell that responds to a stimulus in the internal or external environment by generating a nerve impulse. The nerve impulse then travels along with the sensory (afferent) nerve to the central nervous system for processing and to form a response.

There are several different types of sensory receptors that respond to different kinds of stimuli:

- **Mechanoreceptors** respond to mechanical forces such as pressure, roughness, vibration, and stretching. Most mechanoreceptors are found in the skin and are needed for the sense of touch. Mechanoreceptors are also found in the inner ear where they are needed for the senses of hearing and balance.
- **Thermoreceptors** respond to variations in temperature. They are found mostly in the skin and detect temperatures that are above or below body temperature.
- **Nociceptors** respond to potentially damaging stimuli, which are generally perceived as pain. They are found in internal organs as well as on the surface of the body. Different nociceptors are activated depending on the particular stimulus. For example, some detect damaging heat or cold, others detect excessive pressure, and still, others detect painful chemicals such as very hot spices in food.
- **Photoreceptors** detect and respond to light. Most photoreceptors are found in the eyes and are needed for the sense of vision.
- **Chemoreceptors** respond to certain chemicals. They are found mainly in taste buds on the tongue, where they are needed for the sense of taste; and in nasal passages, where they are needed for the sense of smell.

## TOUCH

**Touch** is the ability to sense pressure, vibration, temperature, pain, and other tactile stimuli. These types of stimuli are detected by mechanoreceptors, thermoreceptors, and nociceptors all over the body, but most noticeably in the skin. These receptors are especially concentrated on the tongue, lips, face, palms of the hands, and soles of the feet. Various types of tactile receptors in the skin are shown in Figure **7.7.2**.

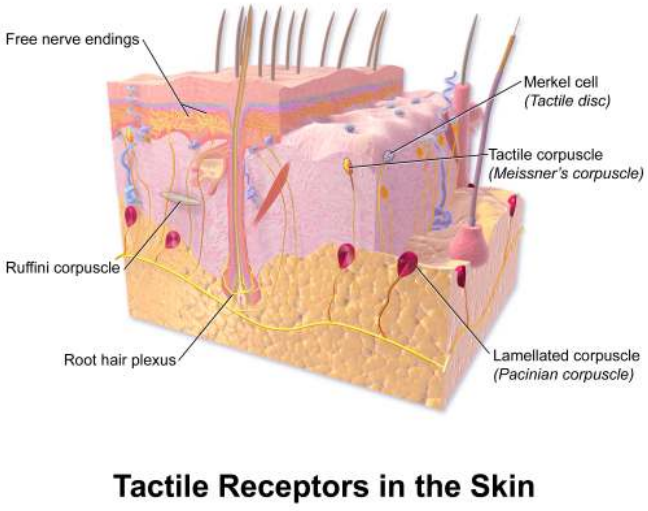



Figure **7.7.2**: Tactile receptors in the skin include free nerve endings, Merkel cells, Meissner's corpuscles, Pacinian corpuscles, root hair plexuses, and Ruffini corpuscles. Each type of sensory receptor responds to a different kind of tactile stimulus. For example, free nerve endings generally respond to pain and temperature variations, whereas Merkel cells are associated with the sense of light touch and the discrimination of shapes and textures.

# VISION

**Vision,** or sight, is the ability to sense light and see. The **eye** is the special sensory organ that collects and focuses light and forms images. However, the eye is not sufficient for us to see. The brain also plays a necessary role in vision.

## HOW THE EYE WORKS

Figure **7.7.3** shows the anatomy of the human eye in cross-section. The eye gathers and focuses light to form an image and then changes the image to nerve impulses that travel to the brain. How the eye performs these functions is summarized in the following steps.

1. Light passes first through the cornea, which is a clear outer layer that protects the eye and helps to focus the light by refracting, or bending, it.
2. Light next enters the interior of the eye through an opening called the pupil. The size of this opening is controlled by the colored part of the eye, called the iris, which adjusts the size based on the brightness of the light. The iris causes the pupil to narrow in bright light and widen in dim light.
3. The light then passes through the lens, which refracts the light even more and focuses it on the retina at the back of the eye as an inverted image.
4. The **retina** contains photoreceptor cells of two types, called rods and cones. Rods, which are found mainly in all areas of the retina other than the very center, are particularly sensitive to low levels of light. Cones, which are found mainly in the center of the retina, are sensitive to light of different colors and allow color vision. The rods and cones convert the light that strikes them to nerve impulses.
5. The nerve impulses from the rods and cones travel to the optic nerve via the optic disc, which is a circular area at the back of the eye where the optic nerve connects to the retina.

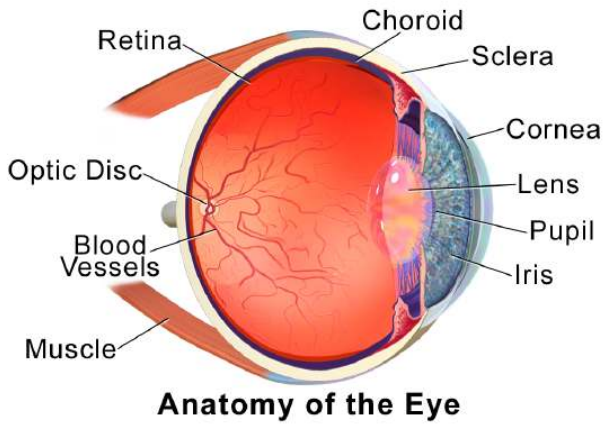



Figure **7.7.3**: In this image, you can see the three layers of the eyeball, the sclera (cornea at the front), choroid, and retina. Lens, pupil, Irish, optic disc, option nerve (not labeled), blood vessels, and eye muscles are also visible. Trace the path of light through the eye as you read about in the five steps described in the text

## ROLE OF THE BRAIN IN VISION

The optic nerves from both eyes meet and cross just below the bottom of the hypothalamus in the brain. The information from both eyes is sent to the visual cortex in the occipital lobe of the cerebrum, which is part of the cerebral cortex. The visual cortex is the largest system in the human brain and is responsible for processing visual images. It interprets messages from both eyes and "tells" us what we are seeing.

## VISION PROBLEMS

Vision problems are very common. Two of the most common are myopia and hyperopia, and they often start in childhood or adolescence. Another common problem, called presbyopia, occurs in most people beginning in middle adulthood. All three problems result in blurred vision due to the failure of the eyes to focus images correctly on the retina.

### *MYOPIA*

**Myopia,** or nearsightedness, occurs when the light that comes into the eye does not directly focus on the retina but in front of it, as shown in Figure **7.7.4**. This causes the image of distant objects to be out of focus but does not affect the focus of close objects. Myopia may occur because the eyeball is elongated from front to back or because the cornea is too curved. Myopia can be corrected through the use of corrective lenses, either eyeglasses or contact lenses. Myopia can also be corrected by refractive surgery performed with a laser.

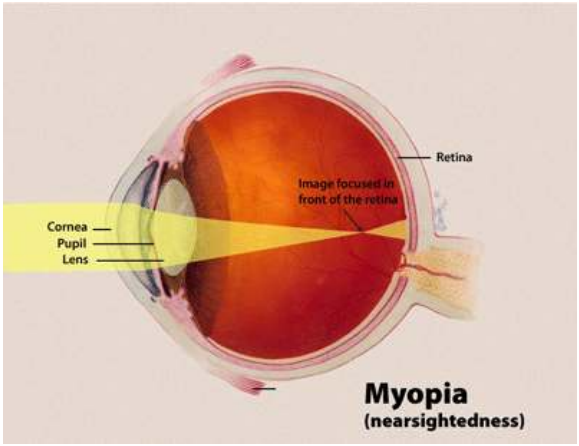



Figure **7.7.4**: In myopia, the focal point of images is in front of the retina because the eyeball is elongated.

### *HYPEROPIA*

**Hyperopia,** or farsightedness, occurs when the light that comes into the eye does not directly focus on the retina but behind it, as shown in Figure **7.7.5**. This causes the image of close objects to be out of focus but does not affect the focus of distant objects. Hyperopia may occur because the eyeball is too short from front to back or because the lens is not curved enough. Hyperopia can be corrected through the use of corrective lenses or laser surgery.

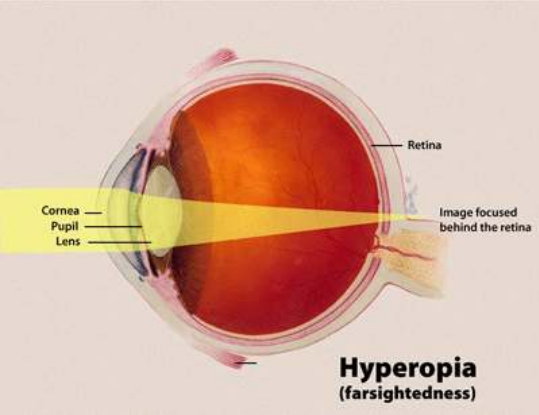



Figure **7.7.5**: In hyperopia, the focal point of images is behind the retina because the eyeball is too short.

### *PRESBYOPIA*

**Presbyopia** is a vision problem associated with aging in which the eye gradually loses its ability to focus on close objects. The precise cause of presbyopia is not known for certain, but evidence suggests that the lens may become less elastic with age, and the muscles that control the lens may lose power as people grow older. The first signs of presbyopia – eyestrain, difficulty seeing in dim light, problems focusing on small objects, and fine print – are usually first noticed between the ages of 40 and 50. Most older people with this problem use corrective lenses to focus on close objects because surgical procedures to correct presbyopia have not been as successful as those for myopia and hyperopia.

## HEARING

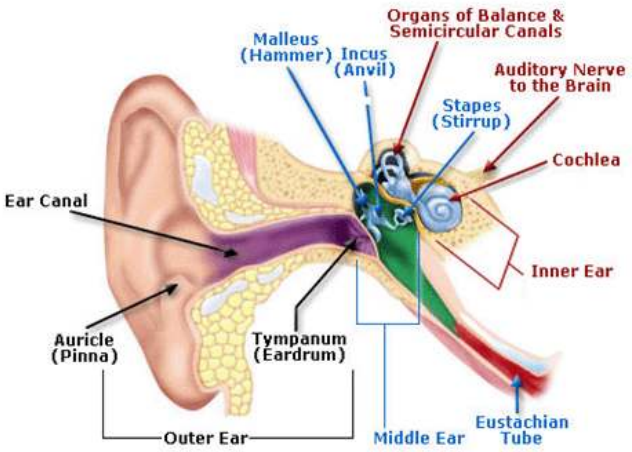



Figure **7.7.6**: The image shows structures of the outer, middle and inner ear. The outer ear has an auricle and an ear canal in it. The eardrum is in the middle of the outer and middle ear. The middle ear contains a hammer, anvil, and stirrup, and the inner ear has a cochlea, vestibule (not labeled), semicircular canal, and Eustachian tube. Most of the structures of the ear are involved in hearing. Only the semicircular canals are not involved in hearing. Instead, they sense head position, which is used to monitor balance.

**Hearing** is the ability to sense sound waves, and the ear is the organ that senses sound. Sound waves enter the ear through the ear canal and travel to the eardrum (see the diagram of the ear in Figure **7.7.6**). The sound waves strike the eardrum and make it vibrate. The vibrations then travel through the three tiny bones (hammer, anvil, and stirrup) of the middle ear, which amplify the vibrations. From the middle ear, the vibrations pass to the cochlea in the inner ear. The cochlea is a coiled tube filled with liquid. The liquid moves in response to the vibrations, causing tiny hair cells (which are mechanoreceptors) lining the cochlea to bend. In response, the hair cells send nerve impulses to the auditory nerve, which carries the impulses to the brain. The brain interprets the impulses and "tells" us what we are hearing.

## TASTE AND SMELL

Taste and smell are both abilities to sense chemicals, so taste and olfactory (odor) receptors are chemoreceptors. Both types of chemoreceptors send nerve impulses to the brain along sensory nerves, and the brain "tells" us what we are tasting or smelling.

Taste receptors are found in tiny bumps on the tongue called **taste buds.** You can see a diagram of a taste receptor cell and related structures in Figure **7.7.7**. Taste receptor cells make contact with chemicals in food through tiny openings called taste pores. When certain chemicals bind with taste receptor cells, it generates nerve impulses that travel through afferent nerves to the CNS. There are separate taste receptors for sweet, salty, sour, bitter, and meaty tastes. The meaty or savory taste is called umami.

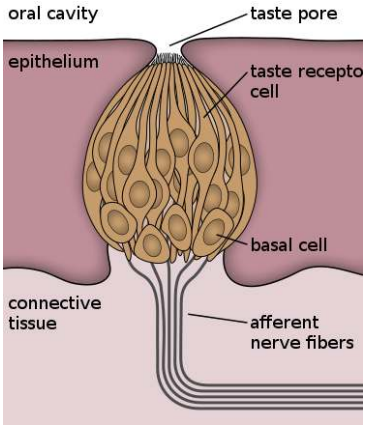



Figure **7.7.7**.Taste receptor cells are in taste buds on the tongue. Taste pore exposes these cells into the oral cavity. Basal cells are not involved in tasting but differentiate into taste receptor cells.

**Olfactory receptors** line the passages inside the nasal passages (Figure **7.7.8**). There are millions of olfactory receptors, which sense chemicals in the air. Unlike taste receptors, which can sense only five different tastes, olfactory receptors can sense hundreds of different odors and send signals to the olfactory bulb of the brain. Did you ever notice that food seems to have less taste when you have a stuffy nose? This occurs because the sense of smell contributes to the sense of taste, and a stuffy nose interferes with the ability to smell.

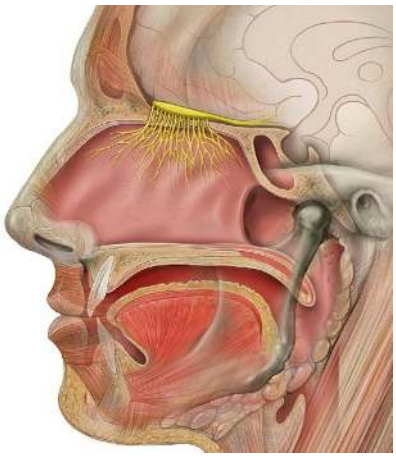


Figure 7.7.8: The yellow structures inside this drawing of the nasal passages are an olfactory nerve with many nerve endings. The nerve endings are located at the roof of the nasal cavity. The nerve endings sense chemicals in the air as it passes through the nasal cavities.

## FEATURE: HUMAN BIOLOGY IN THE NEWS

The most common cause of blindness in the Western hemisphere is **age-related macular degeneration (AMD).** About 15 million people in the United States have this type of blindness, and 30 million people are affected worldwide. At present, there is no cure for AMD. The disease occurs with the death of a layer of cells called retinal pigment epithelium, which normally provides nutrients and other support to the macula of the eye. The macula is an oval-shaped pigmented area near the center of the retina that is specialized for high visual acuity and has the retina's greatest concentration of cones. When the epithelial cells die and the macula is no longer supported or nourished, the macula also starts to die. Patients experience a black spot in the center of their vision, and as the disease progresses, the black spot grows outward. Patients eventually lose the ability to read and even to recognize familiar faces before developing total blindness.

In 2016, a landmark surgery was performed as a trial on a patient with severe AMD. In the first-ever operation of its kind, Dr. Pete Coffey of the University of London implanted a tiny patch of cells behind the retina in each of the patient's eyes. The cells were retinal pigmented epithelial cells that had been grown in a lab from **stem cells,** which are undifferentiated cells that have the ability to develop into other cell types. By six months out from the operation, the new cells were still surviving, and the doctor was hopeful that the patient's vision loss would stop and even be reversed. At that point, several other operations had already been planned to test the new procedure. If these cases are a success, Dr. Coffey predicts that the surgery will become as routine as cataract surgery and prevent millions of patients from losing their vision.

## REVIEW

1. Compare and contrast special senses and general senses.
2. What are sensory receptors?
3. List five types of sensory receptors and the type of stimulus each detects.
4. Describe the range of tactile stimuli that are detected in the sense of touch.
5. Explain how the eye collects and focuses light to form an image and converts it to nerve impulses.
6. Identify two common vision problems, including both their causes and their effects on vision.
7. Explain how the structures of the ear collect and amplify sound waves and transform them into nerve impulses.
8. What role does the ear play in balance? Which structures of the ear are involved in balance?
9. Describe two ways that the body senses chemicals and the special sense organs that are involved in these senses.
10. Explain why your skin can detect different types of stimuli, such as pressure and temperature.
11. *Choose one.* Sensory information is sent to the central nervous system via (efferent/afferent) nerves.
12. Identify a mechanoreceptor used in two different human senses, and describe the type of mechanical stimuli that each one detects.
13. If a person is blind but their retina is functioning properly, where do you think the damage might be? Explain your answer.
14. When you see colors, what receptor cells are activated? Where are these receptors located? What lobe of the brain is primarily used to process visual information?
15. The auditory nerve carries:

    A. Smell information
    B. Taste information
    C. Balance information
    D. Sound information

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# 7.8: PSYCHOACTIVE DRUGS

## ART IN A CUP

Who knew that a cup of coffee could also be a work of art? A talented barista can make coffee look as good as it tastes. If you are a coffee drinker, you probably know that coffee can also affect your mental state. It can make you more alert and may improve your concentration. That's because the caffeine in coffee is a psychoactive drug. In fact, caffeine is the most widely consumed psychoactive substance in the world. In North America, for example, 90 percent of adults consume caffeine daily.



Figure **7.8.1**: Murano Coffee with decoration on the surface.

**Psychoactive drugs** are substances that change the function of the brain and result in alterations of mood, thinking, perception, and/or behavior. Psychoactive drugs may be used for many purposes, including therapeutic, ritual, or recreational purposes. Besides caffeine, other examples of psychoactive drugs include cocaine, LSD, alcohol, tobacco, codeine, and morphine. Psychoactive drugs may be legal prescription medications (e.g., codeine and morphine), legal nonprescription drugs (e.g., alcohol and tobacco), or illegal drugs (cocaine and LSD).




Figure **7.8.2**: Advertising for legal psychoactive drugs is ubiquitous.

Cannabis (or marijuana) is also a psychoactive drug, but its status is in flux, at least in the United States. Depending on the jurisdiction, cannabis may be used recreationally and/or medically, and it may be either legal or illegal. Legal prescription medications such as opioids are also used illegally by increasingly large numbers of people. Some legal drugs, such as alcohol and nicotine, are readily available almost everywhere, as illustrated by the sign pictured in Figure **7.8.2**.

## CLASSES OF PSYCHOACTIVE DRUGS

Psychoactive drugs are divided into different classes according to their pharmacological effects. Several classes are listed below, along with examples of commonly used drugs in each class.

- Stimulants are drugs that stimulate the brain and increase alertness and wakefulness. Examples of stimulants include caffeine, nicotine, cocaine, and amphetamines such as Adderall.
- Depressants are drugs that calm the brain, reduce anxious feelings, and induce sleepiness. Examples of depressants include ethanol (in alcoholic beverages) and opioids such as codeine and heroin.
- Anxiolytics are drugs that have a tranquilizing effect and inhibit anxiety. Examples of anxiolytic drugs include benzodiazepines such as diazepam (Valium), barbiturates such as phenobarbital, opioids, and antidepressant drugs such as sertraline (Zoloft).
- Euphoriants are drugs that bring about a state of euphoria, or intense feelings of well-being and happiness. Examples of euphoriants include the so-called club drug MDMA (ecstasy), amphetamines, ethanol, and opioids such as morphine.
- Hallucinogens are drugs that can cause hallucinations and other perceptual anomalies. They also cause subjective changes in thoughts, emotions, and consciousness. Examples of hallucinogens include LSD, mescaline, nitrous oxide, and psilocybin.
- Empathogens are drugs that produce feelings of empathy, or sympathy with other people. Examples of empathogens include amphetamines and MDMA.



Figure **7.8.3**: Ecstasy (MDMA) is most commonly taken in tablet form, like the colorful and decorated tablets shown here.

Many psychoactive drugs have multiple effects so they may be placed in more than one class. An example is MDMA, pictured below, which may act both as a euphoriant and as an empathogen. In some people, MDMA may also have stimulant or hallucinogenic effects. As of 2016, MDMA had no accepted medical uses, but it was undergoing testing for use in the treatment of post-traumatic stress disorder and certain other types of anxiety disorders.

### MECHANISMS OF ACTION

Psychoactive drugs generally produce their effects by affecting brain chemistry, which in turn may cause changes in a person's mood,

thinking, perception, and/or behavior. Each drug tends to have a specific action on one or more neurotransmitters or neurotransmitter receptors in the brain. Generally, they act as either agonists or antagonists.

- **Agonists** are drugs that increase the activity of particular neurotransmitters. They might act by promoting the synthesis of the neurotransmitters, reducing their reuptake from synapses, or mimicking their action by binding to receptors for the neurotransmitters.
- **Antagonists** are drugs that decrease the activity of particular neurotransmitters. They might act by interfering with the synthesis of the neurotransmitters or by blocking their receptors so the neurotransmitters cannot bind to them.

Consider the example of the neurotransmitter GABA. This is one of the most common neurotransmitters in the brain, and it normally has an inhibitory effect on cells. GABA agonists, which increase its activity, include ethanol, barbiturates, and benzodiazepines, among other psychoactive drugs. All of these drugs work by promoting the activity of GABA receptors in the brain.

## USES OF PSYCHOACTIVE DRUGS

You may have been prescribed psychoactive drugs by your doctor. For example, you may have been prescribed an opioid drug such as codeine for pain (most likely in the form of Tylenol with added codeine). Chances are you also use nonprescription psychoactive drugs, such as caffeine for mental alertness. These are just two of the many possible uses of psychoactive drugs.

### MEDICAL USES



Figure **7.8.4**: This child is being prepared to receive a general anesthetic prior to surgery

Medical uses of psychoactive drugs include general anesthesia, in which pain is blocked and unconsciousness is induced. General anesthetics are most often used during surgical procedures and may be administered in gaseous form, as in the photo below. General anesthetics include the drugs halothane and ketamine. Other psychoactive drugs are used to manage pain without affecting consciousness. They may be prescribed either for acute pain in cases of trauma such as broken bones; or for chronic pain such as pain caused by arthritis, cancer, or fibromyalgia. Most often, the drugs used for pain control are opioids, such as morphine and codeine.

Many psychiatric disorders are also managed with psychoactive drugs. For example, antidepressants such as sertraline are used to treat depression, anxiety, and eating disorders. Anxiety disorders may also be treated with anxiolytics, such as buspirone and diazepam. Stimulants such as amphetamines are used to treat attention deficit disorder. Antipsychotics such as clozapine and risperidone, as well as mood stabilizers such as lithium, are used to treat schizophrenia and bipolar disorder.

### RITUAL USES

Certain psychoactive drugs, particularly hallucinogens, have been used for ritual purposes since prehistoric times. For example, Native Americans have used the mescaline-containing peyote cactus (pictured below) for religious ceremonies for as long as 5,700 years. In prehistoric Europe, the mushroom *Amanita muscaria*, which contains a hallucinogenic drug called muscimol, was used for similar purposes. Various other psychoactive drugs — including jimsonweed, psilocybin mushrooms, and cannabis — have also been used by various peoples for ritual purposes for millennia.



Figure **7.8.5**: The peyote cactus contains a hallucinogenic drug that is still used by some Native Americans for religious rituals.

### RECREATIONAL USES

The recreational use of psychoactive drugs generally has the purpose of altering one's consciousness and creating a feeling of euphoria commonly called a "high." Some of the drugs used most commonly for recreational purposes include cannabis, ethanol, opioids, and stimulants such as nicotine. Hallucinogens are also used recreationally, primarily for the alterations in thinking and perception that they cause.

Some investigators have suggested that the urge to alter one's state of consciousness is a universal human drive, similar to the drive to satiate thirst, hunger, or sexual desire. They think that the drive to alter one's state of mind is even present in children, who may attain an altered state by repetitive motions such as spinning or swinging. Some nonhuman animals also exhibit a drive to experience altered states. For example, they may consume fermented berries or fruit and become intoxicated. The way cats respond to catnip (Figure **7.8.6**) is another example.



Figure **7.8.6**: This cat is holding a catnip toy and apparently enjoying its psychoactive effects.

## ADDICTION, DEPENDENCE, AND REHABILITATION

Psychoactive substances often bring about subjective changes that the user may find pleasant (for example, euphoria) or advantageous (for example, increased alertness). These changes are rewarding and positively reinforcing, so they have the potential for misuse, addiction, and dependence. **Addiction** refers to the compulsive use of a drug despite the negative consequences that such use may entail. Sustained use of an addictive drug may produce dependence on the drug. **Dependence** may be physical and/or psychological. It occurs when cessation of drug use produces withdrawal symptoms. Physical dependence produces physical withdrawal symptoms, which may include tremors, pain, seizures, or insomnia. Psychological dependence produces psychological withdrawal symptoms, such as anxiety, depression, paranoia, or hallucinations.

Rehabilitation for drug dependence and addiction typically involves psychotherapy, which may include both individual and group therapy. Organizations such as Alcoholics Anonymous (AA) and Narcotics Anonymous (NA) may also be helpful for people trying to recover from addiction. These groups are self-described as international mutual aid fellowships with the primary purpose of helping addicts achieve and maintain sobriety. In some cases, rehabilitation is aided by the temporary use of psychoactive substances that reduce cravings and withdrawal symptoms without creating addiction themselves. For example, the drug methadone is commonly used in the treatment of heroin addiction.

### FEATURE: HUMAN BIOLOGY IN THE NEWS

Currently, in the United States, a lot of media attention is being given to a rising tide of opioid addiction and overdose deaths. **Opioids** are drugs derived from the opium poppy or synthetic versions of such drugs. They include illegal drug heroin and prescription painkillers such as codeine, morphine, hydrocodone, oxycodone, and fentanyl. In 2016, fentanyl received wide media attention when it was announced that an accidental fentanyl overdose was responsible for the death of rock-music icon Prince. Fentanyl is an extremely strong and dangerous drug, said to be 50 to 100 times stronger than morphine, making the risk of overdose death from fentanyl very high.

The dramatic increase in opioid addiction and overdose deaths has been called an opioid epidemic. It is considered to be the worst drug crisis in American history. Consider the following facts:

- In 1999, there were more than twice as many accidental deaths from motor vehicle crashes than from drug overdoses. By 2014, these causes of accidental death were reversed, with close to 40 percent more accidental deaths from drug overdoses than car crashes. The majority of these drug overdose deaths were from heroin and opioid painkillers.
- In 1999, the stimulant drug cocaine killed about twice as many people as did heroin. By 2014, deaths from heroin were up by 439 percent. During the same interval, deaths from cocaine also rose slightly but were a much smaller proportion of all drug deaths than those caused by heroin.

The opioid epidemic in the United States has occurred in all demographic groups, including every ethnic, age, gender, and socioeconomic category. What has caused this epidemic? The answer appears to be an equally dramatic increase in the medical use of prescription painkillers. In 1991, about 76 million prescriptions were written for painkillers. In 2011, the number of prescriptions for these drugs had risen to 219 million, an almost three-fold increase. During these same two decades, Mexican drug cartels began shipping huge amounts of heroin to the United States. Heroin became cheaper and easier to buy than prescription painkillers. Many people who became addicted to prescription opioids switched to heroin. About 80 percent of new heroin users in 2014 reported started out misusing prescription painkillers.

Doctors, public health professionals, and politicians have all called for new policies, funding, programs, and laws to address the opioid epidemic. Changes that have already been made include a shift from criminalizing to medicalizing the problem, an increase in treatment programs, and more widespread distribution and use of the opioid-overdose antidote naloxone (Narcan). Opioids can slow or stop a person's breathing, which is what usually causes overdose deaths. Naloxone helps the person wake up and keeps them breathing until emergency medical treatment can be provided.

## REVIEW

1. What are psychoactive drugs?
2. Identify six classes of psychoactive drugs and an example of a drug in each class.
3. Compare and contrast psychoactive drugs that are agonists and psychoactive drugs that are antagonists.
4. Describe two medical uses of psychoactive drugs.
5. Give an example of a ritual use of a psychoactive drug.
6. Why do people generally use psychoactive drugs recreationally?

7. Define addiction.
8. Identify possible withdrawal symptoms associated with physical dependence on a psychoactive drug.
9. Why might a person with a heroin addiction be prescribed the psychoactive drug methadone?
10. The prescription drug Prozac inhibits the reuptake of the neurotransmitter serotonin, causing more serotonin to be present in the synapse. Prozac can elevate mood, which is why it is sometimes used to treat depression. Answer the following questions about Prozac.
    A. Is Prozac an agonist or an antagonist for serotonin? Explain your answer.
    B. Is Prozac a psychoactive drug? Explain your answer.
11. Name 3 classes of psychoactive drugs that include opioids.
12. *True or False*. All psychoactive drugs are either illegal or available by prescription only.
13. *True or False*. Anxiolytics might be prescribed by a physician.
14. Name two drugs that activate receptors for the neurotransmitter GABA. Why do you think these drugs generally have a depressant effect?

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# 7.9: CASE STUDY CONCLUSION- MEMORY AND CHAPTER SUMMARY

## CASE STUDY CONCLUSION: FADING MEMORY

Figure **7.9.1** illustrates some of the molecular and cellular changes that occur in **Alzheimer's disease** (AD), which Rosa was diagnosed with at the beginning of this chapter, after experiencing memory problems and other changes in her cognitive functioning, mood, and personality. These abnormal changes in the brain include the development of amyloid plaques between brain cells and neurofibrillary tangles inside of neurons. These hallmark characteristics of AD are associated with the loss of synapses between neurons, and ultimately the death of neurons.

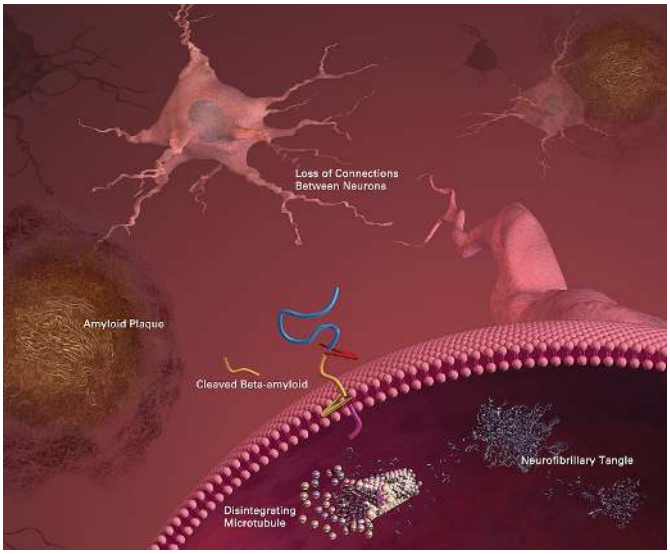



Figure **7.9.1**: Characteristics of Alzheimer's disease. On a microscopic level, some of the changes that happen are depicted above. For example, the neurons lose connections, plaque accumulates, microtubes disintegrate, and much more.

After reading this chapter, you should have a good appreciation for the importance of keeping neurons alive and communicating with each other at synapses. The nervous system coordinates all of the body's voluntary and involuntary activities. It interprets information from the outside world through sensory systems and makes appropriate responses through the motor system, through communication between the PNS and CNS. The brain directs the rest of the nervous system and controls everything from basic vital functions such as heart rate and breathing to high-level functions such as problem-solving and abstract thought. The nervous system is able to perform these important functions by generating action potentials in neurons in response to stimulation and sending messages between cells at synapses, typically using chemical neurotransmitter molecules. When neurons are not functioning properly, lose their synapses, or die, they cannot carry out the signaling that is essential for the proper functioning of the nervous system.

AD is a progressive neurodegenerative disease, meaning that the damage to the brain becomes more extensive as time goes on. Figure **7.9.2** illustrates how the damage progresses from before AD is diagnosed (preclinical AD), to mild and moderate AD, and finally to severe AD.

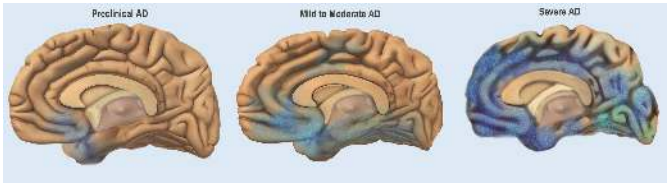



Figure **7.9.2**: Illustration showing the areas of the brain that become damaged as Alzheimer's disease (AD) progresses. This is a side view along the middle of the brain, with the front of the brain shown to the left. Damaged are (blue shade) is widespread in severe AD.

You can see that the damage starts in a relatively small location towards the bottom of the brain. One of the earliest brain areas to be affected by AD is the hippocampus. The hippocampus is important for learning and memory. This explains why many of Rosa's symptoms of mild AD involve deficits in memory, such as trouble remembering where she placed objects, recent conversations, and appointments.

As AD progresses, more of the brain is affected, including areas involved in emotional regulation, social behavior, planning, language, spatial navigation, and higher-level thought. Rosa is beginning to show signs of problems in these areas, including irritability, lashing out at family members, getting lost in her neighborhood, problems finding the right words, putting objects in unusual locations, and difficulty in managing her finances. You can see that as AD progresses, damage spreads further across the cerebrum, which you now know controls conscious functions such as reasoning, language, and interpretation of sensory stimuli. You can also see how the frontal lobe, which controls executive functions such as planning, self-control, and abstract thought, becomes increasingly damaged.

Increasing damage to the brain causes corresponding deficits in functioning. In moderate AD, patients have increased memory, language, and cognitive deficits compared to mild AD. They may not recognize their own family members, and may wander and get lost, engage in inappropriate behaviors, become easily agitated, and have trouble carrying out daily activities such as dressing. In severe AD, much of the brain is affected. Patients usually cannot recognize family members or communicate and are fully dependent on others for their care. They begin to lose the ability to control their basic functions, such as bladder and bowel control and proper swallowing. Eventually, AD causes death, usually as a result of this loss of basic functions.

For now, Rosa only has mild AD is still able to function relatively well with care from her family. The medication her doctor gave her has helped improve some of her symptoms. It is a cholinesterase inhibitor, which blocks an enzyme that normally degrades the neurotransmitter acetylcholine. With more of the neurotransmitter available, more of it can bind to neurotransmitter receptors on postsynaptic cells. Therefore, this drug acts as an agonist for

acetylcholine, which enhances communication between neurons in Rosa's brain. This increase in neuronal communication can help restore some of the functions lost in early Alzheimer's disease and may slow the progression of symptoms.

But medication such as this is only a short-term measure and does not halt the progression of the underlying disease. Ideally, the damaged or dead neurons would be replaced by new, functioning neurons. Why does this not happen automatically in the body? As you have learned, neurogenesis is very limited in adult humans, so once neurons in the brain die, they are not normally replaced to any significant extent. However, scientists are studying the ways in which neurogenesis might be able to be increased in cases of disease or injury to the brain. Also, they are investigating the possibility of using stem cell transplants to replace damaged or dead neurons with new neurons. But this research is in very early stages and is not currently a treatment for AD.

One promising area of research is in the development of methods to allow earlier detection and treatment of AD, given that the changes in the brain may actually start 10 to 20 years before the diagnosis of AD. For example, a radiolabeled chemical called Pittsburgh Compound B (PiB) binds to amyloid plaques in the brain and in the future may be used in conjunction with brain imaging techniques to detect early signs of AD. Scientists are also looking for biomarkers in bodily fluids such as blood and cerebrospinal fluid that might indicate the presence of AD before symptoms appear. Finally, researchers are also investigating possible early and subtle symptoms, such as changes in how people move or a loss of smell, to see whether they can be used to identify people who will go on to develop AD. This research is in the early stages, but the hope is that patients can be identified earlier to provide earlier and possibly more effective treatment and to allow families more time to plan.

Scientists are also still trying to fully understand the causes of AD, which affects more than 5 million Americans. Some genetic mutations have been identified that play a role, but environmental factors also appear to be important. With more research into the causes and mechanisms of AD, hopefully, a cure can be found, and people like Rosa can live a longer and better life.

## CHAPTER SUMMARY

In this chapter, you learned about the human nervous system. Specifically, you learned that:

- The nervous system is the organ system that coordinates all of the body's voluntary and involuntary actions by transmitting signals to and from different parts of the body. It has two major divisions, the central nervous system (CNS) and the peripheral nervous system (PNS).
- The CNS includes the brain and spinal cord.
- The PNS consists mainly of nerves that connect the CNS with the rest of the body. It has two major divisions: the somatic nervous system and the autonomic nervous system. The somatic system controls activities that are under voluntary control. The autonomic system controls activities that are involuntary.
- The autonomic nervous system is further divided into the sympathetic division, which controls the fight-or-flight response; the parasympathetic division, which controls most routine involuntary responses; and the enteric division, which provides local control for digestive processes.
- Signals sent by the nervous system are electrical signals called nerve impulses. They are transmitted by special, electrically excitable cells called neurons, which are one of two major types of cells in the nervous system.
- Glial cells are the other major type of nervous system cells. There are many types of glial cells, and they have many specific functions. In general, glial cells function to support, protect, and nourish neurons.
- The main parts of a neuron include the cell body, dendrites, and axon. The cell body contains the nucleus. Dendrites receive nerve impulses from other cells, and the axon transmits nerve impulses to other cells at axon terminals. A synapse is a complex membrane junction at the end of an axon terminal that transmits signals to another cell.
- Axons are often wrapped in an electrically-insulating myelin sheath, which is produced by glial cells. Electrical impulses called action potentials occur at gaps in the myelin sheath, called nodes of Ranvier, which speeds the conduction of nerve impulses down the axon.
- Neurogenesis, or the formation of new neurons by cell division, may occur in a mature human brain but only to a limited extent.
- The nervous tissue in the brain and spinal cord consists of gray matter, which contains mainly the cell bodies of neurons; and white matter, which contains mainly myelinated axons of neurons. Nerves of the peripheral nervous system consist of long bundles of myelinated axons that extend throughout the body.
- There are hundreds of types of neurons in the human nervous system, but many can be classified on the basis of the direction in which they carry nerve impulses. Sensory neurons carry nerve impulses away from the body and toward the central nervous system, motor neurons carry them away from the central nervous system and toward the body, and interneurons often carry them between sensory and motor neurons.
- A nerve impulse is an electrical phenomenon that occurs because of a difference in electrical charge across the plasma membrane of a neuron.
- The sodium-potassium pump maintains an electrical gradient across the plasma membrane of a neuron when it is not actively transmitting a nerve impulse. This gradient is called the resting potential of the neuron.
- An action potential is a sudden reversal of the electrical gradient across the plasma membrane of a resting neuron. It begins when the neuron receives a chemical signal from another cell or some other type of stimulus. The action potential travels rapidly down the neuron's axon as an electric current.
- A nerve impulse is transmitted to another cell at either an electrical or a chemical synapse. At a chemical synapse, neurotransmitter chemicals are released from the presynaptic cell

into the synaptic cleft between cells. The chemicals travel across the cleft to the postsynaptic cell and bind to receptors embedded in its membrane.

- There are many different types of neurotransmitters. Their effects on the postsynaptic cell generally depend on the type of receptor they bind to. The effects may be excitatory, inhibitory, or modulatory in more complex ways. Both physical and mental disorders may occur if there are problems with neurotransmitters or their receptors.
- The CNS includes the brain and spinal cord. It is physically protected by bones, meninges, and cerebrospinal fluid. It is chemically protected by the blood-brain barrier.
- The brain is the control center of the nervous system and of the entire organism. The brain uses a relatively large proportion of the body's energy, primarily in the form of glucose.
- The brain is divided into three major parts, each with different functions: brain stem, cerebellum, and cerebrum. The cerebrum is further divided into left and right hemispheres. Each hemisphere has four lobes: frontal, parietal, temporal, and occipital. Each lobe is associated with specific senses or other functions.
- The cerebrum has a thin outer layer called the cerebral cortex. Its many folds give it a large surface area. This is where most information processing takes place.
- Inner structures of the brain include the hypothalamus, which controls the endocrine system via the pituitary gland; and the thalamus, which has several involuntary functions.
- The spinal cord is a tubular bundle of nervous tissues that extends from the head down the middle of the back to the pelvis. It functions mainly to connect the brain with the PNS. It also controls certain rapid responses called reflexes without input from the brain.
- A spinal cord injury may lead to paralysis (loss of sensation and movement) of the body below the level of the injury because nerve impulses can no longer travel up and down the spinal cord beyond that point.
- The PNS consists of all the nervous tissue that lies outside of the CNS. Its main function is to connect the CNS to the rest of the organism.
- The tissues that make up the PNS are nerves and ganglia. Ganglia act as relay points for messages that are transmitted through nerves. Nerves are classified as sensory, motor, or a mix of the two.
- The PNS is not as well protected physically or chemically as the CNS, so it is more prone to injury and disease. PNS problems include injury from diabetes, shingles, and heavy metal poisoning. Two disorders of the PNS are Guillain-Barre syndrome and Charcot-Marie-Tooth disease.
- The human body has two major types of senses, special senses, and general senses. Special senses have specialized sense organs and include vision (eyes), hearing (ears), balance (ears), taste (tongue), and smell (nasal passages). General senses are all associated with touch and lack special sense organs. Touch receptors are found throughout the body but particularly in the skin.
- All senses depend on sensory receptor cells to detect sensory stimuli and transform them into nerve impulses. Types of sensory receptors include mechanoreceptors (mechanical forces), thermoreceptors (temperature), nociceptors (pain), photoreceptors (light), and chemoreceptors (chemicals).
- Touch includes the ability to sense pressure, vibration, temperature, pain, and other tactile stimuli. The skin includes several different types of touch receptor cells.
- Vision is the ability to sense light and see. The eye is the special sensory organ that collects and focuses light, forms images, and changes them to nerve impulses. Optic nerves send information from the eyes to the brain, which processes the visual information and "tells" us what we are seeing.
- Common vision problems include myopia (nearsightedness), hyperopia (farsightedness), and presbyopia (age-related decline in close vision).
- Hearing is the ability to sense sound waves, and the ear is the organ that senses sound. It changes sound waves to vibrations that trigger nerve impulses, which travel to the brain through the auditory nerve. The brain processes the information and "tells" us what we are hearing.
- The ear is also the organ that is responsible for the sense of balance, which is the ability to sense and maintain an appropriate body position. The ears send impulses on head position to the brain, which sends messages to skeletal muscle via the peripheral nervous system. The muscles respond by contracting to maintain balance.
- Taste and smell are both abilities to sense chemicals. Taste receptors in taste buds on the tongue sense chemicals in food and olfactory receptors in the nasal passages sense chemicals in the air. The sense of smell contributes significantly to the sense of taste.
- Psychoactive drugs are substances that change the function of the brain and result in alterations of mood, thinking, perception, and/or behavior. They include prescription medications such as opioid painkillers, legal substances such as nicotine and alcohol, and illegal drugs such as LSD and heroin.
- Psychoactive drugs are divided into different classes according to their pharmacological effects. They include stimulants, depressants, anxiolytics, euphoriants, hallucinogens, and empathogens. Many psychoactive drugs have multiple effects so they may be placed in more than one class.
- Psychoactive drugs generally produce their effects by affecting brain chemistry. Generally, they act either as agonists, which enhance the activity of particular neurotransmitters; or as antagonists, which decrease the activity of particular neurotransmitters.
- Psychoactive drugs are used for various purposes, including medical, ritual, and recreational purposes.
- Misuse of psychoactive drugs may lead to addiction, which is the compulsive use of a drug despite negative consequences.

Sustained use of an addictive drug may produce physical or psychological dependence on the drug. Rehabilitation typically involves psychotherapy and sometimes the temporary use of other psychoactive drugs.

In addition to the nervous system, there is another system of the body that is important for coordinating and regulating many different functions – the endocrine system. You will learn about the endocrine system in the next chapter.

## CHAPTER SUMMARY REVIEW

1. Imagine that you decide to make a movement. To carry out this decision, a neuron in the cerebral cortex of your brain (neuron A) fires a nerve impulse that is sent to a neuron in your spinal cord (neuron B). Neuron B then sends the signal to a muscle cell, causing it to contract, resulting in movement. Answer the following questions about this pathway.
   a. Which part of the brain is neuron A located in — the cerebellum, cerebrum, or brain stem? Explain how you know.
   b. The cell body of neuron A is located in a lobe of the brain that is involved in abstract thought, problem-solving and planning. Which lobe is this?
   c. Part of neuron A travels all the way down to the spinal cord to meet neuron B. Which part of neuron A travels to the spinal cord?
   d. Neuron A forms a chemical synapse with neuron B in the spinal cord. How is the signal from neuron A transmitted to neuron B?
   e. Is neuron A in the central nervous system (CNS) or peripheral nervous system (PNS)?
   f. The axon of neuron B travels in a nerve to a skeletal muscle cell. Is the nerve part of the CNS or PNS? Is this an afferent nerve or an efferent nerve?
   g. What part of the PNS is involved in this pathway — the autonomic nervous system or the somatic nervous system? Explain your answer.
2. What are the differences between a neurotransmitter receptor and a sensory receptor?
3. Which part of a postsynaptic neuron typically receives the signals from a presynaptic neuron?
   A. The axon terminal
   B. The nodes of Ranvier
   C. The dendrites
   D. The cell body
4. *True or False.* Glial cells produce action potentials.
5. *True or False.* The spinal cord consists of white matter only.
6. *True or False.* Axons may be more than a meter long in adult humans.
7. If a person has a stroke and as a result has trouble using language correctly, which hemisphere of their brain was most likely damaged? Explain your answer.
8. The right side of the brain generally controls the which side of the body?
   A. right side
   B. left side
   C. head region
   D. trunk and leg regions
9. Electrical gradients are responsible for the resting potential and action potential in neurons. Answer the following questions about the electrical characteristics of neurons.
   a. Define what an electrical gradient is, in the context of a cell.
   b. What is responsible for maintaining the electrical gradient that results in the resting potential?
   c. Compare and contrast the resting potential and the action potential.
   d. Where along a myelinated axon does the action potential occur? Why does it happen here?
10. What does it mean that the action potential is “all-or-none?”
11. What determines whether a neurotransmitter has an excitatory or inhibitory effect? Choose the best answer.
    A. The neurotransmitter itself
    B. The specific receptor for the neurotransmitter on the postsynaptic cell
    C. The number of synaptic vesicles in the axon terminal
    D. Whether it is in a sensory neuron or a motor neuron
12. Compare and contrast Schwann cells and oligodendrocytes.
13. *True or False.* The cerebellum makes up most of the brain and is divided into four lobes.
14. *True or False.* The hypothalamus is part of the brain.
15. Which lobe of the brain processes touch information?
    A. Parietal
    B. Occipital
    C. Cochlea
    D. Temporal
16. Information about sounds is mainly sent to which lobe of the brain?
    A. Parietal
    B. Occipital
    C. Cochlea
    D. Temporal
17. Rods and cones in the retina are:
    A. Mechanoreceptors
    B. Nociceptors
    C. Photoreceptors
    D. Chemoreceptors
18. For the senses of smell and hearing, name their respective sensory receptor cells, what type of receptor cells they are, and what stimuli they detect.
19. *True or False.* Sensory information such as smell, taste, and sound, are carried to the CNS by cranial nerves.
20. *True or False.* The parasympathetic nervous system is a division of the central nervous system.

## ATTRIBUTIONS

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# CHAPTER OVERVIEW

## 8: THE ENDOCRINE SYSTEM

This chapter describes the endocrine system and its vital roles in communication, control, and homeostasis within the human body. The focus is on the pituitary gland, as the master gland of the endocrine system, and three other endocrine glands: the thyroid gland, adrenal glands, and pancreas. The chapter also explains the differing mechanisms of steroid and non-steroid endocrine hormones.


8.1: Case Study- Hormones and Health

8.2: Introduction to the Endocrine System

8.3: Endocrine Hormones

8.4: Pituitary Gland

8.5: Thyroid Gland

8.6: Adrenal Glands

8.7: Pancreas

8.8: Case Study Conclusion- Hormonal and Chapter Summary


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# 8.1: CASE STUDY- HORMONES AND HEALTH

## CASE STUDY: HORMONAL HAVOC

18-year-old Gabrielle checks her calendar. It has been 42 days since her last menstrual period, two weeks later than the length of the average woman's menstrual cycle. Although many women would suspect pregnancy if their period was late, Gabrielle has not been sexually active. She is not even sure she is "late" because her period has never been regular. Ever since her first period at 13 years of age, her cycle lengths have varied greatly, and there are months where she does not get a period at all. Her mother told her that a girl's period is often irregular when it first starts, but Gabrielle's still has not become regular five years later. She decides to go to the student health center on her college campus to get it checked out.




Figure **8.1.1**: Calendar

The doctor asks her about the timing of her menstrual periods and performs a pelvic exam. She also notices that Gabrielle is overweight, has acne, and excess facial hair. As she explains to Gabrielle, while these physical characteristics can be perfectly normal, in combination with an irregular period they can be signs of a disorder of the endocrine, or hormonal, system called polycystic ovary syndrome (PCOS).

In order to check for PCOS, the doctor refers Gabrielle for a pelvic ultrasound and sends her to the lab to get blood work done. When her lab results come back, Gabrielle learns that her levels of androgens (a group of hormones) are high, and so is her blood glucose (sugar). The ultrasound showed that she has multiple fluid-filled sacs known as cysts in her ovaries. Based on Gabrielle's symptoms and test results, the doctor tells her that she does indeed have PCOS.

PCOS is common in young women. It is estimated that between 1 in 10 to 20 women of childbearing age have PCOS — as many as five million women in the United States. You may know someone with PCOS or may have it yourself.

Read the rest of this chapter to learn about the glands and hormones of the endocrine system, their functions, how they are regulated, and the disorders — such as PCOS — that can arise when hormones are not regulated properly. At the end of the chapter, you will learn more about PCOS, its possible long-term consequences including fertility problems and diabetes, and how these negative outcomes can sometimes be prevented with lifestyle changes and medications.

## CHAPTER OVERVIEW: ENDOCRINE SYSTEM

In this chapter, you will learn about the endocrine system, a system of glands that secrete hormones that regulate many of the body's functions. Specifically, you will learn about:

- The glands that make up the endocrine system and how hormones act as chemical messengers in the body.
- The general types of endocrine system disorders.
- The types of endocrine hormones, including steroid hormones such as sex hormones, and non-steroid hormones such as insulin; and how they affect the functions of their target cells by binding to different types of receptor proteins.
- How the levels of hormones are regulated mostly through negative, but sometimes through positive, feedback loops.
- The master gland of the endocrine system, the pituitary gland, controls other parts of the endocrine system through the hormones that it secretes; and how the pituitary itself is regulated by hormones secreted from the hypothalamus of the brain.
- The thyroid gland and its hormones, which regulate processes such as metabolism and calcium homeostasis; how the thyroid is regulated; and the disorders that can occur when there are problems in thyroid hormone regulation, such as hyperthyroidism and hypothyroidism.
- The adrenal glands, which secrete hormones that regulate processes such as metabolism, electrolyte balance, responses to stress, and reproductive functions; and the disorders that can occur when there are problems in adrenal hormone regulation, such as Cushing's syndrome and Addison's disease.
- The pancreas, which secretes hormones that regulate blood glucose levels such as insulin; and disorders of the pancreas and its hormones including diabetes.

As you read this chapter, think about the following questions:

1. Why can hormones have such a broad-range effect on the body, such as is seen in PCOS?
2. Which hormones normally regulate blood glucose and how is this related to diabetes?
3. What are androgens? How do you think their functions relate to some of the symptoms that Gabrielle is experiencing?

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# 8.2: INTRODUCTION TO THE ENDOCRINE SYSTEM

## MOON FACE

The patient in Figure **8.2.1** has the characteristic moon face of a disorder named Cushing's syndrome. Other signs and symptoms of this disorder include abnormal weight gain, acne, and excessive hairiness, among many other abnormalities. What can cause so many different problems in one patient? The answer is the overproduction of the endocrine system hormone cortisol.



Figure **8.2.1**: a person with Cushing's syndrome

## OVERVIEW OF THE ENDOCRINE SYSTEM

The **endocrine system** is a system of glands called **endocrine glands** that release chemical messenger molecules called hormones into the bloodstream. Other glands of the body, including sweat glands and salivary glands, also secrete substances but not into the bloodstream. Instead, they secrete them through ducts that carry them to nearby body surfaces. These other glands are called **exocrine glands.**

Endocrine hormones must travel through the bloodstream to the cells they affect, and this takes time. Because endocrine hormones are released into the bloodstream, they travel throughout the body wherever blood flows. As a result, endocrine hormones may affect many cells and have body-wide effects. Endocrine hormones may cause effects that last for days, weeks, or even months.

## GLANDS OF THE ENDOCRINE SYSTEM

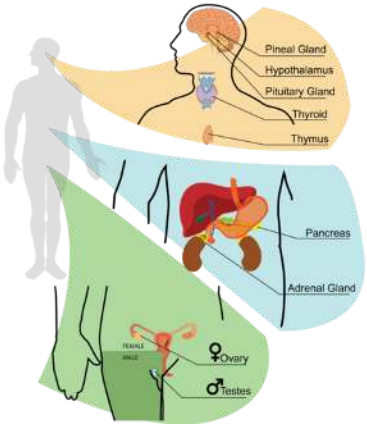



Figure **8.2.2**: Pineal gland, hypothalamus, Pituitary gland, Thyroid, Thymus, Pancreas, Adrenal gland, over and testes are part of the endocrine system. Note that the ovary and testis are the only endocrine glands that differ in males and females

The major glands of the endocrine system are shown in Figure **8.2.2**. The glands in the figure are described briefly in the rest of this section. Refer to the figure as you read about the glands in the following text.

### PITUITARY GLAND

The pituitary gland is located at the base of the brain. It is controlled by the nervous system via the brain structure called the hypothalamus, to which it is connected by a thin stalk. The pituitary gland consists of two lobes, called the anterior (front) lobe and posterior (back) lobe. The posterior lobe stores and secretes hormones synthesized by the hypothalamus. The anterior lobe synthesizes and secretes its own endocrine hormones, also under the influence of the hypothalamus. One endocrine hormone secreted by the pituitary gland is growth hormone, which stimulates cells throughout the body to synthesize proteins and divide. Most of the other endocrine hormones secreted by the pituitary gland control other endocrine glands. Generally, these hormones direct the other glands to secrete either more or less of their hormones. This is why the pituitary gland is often referred to as the "master gland" of the endocrine system.

### REMAINING GLANDS OF THE ENDOCRINE SYSTEM

Each of the other glands of the endocrine system is summarized below. Several of these endocrine glands are also discussed in greater detail in other concepts in the present chapter.

- The thyroid gland is a large gland in the neck. Thyroid hormones such as thyroxine increase the rate of metabolism in cells throughout the body. They control how quickly cells use energy and make proteins.
- The four parathyroid glands are located in the neck behind the thyroid gland. The parathyroid hormone helps keep the level of calcium in the blood within a narrow range. It stimulates bone cells to dissolve calcium and release it into the blood.
- The pineal gland is a tiny gland located near the center of the brain. It secretes the hormone melatonin, which controls the sleep-wake cycle and several other processes. The production of melatonin is stimulated by darkness and inhibited by light. Cells in the retina of the eye detect light and send signals to a structure in the brain named the suprachiasmatic nucleus (SCN). Nerve fibers carry the signals from the SCN to the pineal gland via the autonomic nervous system.
- The pancreas is located near the stomach. Its endocrine hormones include insulin and glucagon, which work together to control the level of glucose in the blood. The pancreas also secretes digestive enzymes into the small intestine.
- The two adrenal glands are located above the kidneys. Adrenal glands secrete several different endocrine hormones, including the hormone adrenaline, which is involved in the fight-or-flight response. Other endocrine hormones secreted by the adrenal glands have a variety of functions. For example, the hormone

aldosterone helps to regulate the balance of minerals in the body. The hormone cortisol, which causes Cushing's syndrome when it is produced in excess, is also an adrenal gland hormone.

- The gonads include the ovaries in females and testes in males. They secrete sex hormones, such as testosterone (in males) and estrogen (in females). These hormones control sexual maturation during puberty and the production of gametes (sperm or egg cells) by the gonads after sexual maturation.
- The thymus gland is located in front of the heart. It is the site where immune system cells called T cells mature. T cells are critical to the adaptive immune system, in which the body adapts to specific pathogens.

## ENDOCRINE SYSTEM DISORDERS

Diseases of the endocrine system are relatively common. An endocrine system disease usually involves the secretion of too much or not enough of a hormone. When too much hormone is secreted, the condition is called **hypersecretion.** When not enough hormone is secreted, the condition is called **hyposecretion.**

### HYPERSECRETION



Figure **8.2.3**: Martin Van Buren Bates

Hypersecretion by an endocrine gland is often caused by a tumor. For example, a tumor of the pituitary gland can cause hypersecretion of growth hormone. If this occurs in childhood and goes untreated, it results in very long arms and legs and abnormally tall stature by adulthood (see ). This condition is commonly known as gigantism. Martin Van Buren Bates is depicted in Figure **8.2.3** standing next to a man of average size. Bates was a Civil War-era American famed for his incredibly large size. He was at least 7 feet 9 inches tall and weighed close to 500 pounds. He was normal in size at birth but started to grow very rapidly by about age 6 years, presumably because of the hypersecretion of growth hormone.

### HYPOSECRETION

Hyposecretion by an endocrine gland is often caused by the destruction of the hormone-secreting cells of the gland. As a result, not enough of the hormone is secreted. An example of this is type 1 diabetes, in which the body's own immune system attacks and destroys cells of the pancreas that secrete insulin. This type of diabetes is generally treated with frequent injections of insulin.

### HORMONE INSENSITIVITY

In some cases, an endocrine gland secretes a normal amount of hormone, but target cells do not respond normally to it. This may occur because target cells have become resistant to the hormone. An example of this type of endocrine disorder is Androgen Insensitivity Disorder. Individuals with this disorder are born with an X and Y chromosome but develop and raised as females. This is due to a mutation in the Androgen Receptor (AR) gene which is located on the X chromosome. Testosterone is an androgen hormone that causes testes to descend and typical male characteristics to develop. People with this form of the condition have the external sex characteristics of females but do not have a uterus and therefore do not menstruate and are unable to conceive a child (infertile). They are typically raised as females and have a female gender identity. Affected individuals have male internal sex organs (testes) that are undescended, which means they are located in the pelvis or abdomen.

## REVIEW

1. What is the endocrine system? What is its general function?
2. Compare and contrast endocrine and exocrine glands.
3. How do endocrine system messages differ from those of the nervous system?
4. Describe the role of the pituitary gland in the endocrine system.
5. List three endocrine glands other than the pituitary gland, and identify their functions.
6. Which endocrine gland has an important function in the immune system? What is that function?
7. Define hypersecretion and hyposecretion.
8. Name an endocrine disorder in which too much of a hormone is produced.
9. What are two reasons people with diabetes might have signs and symptoms of inadequate insulin?
10. Choose one. Cushing's syndrome is an example of (hyposecretion/hypersecretion).
11. *True or False.* The hypothalamus is the master gland of the endocrine system.
12. *True or False.* Mammary glands that produce milk for offspring are part of the endocrine system.
13. Melatonin is produced by the:
    A. A. Pituitary gland
    B. B. Hypothalamus
    C. C. Pineal gland
    D. D. Pancreas
14. Besides location, what is the main difference between the anterior lobe of the pituitary and the posterior lobe of the pituitary?
15. Which endocrine glands differ between males and females? Which hormones do they produce?

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# 8.3: ENDOCRINE HORMONES

## PILLS FROM PEE

The medication pictured above with the brand name Progynon was a drug used to control the effects of menopause in women. The pills first appeared in 1928 and contained the human sex hormone estrogen. Estrogen secretion declines in women around the time of menopause and may cause symptoms such as mood swings and hot flashes. The pills were supposed to ease the symptoms by supplementing estrogen in the body. The manufacturer of Progynon obtained estrogen for the pills from the urine of pregnant women because it was a cheap source of the hormone. Progynon is still used today to treat menopausal symptoms. Although the drug has been improved over the years, it still contains estrogen. Estrogen is an example of an endocrine hormone.




Figure **8.3.1**: Progynon pills bottle circa 1930 UK

## HOW DO ENDOCRINE HORMONES WORK?

**Endocrine hormones** like estrogen are messenger molecules that are secreted by endocrine glands into the bloodstream. They travel throughout the body in the circulation. Although they reach virtually every cell in the body in this way, each hormone affects only certain cells, called target cells. A **target cell** is the type of cell on which a hormone has an effect. A target cell is affected by a particular hormone because it has receptor proteins — either on the cell surface or within the cell — that are specific to that hormone. An endocrine hormone travels through the bloodstream until it finds a target cell with a matching receptor to which it can bind. When the hormone binds to the receptor, it causes changes within the cell. The manner in which it changes the cell depends on whether the hormone is a steroid hormone or a non-steroid hormone.

### STEROID HORMONES

A **steroid hormone** such as estrogen is made of lipids. It is fat soluble, so it can diffuse across a target cell's plasma membrane, which is also made of lipids. Once inside the cell, a steroid hormone binds with receptor proteins in the cytoplasm. As you can see in the diagram below, the steroid hormone and its receptor form a complex, called a steroid complex, which moves into the nucleus where it influences the expression of genes. Examples of steroid hormones include cortisol, which is secreted by the adrenal glands, and sex hormones, which are secreted by the gonads.

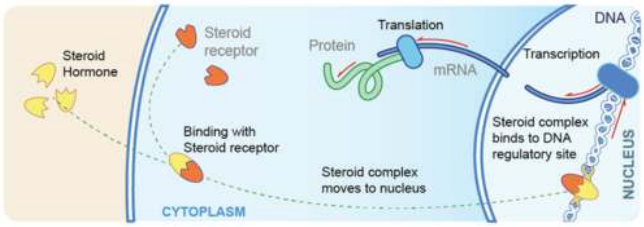



Figure **8.3.2**: A steroid hormone crosses the plasma membrane of a target cell, binds with a receptor protein within the cytoplasm, and forms a complex that moves to the nucleus where it affects gene expression.

### NON-STEROID HORMONES

A **non-steroid hormone** is made of amino acids. It is not fat soluble, so it cannot diffuse across the plasma membrane of a target cell. Instead, it binds to a receptor protein on the cell membrane. In the following diagram, you can see that the binding of the hormone with the receptor activates an enzyme in the cell membrane. The enzyme then stimulates another molecule, called the second messenger, which influences processes inside the cell. Most endocrine hormones are non-steroid hormones. Examples include glucagon and insulin, both produced by the pancreas.

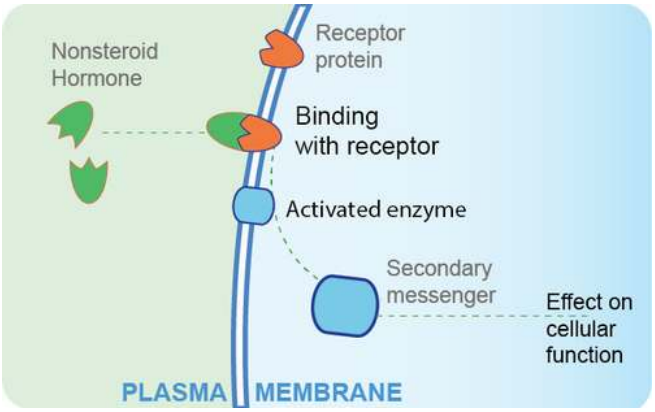



Figure **8.3.3**: A non-steroid hormone binds with a receptor protein on the plasma membrane of a target cell. This activates an enzyme, which controls a secondary messenger molecule.

## REGULATION OF ENDOCRINE HORMONES

Endocrine hormones regulate many body processes, but what regulates the secretion of endocrine hormones? Most endocrine hormones are controlled by feedback mechanisms. A feedback mechanism is a loop in which a product feeds back to control its own production. Feedback loops may be either negative or positive.

- Most endocrine hormones are regulated by negative feedback loops. Negative feedback keeps the concentration of a hormone within a relatively narrow range and maintains homeostasis.
- Very few endocrine hormones are regulated by positive feedback loops. Positive feedback causes the concentration of a hormone

to become increasingly higher.

## REGULATION BY NEGATIVE FEEDBACK

A negative feedback loop controls the synthesis and secretion of hormones by the thyroid gland. This loop includes the hypothalamus and pituitary gland in addition to the thyroid, as shown in Figure 8.3.4. When the levels of thyroid hormones circulating in the blood fall too low, the hypothalamus secretes thyrotropin releasing hormone (TRH). This hormone travels directly to the pituitary gland through the thin stalk connecting the two structures. In the pituitary gland, TRH stimulates the pituitary to secrete thyroid stimulating hormone (TSH). TSH, in turn, travels through the bloodstream to the thyroid gland and stimulates it to secrete thyroid hormones. This continues until the blood levels of thyroid hormones are high enough. At that point, the thyroid hormones feedback to stop the hypothalamus from secreting TRH and the pituitary from secreting TSH. Without the stimulation of TSH, the thyroid gland stops secreting its hormones. Eventually, the levels of thyroid hormones in the blood start to fall too low again. When that happens, the hypothalamus releases TRH, and the loop repeats.

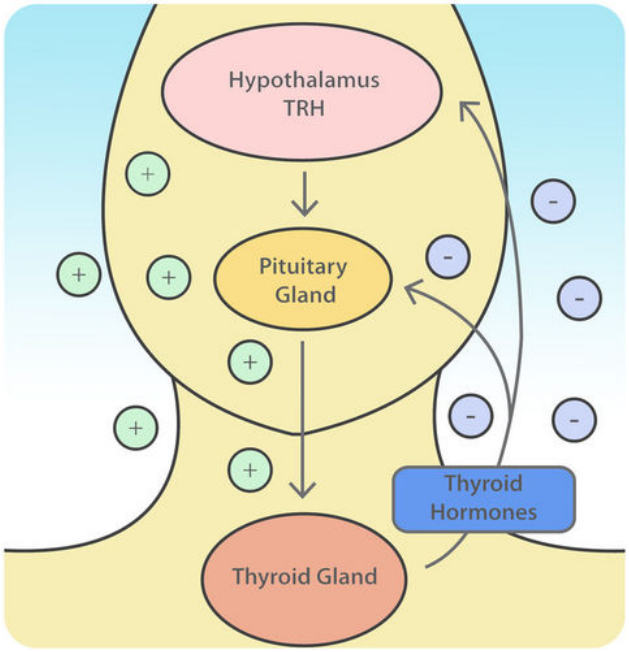



Figure 8.3.4: This diagram shows how the thyroid gland is regulated by a negative feedback loop that also involves the hypothalamus and pituitary gland.

## REGULATION BY POSITIVE FEEDBACK

Prolactin is a non-steroid endocrine hormone secreted by the pituitary gland. One of the functions of prolactin is to stimulate a nursing mother's mammary glands to produce milk. The regulation of prolactin in the mother is controlled by a positive feedback loop that involves the nipples, hypothalamus, pituitary gland, and mammary glands. Positive feedback begins when a baby suckles on the mother's nipple. Nerve impulses from the nipple reach the hypothalamus, which stimulates the pituitary gland to secrete prolactin. Prolactin travels in the blood to the mammary glands and stimulates them to produce milk. The release of milk causes the baby to continue suckling, which causes more prolactin to be secreted and more milk to be produced. The positive feedback loop continues until the baby stops suckling at the breast.

### FEATURE: MYTH VS. REALITY

Anabolic steroids are synthetic versions of the naturally occurring male sex hormone testosterone. Male hormones have androgenic, or masculinizing, effects, but they also have anabolic, or muscle-building effects. The anabolic effects are the reason that synthetic steroids are used by athletes. In addition to building muscles, they also accelerate the development of bones and red blood cells, increase endurance so athletes can train harder and longer, and speed up muscle recovery. Unfortunately, these benefits of steroid use come with costs. If you ever consider taking anabolic steroids to build muscles and improve athletic performance, consider the following myths and corresponding realities.

**Myth:** Steroids are safe.

**Reality:** Steroid use may cause several serious side effects. Prolonged use may increase the risk of liver cancer, heart disease, and high blood pressure.

**Myth:** Steroids will not stunt your growth.

**Reality:** Teens who take steroids before they have finished growing in height may have their growth stunted so they remain shorter throughout life than they would otherwise have been. Such stunting occurs because steroids increase the rate at which skeletal maturity is reached. Once skeletal maturity occurs, additional growth in height is impossible.

**Myth:** Steroids do not cause drug dependency.

**Reality:** Steroid use may cause dependency as evidenced by the negative effects of stopping steroid use. These negative effects may include insomnia, fatigue, and depressed mood, among others.

**Myth:** There is no such thing as "roid rage."

**Reality:** Steroid use has been shown to increase aggressiveness in some people. It has also been implicated in a number of violent acts committed by people who had not demonstrated violent tendencies until they started using steroids.

**Myth:** Only males use steroids.

**Reality:** Although steroid use is more common in males than females, some females also use steroids. They use them to build muscle and improve physical performance, generally either for athletic competition or for self-defense.

## REVIEW

1. What are endocrine hormones?
2. Define the target cell in the context of endocrine hormones.
3. Explain how steroid hormones influence target cells.
4. How do non-steroid hormones affect target cells?
5. Compare and contrast negative and positive feedback loops.

6. Outline the way feedback controls the production of thyroid hormones.
7. Describe the feedback mechanism that controls milk production by the mammary glands.
8. Why do endocrine hormones only affect some of the cells in the body? Choose the best answer.
   A. They only reach certain cells.
   B. Many hormones cannot cross the plasma membrane of cells.
   C. Some cells feedback negatively in response to a hormone.
   D. Only some cells have receptor proteins that can bind to a given hormone.
9. People with a condition called hyperthyroidism produce too much thyroid hormone. What do you think this does to the level of TSH? Explain your answer.
10. Which is more likely to maintain homeostasis — negative feedback or positive feedback? Explain your answer.
11. Does testosterone bind to receptors on the plasma membrane of target cells or in the cytoplasm of target cells? Explain your answer.
12. *True or False.* Endocrine hormones can affect the expression of genes.
13. *True or False.* Non-steroid hormones cannot affect intracellular processes.
14. *True or False.* Insulin binds to receptors on the plasma membrane of cells.
15. Which hormone is secreted by the pituitary gland?
    A. Prolactin
    B. Insulin
    C. Cortisol
    D. Thyrotropin releasing hormone

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# 8.4: PITUITARY GLAND

## MILK ON DEMAND

This adorable nursing infant is part of a positive feedback loop. When he suckles on the nipple, it sends nerve impulses to his mother's hypothalamus, which "tell" her pituitary gland to release the hormone prolactin into her bloodstream. Prolactin travels to the mammary glands in the breasts and stimulates milk production, which motivates the infant to keep suckling.



Figure **8.4.1**: Nursing infant

## WHAT IS THE PITUITARY GLAND?

The **pituitary gland** is the master gland of the endocrine system, the system of glands that secrete hormones into the bloodstream. Endocrine hormones control virtually all physiological processes. For example, they control growth, sexual maturation, reproduction, body temperature, blood pressure, and metabolism. The pituitary gland is considered the master gland of the endocrine system because it controls the rest of the endocrine system. Many pituitary hormones either promote or inhibit hormone secretion by other endocrine glands.

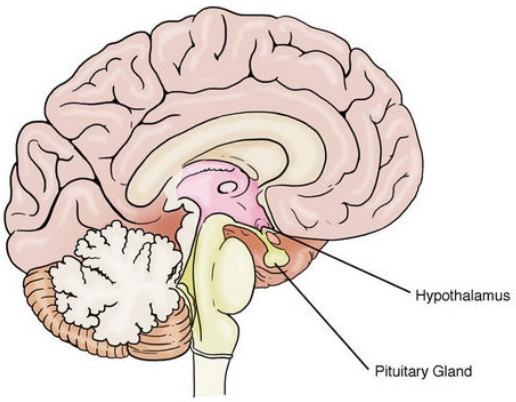



Figure **8.4.2**: The pituitary gland in the endocrine system is closely connected to the hypothalamus in the brain

## STRUCTURE AND FUNCTION OF THE PITUITARY GLAND

The pituitary gland is about the size of a pea. It protrudes from the bottom of the hypothalamus at the base of the inner brain (Figure **8.4.2**). The pituitary is connected to the hypothalamus by a thin stalk (called the infundibulum). Blood vessels and nerves in the stalk allow direct connections between the hypothalamus and the pituitary gland. The pituitary gland consists of two bulb-like lobes: an anterior lobe and a posterior lobe (Figure **8.4.3**).

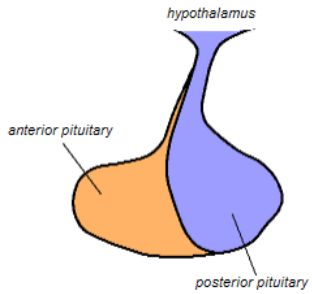



Figure **8.4.3**: Both anterior and posterior lobes of the pituitary gland are directly connected to the hypothalamus by capillaries (anterior lobe) and nerve axons (posterior lobe)

### ANTERIOR LOBE

The **anterior pituitary** is at the front of the pituitary gland. It synthesizes and releases hormones into the blood. Table **8.4.1** shows some of the endocrine hormones released by the anterior pituitary, including their targets and effects.

Table **8.4.1**: Anterior Pituitary Hormones

| Hormone | Target | Effect(s) |
|---|---|---|
| Adrenocorticotropic hormone (ACTH) | Adrenal glands | Stimulates the cortex of each adrenal gland to secrete its hormones |
| Thyroid-stimulating hormone (TSH) | Thyroid gland | Stimulates the thyroid gland to secrete thyroid hormone |
| Growth hormone (GH) | Body cells | Stimulates body cells to synthesize proteins and grow |
| Follicle-stimulating hormone (FSH) | Ovaries, testes | Stimulates the ovaries to develop mature eggs; stimulates the testes to produce sperm |
| Luteinizing hormone (LH) | Ovaries, testes | Stimulates the ovaries and testes to secrete sex hormones; stimulates the ovaries to release eggs |
| Prolactin (PRL) | Mammary glands | Stimulates the mammary glands to produce milk |

The anterior pituitary gland is regulated mainly by hormones from the hypothalamus. The hypothalamus secretes hormones called releasing hormones and inhibiting hormones that travel through capillaries directly to the anterior lobe of the pituitary gland. The hormones stimulate the anterior pituitary to either release or stop releasing particular pituitary hormones. Several of these hypothalamic hormones and their effects on the anterior pituitary are shown in Table **8.4.2**.

Table 8.4.2: Hypothalamic Hormones and Their Effects on the Anterior Pituitary

| Hypothalamic Hormone | Effect on Anterior Pituitary |
|---|---|
| Thyrotropin releasing hormone (TRH) | Release of thyroid stimulating hormone (TSH) |
| Corticotropin releasing hormone (CRH) | Release of adrenocorticotropic hormone (ACTH) |
| Gonadotropin releasing hormone (GnRH) | Release of follicle-stimulating hormone (FSH) and luteinizing hormone (LH) |
| Growth hormone releasing hormone (GHRH) | Release of growth hormone (GH) |
| Growth hormone inhibiting hormone (GHIH) (Somatostatin) | Stopping of growth hormone release |
| Prolactin releasing hormone (PRH) | Release of prolactin |
| Prolactin inhibiting hormone (PIH) (Dopamine) | Stopping of prolactin release |

## POSTERIOR LOBE

The **posterior pituitary** is at the back of the pituitary gland. This lobe does not synthesize any hormones. Instead, the posterior lobe stores hormones that come from the hypothalamus along the axons of nerves connecting the two structures (Figure 8.4.3). The posterior pituitary then secretes the hormones into the bloodstream as needed. Hypothalamic hormones secreted by the posterior pituitary include vasopressin and oxytocin.

- Vasopressin (also called antidiuretic hormone, or ADH) helps to maintain homeostasis in body water. It stimulates the kidneys to conserve water by producing more concentrated urine. Specifically, vasopressin targets ducts in the kidneys and makes them more permeable to water. This allows more water to be resorbed by the body rather than excreted in the urine.
- Oxytocin (OXY) targets cells in the uterus to stimulate uterine contractions, for example, during childbirth. It also targets cells in the breasts of a nursing mother to stimulate the letdown of milk.

## REVIEW

1. Explain why the pituitary gland is called the master gland of the endocrine system.
2. Compare and contrast the two lobes of the pituitary gland and their general functions.
3. Identify two hormones released by the anterior pituitary, their targets, and their effects.
4. Explain how the hypothalamus influences the output of hormones by the anterior lobe of the pituitary gland.
5. Name and give the function of two hypothalamic hormones released by the posterior pituitary gland.
6. *True or False.* The pituitary gland only secretes hormones that are involved in reproduction.
7. *True or False.* The brain does not produce hormones, only glands produce hormones.
8. If a releasing hormone is secreted from the hypothalamus to the pituitary gland, which part of the pituitary receives it? Explain your answer.
9. Answer the following questions about prolactin releasing hormone (PRH) and prolactin inhibiting hormone (PIH).
   A. Where are these hormones produced?
   B. Where are their target cells located?
   C. What are their effects on their target cells?
   D. What are their ultimate effects on milk production? Explain your answer.
10. e. When a baby nurses, which of these hormones is most likely released in the mother? Explain your answer.
11. For each of the following hormones, state whether it is synthesized in the pituitary or the hypothalamus.
    A. Gonadotropin releasing hormone (GnRH)
    B. Growth hormone (GH)
    C. Oxytocin
12. d. Adrenocorticotropic hormone (ACTH)

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# 8.5: THYROID GLAND

## TOO MUCH OF A GOOD THING

The individual in Figure **8.5.1** has a goiter. A **goiter** is an abnormal enlargement of the thyroid gland, which is located in the neck. The formation of a goiter may occur in a number of different thyroid disorders. You'll learn why in this concept.



Figure **8.5.1**: Goiter

## THYROID STRUCTURE

The **thyroid gland** is one of the largest endocrine glands in the body. It is located in the front of the neck below Adam's apple (see Figure **8.5.2**). The gland is butterfly-shaped and composed of two lobes. The lobes are connected by a narrow band of thyroid tissue called an isthmus.

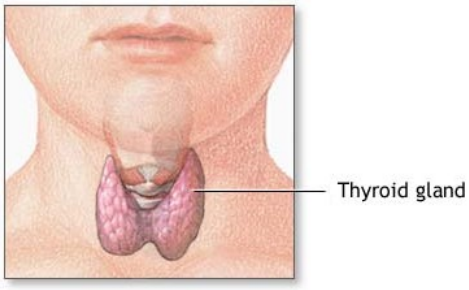



Figure **8.5.2**: The thyroid gland is a two-lobed gland in the front of the neck

Internally, the thyroid gland is composed mainly of follicles. A **follicle** is a small cluster of cells surrounding a central cavity, which stores hormones and other molecules made by the follicular cells. Thyroid follicular cells are unique in being highly specialized to absorb and use iodine. They absorb iodine as iodide ions ($I^-$) from the blood and use the iodide to produce thyroid hormones. The cells also use some of the iodide they absorb to form a protein called thyroglobulin, which serves to store iodide for later hormone synthesis. The outer layer of cells of each follicle secretes thyroid hormones as needed. Scattered among the follicles are another type of thyroid cells, called parafollicular cells (or C cells). These cells synthesize and secrete the hormone calcitonin.

## FUNCTIONS OF THE THYROID

Like all endocrine glands, the function of the thyroid is to synthesize hormones and secrete them into the bloodstream. Once in the blood, they can travel to cells throughout the body and influence their functions.

### THYROID HORMONES: T4 AND T3

There are two main thyroid hormones produced by the follicles: **thyroxine (T4),** which contains four iodide ions and is represented by the structural diagram below; and **triiodothyronine (T3),** which contains three iodide ions. T3 is much more powerful than T4, but T4 makes up about 90 percent of circulating thyroid hormone, and T3 makes up only about 10 percent. However, most of the T4 is converted to T3 by target tissues.

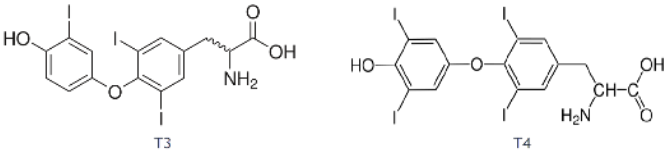



Figure **8.5.3**: This structural model represents a single molecule of triiodothyronine (T3) and thyroxine (T4). The letter I represents the iodide ions they contain. The rings consist mainly of carbon atoms

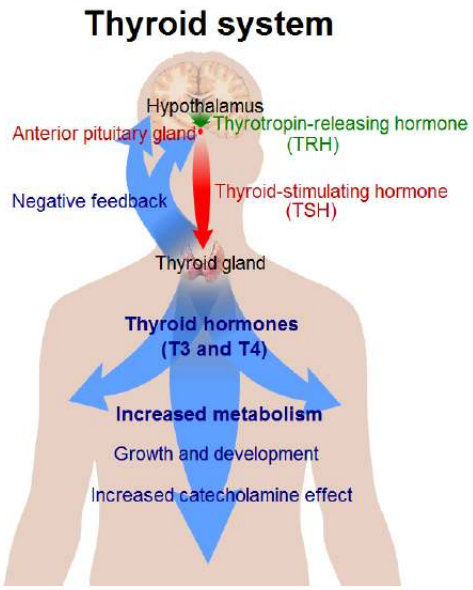



Figure **8.5.4**: The thyroid system is a negative feedback loop that includes the hypothalamus, pituitary gland, and thyroid gland. As this diagram shows, thyroid hormones increase the effect of catecholamines such as adrenaline, a fight-or-flight hormone

Like steroid hormones, T3 and T4 cross cell membranes everywhere in the body and bind to intracellular receptors to regulate gene expression. However, unlike steroid hormones, thyroid hormones can cross cell membranes only with the help of special transporter proteins. Once inside the nucleus of cells, T3 and T4 turn on genes that control protein synthesis. Thyroid hormones increase the rate of metabolism in cells, so cells absorb more carbohydrates, use more energy, and produce more heat. Thyroid hormones also increase the

rate and force of the heartbeat. In addition, they increase the sensitivity of cells to fight-or-flight hormones (that is, catecholamine hormones such as adrenaline).

The production of both T4 and T3 is regulated primarily by thyroid stimulating hormone (TSH), which is secreted by the anterior pituitary gland (see the diagram below). TSH production, in turn, is regulated by thyrotropin releasing hormone (TRH), which is produced by the hypothalamus. The thyroid gland, pituitary gland, and hypothalamus form a negative feedback loop to keep thyroid hormone secretion within a normal range. TRH and TSH production is suppressed when T4 levels start to become too high. The opposite occurs when T4 levels start to become too low.

### CALCITONIN

The **calcitonin** produced by the parafollicular cells of the thyroid gland has the role of helping to regulate blood calcium levels by stimulating the movement of calcium into bone. Calcitonin is secreted in response to rising blood calcium levels. It decreases blood calcium levels by enhancing calcium absorption and deposition in bone. Calcitonin works hand-in-hand with parathyroid hormone, which is secreted by the parathyroid glands and has the opposite effects as calcitonin. Together, these two hormones maintain calcium homeostasis.

## THYROID DISORDERS

As with other endocrine disorders, thyroid disorders are generally associated with either over or under-secretion of hormones. Abnormal secretion of thyroid hormones may occur for a variety of reasons.

### HYPERTHYROIDISM

**Hyperthyroidism** occurs when the thyroid gland produces excessive amounts of thyroid hormones. The most common cause of hyperthyroidism is Graves' disease. **Graves' disease** is an autoimmune disorder in which abnormal antibodies produced by the immune system stimulate the thyroid to secrete excessive quantities of its hormones. This stimulation overrides the usual negative feedback mechanism that normally controls thyroid hormone output. Graves' disease often results in the formation of an enlarged thyroid (goiter) because of the continued stimulation to produce more hormones.

Besides a goiter, other signs and symptoms of hyperthyroidism may include protruding eyes (see photo below), heart palpitations, excessive sweating, diarrhea, weight loss despite increased appetite, muscle weakness, and unusual sensitivity to heat. Medications can be prescribed to mitigate the symptoms of the disease. Anti-thyroid drugs can also be given to decrease the production of thyroid hormones. If the drugs are ineffective, the gland can be partially or entirely removed. This can be done surgically or with the administration of radioactive iodine. Removal of the thyroid produces hypothyroidism.

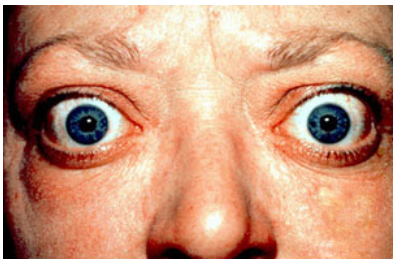


Figure 8.5.5: Protruding eyes are one sign of hyperthyroidism, such as Graves' disease

## HYPOTHYROIDISM

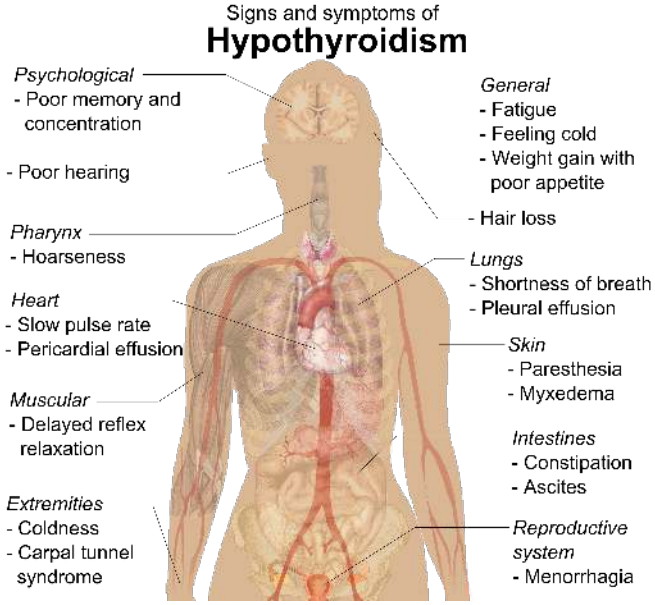



Figure 8.5.6: the signs and symptoms of hypothyroidism may include fatigue, coldness, weight gain, shortness of breath, constipation, menorrhagia, poor memory and hearing, hoarseness, slow heart rate, delayed reflexes, and carpal tunnel syndrome.

**Hypothyroidism** occurs when the thyroid gland produces insufficient amounts of thyroid hormones. It can result from surgical removal of the thyroid. However, worldwide, the most common cause of hypothyroidism is dietary iodine deficiency. In cases of iodine deficiency, the negative feedback loop controlling the release of thyroid hormone causes repeated stimulation of the thyroid. This results in the thyroid gland growing in size and producing a goiter. Although the gland gets larger, it cannot increase hormone output because of the lack of iodine in the diet.

Iodine deficiency is uncommon in the Western world because iodine is added to salt. Where iodine deficiency is not a problem, the most common cause of hypothyroidism is **Hashimoto's thyroiditis.** This is another autoimmune disease, but in this case, the immune system destroys the thyroid gland, producing hypothyroidism. Hashimoto's thyroiditis tends to run in families so it is likely to have a genetic component. It usually appears after the age of 30 and is more common in females than males.

Hypothyroidism produces many signs and symptoms, as shown in Figure 8.5.6. These may include abnormal weight gain, tiredness, baldness, cold intolerance, and slow heart rate. Hypothyroidism is

generally treated with thyroid hormone replacement therapy. This may be needed for the rest of a person's life. Hypothyroidism in a pregnant woman can have serious adverse consequences for the fetus. During the fetal period, cells of the developing brain are a major target for thyroid hormones, which play a crucial role in brain maturation. When levels of thyroid hormones are too low, the fetus may suffer permanent deficits in cognitive abilities. Deafness is also a potential outcome of hypothyroidism *in utero*.

**Feature: Myth vs. Reality**

Thyroid disorders are relatively common, affecting as many as 20 million people in the United States. Because the disorders are common, there are also many common myths about them.

**Myth:** If you have a thyroid problem, you will know something is wrong because you will have obvious symptoms.

**Reality:** The majority of people with a thyroid disorder are not aware they have it because the symptoms are often mild, nonspecific, and easy to ignore. Generally, blood tests of thyroid hormone levels are needed to make a conclusive diagnosis.

**Myth:** If you are diagnosed with a thyroid disorder, you will have to take medication for the rest of your life.

**Reality:** Whether you need to continue thyroid medication for life depends on the cause of the disorder. For example, some women develop hypothyroidism during pregnancy but no longer need medication after the pregnancy is over and hormone levels return to normal.

**Myth:** As soon as you start taking thyroid medication, your symptoms will resolve.

**Reality:** It often takes weeks or even months for thyroid hormone levels to return to normal and symptoms to disappear.

**Myth:** You can take an over-the-counter iodine supplement to correct hypothyroidism.

**Reality:** In the United States, where dietary iodine is almost always adequate, iodine deficiency is unlikely to be the cause of hypothyroidism. Therefore, taking supplemental iodine is not likely to correct the problem.

**Myth:** If thyroid symptoms are mild, you don't need to take medication.

**Reality:** Because thyroid hormones are responsible for so many vital body functions, failing to treat even a mild thyroid disorder may lead to a range of other problems, such as osteoporosis or infertility.

**Myth:** Goiter may be caused by eating "goitrogenic" vegetables, such as broccoli, Brussels sprouts, and spinach.

**Reality:** Although these foods can interfere with the thyroid's ability to process iodide, you would have to eat huge amounts of them to cause goiter.

**Myth:** Thyroid disorders occur only after middle age and only in women.

**Reality:** Thyroid disorders may occur at any age and in any sex. Hypothyroidism occurs more commonly in older adults, but hyperthyroidism occurs more commonly in younger adults. Although women are more likely to develop thyroid disorders, about 20 percent of cases occur in men.

## REVIEW

1. Describe the structure and location of the thyroid gland.
2. Identify the types of cells within the thyroid gland that produce hormones.
3. Compare and contrast T4 and T3.
4. How do T4 and T3 affect body cells?
5. Explain how T4 and T3 production is regulated.
6. What is the function of calcitonin?
7. Identify the chief cause and effects of hyperthyroidism.
8. What are two possible causes of hypothyroidism?
9. List signs and symptoms of hypothyroidism.
10. Why may both hyperthyroidism and hypothyroidism cause goiters?
11. Choose one symptom each for hyperthyroidism and hypothyroidism and explain why they occur based on the functions of thyroid hormones.
12. Which hormone is produced by the thyroid gland?
    A. T3
    B. Calcitonin
    C. Parathyroid hormone
    D. TSH
    E. A and B
13. In cases of hypothyroidism due to Hashimoto's thyroiditis or removal of the thyroid gland to treat hyperthyroidism, patients are often given medication to replace the missing thyroid hormone. Explain why the level of replacement thyroid hormone must be carefully monitored and adjusted if needed.
14. *True or False.* T3 and T4 bind to receptors on the plasma membrane of target cells.
15. Which disease causes too much thyroid hormone to be produced?
    A. Hashimoto's thyroiditis
    B. Graves' disease
    C. Goiter
    D. Iodine deficiency

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# 8.6: ADRENAL GLANDS

EEK!

Being bitten on the nose by an eel certainly qualifies as a frightening experience! The fear this man is experiencing produces the same physiological responses in most people—racing heart, rapid breathing, clammy hands. These and other fight-or-flight responses prepare the body to either defend itself or run away from danger. Why does fear elicit these changes in the body? The responses occur in large part because of hormones secreted by the adrenal glands.



Figure **8.6.1**: Attack

## INTRODUCTION TO THE ADRENAL GLANDS

The **adrenal glands** are endocrine glands that produce a variety of hormones. Adrenal hormones include the fight-or-flight hormone adrenaline and the steroid hormone cortisol. The two adrenal glands are located on both sides of the body, just above the kidneys, as shown in Figure **8.6.2**. The right adrenal gland (on the left in the figure) is smaller and has a pyramidal shape. The left adrenal gland (on the right in the figure) is larger and has a half-moon shape.

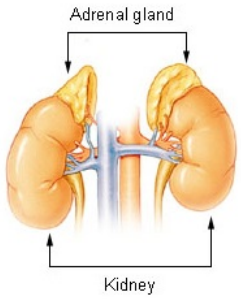



Figure **8.6.2**: Each of the two adrenal glands is found above a kidney

Each adrenal gland has two distinct parts, and each part has a different function, although both parts produce hormones. There is an outer layer, called the adrenal cortex, which produces steroid hormones including cortisol. There is also an inner layer, called the adrenal medulla, which produces non-steroid hormones including adrenaline.

## ADRENAL CORTEX

The **adrenal cortex,** or the outer layer of the adrenal gland, is divided, in turn, into three additional layers, called zones (Figure **8.6.3**). Each zone has distinct enzymes that produce different hormones from the common precursor molecule cholesterol, which is a lipid.

1. Zona glomerulosa is the outermost layer of the adrenal cortex. It lies immediately under the outer fibrous capsule that encloses the adrenal gland.
2. Zona fasciculata is the middle layer of the adrenal cortex. It is the largest of the three zones, accounting for nearly 80 percent of the adrenal cortex.
3. Zona reticularis is the innermost layer of the adrenal cortex. It is directly adjacent to the medulla of the adrenal gland.

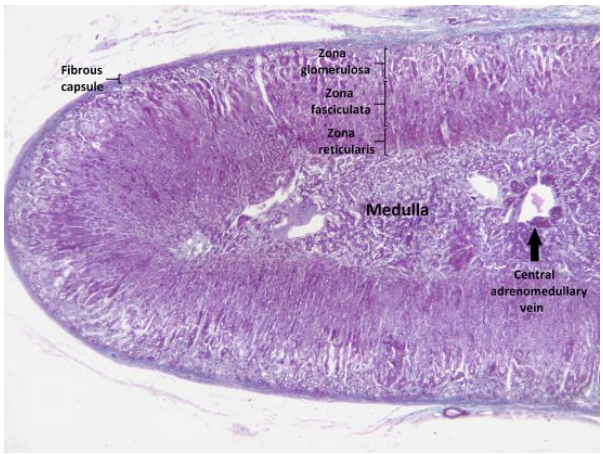



Figure **8.6.3**: The adrenal cortex is divided into three zones, zona glomerulosa, zona fasciculata, and zona reticularis. Each zone produces a different type of steroid hormone. This photomicrograph also shows the medulla of the adrenal gland.

## TYPES OF ADRENAL CORTEX HORMONES

Hormones produced by the adrenal cortex are called **corticosteroids.** As steroid hormones, corticosteroids are endocrine hormones that are made of lipids and exert their effects on target cells by crossing the plasma membrane and binding with receptors within the cytoplasm. A steroid hormone and its receptor form a complex that enters the cell nucleus and affects gene expression. There are three types of corticosteroids synthesized and secreted by the adrenal cortex. Each type is produced by a different zone of the adrenal cortex, as shown in Figure **8.6.3**.

### *MINERALOCORTICOIDS*

Mineralocorticoids are produced in the zona glomerulosa and include the hormone aldosterone. These hormones help control the balance of mineral salts (electrolytes) in the body. In the kidneys, aldosterone increases the reabsorption of sodium ions and the excretion of potassium ions. Aldosterone also stimulates the retention of sodium ions by cells in the colon and by the sweat glands. The amount of sodium in the body affects the volume of

extracellular fluids including the blood and thereby affects blood pressure. In this way, mineralocorticoids help control blood volume and blood pressure.

#### GLUCOCORTICOIDS

Glucocorticoids are produced in the zona fasciculata and include the hormone **cortisol,** which is released in response to stress and is considered the primary stress hormone. Glucocorticoids help control the rate of metabolism of proteins, fats, and sugars. In general, they increase the level of glucose and fatty acids circulating in the blood. Cells rely primarily on glucose for energy, but they can also use fatty acids for energy as an alternative to glucose. Glucocorticoids are also involved in the suppression of the immune system, having a potent anti-inflammatory effect. In addition, cortisol reduces the production of new bone and decreases the absorption of calcium from the gastrointestinal tract.

#### ANDROGENS

**Androgens** are produced in the zona reticularis and include the hormone DHEA (dehydroepiandrosterone). Androgens are a general term for male sex hormones, although this is somewhat misleading as adrenal cortex androgens are produced by both males and females. In adult males, they are converted to more potent androgens such as testosterone in the male gonads (testes). In adult females, they are converted to female sex hormones called estrogens in the female gonads (ovaries).

### REGULATION OF ADRENAL CORTEX HORMONES

Steroid hormone production by the three zones of the adrenal cortex is regulated by hormones secreted by the anterior lobe of the pituitary gland as well as by other physiological stimuli. For example, the production of glucocorticoids such as cortisol is stimulated by adrenocorticotropic hormone (ACTH) from the anterior pituitary, which in turn is stimulated by corticotropin releasing hormone (CRH) from the hypothalamus. When levels of glucocorticoids start to rise too high, they provide negative feedback to the hypothalamus and pituitary gland to stop secreting CRH and ACTH, respectively. This negative feedback mechanism is illustrated in Figure **8.6.4**. The opposite occurs when levels of glucocorticoids start to fall too low.

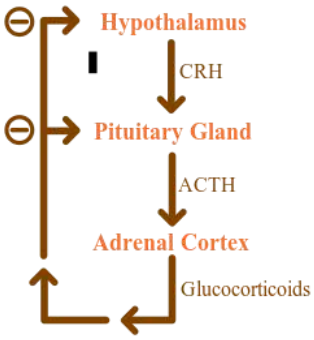



Figure **8.6.4**: The negative feedback loop that controls the production of glucocorticoids includes the pituitary gland and hypothalamus in addition to the adrenal cortex.

## ADRENAL MEDULLA

The **adrenal medulla** is at the center of each adrenal gland and is surrounded by the adrenal cortex. It contains a dense network of blood vessels into which it secretes its hormones. The hormones synthesized and secreted by the adrenal medulla are called **catecholamines**, and they include **adrenaline** (also called epinephrine) and noradrenaline (also called norepinephrine). These are water-soluble, non-steroid hormones are made of amino acids. As non-steroid hormones, they cannot cross the plasma membrane of target cells. Instead, they exert their effects by binding to receptors on the surface of target cells. The binding of hormones and receptors activates an enzyme in the plasma membrane that controls a second messenger. It is the second messenger that influences processes inside the cell.

Catecholamines function to produce a rapid response throughout the body in stressful situations. They bring about such changes as increased heart rate, more rapid breathing, constriction of blood vessels in certain parts of the body, and an increase in blood pressure. The release of catecholamines by the adrenal medulla is stimulated by activation of the sympathetic division of the autonomic nervous system.

## DISORDERS OF THE ADRENAL GLANDS

Disorders of the adrenal glands generally include either hypersecretion or hyposecretion of adrenal hormones. The underlying cause of the abnormal secretion may be a problem with the adrenal glands or with the pituitary gland, which controls adrenal cortex hormone production. Both adrenal and pituitary glands are subject to the formation of tumors, which may cause adrenal disorders. The adrenal gland may also be affected by infections or autoimmune diseases.

### ADRENAL HYPERSECRETION: CUSHING'S SYNDROME

Hypersecretion of the glucocorticoid hormone cortisol leads to a disorder named **Cushing's syndrome.** The most common cause of Cushing's syndrome is a pituitary tumor, which causes excessive production of ACTH. The disease produces a wide variety of signs and symptoms, which may include obesity, diabetes, high blood pressure (hypertension), excessive body hair, osteoporosis, and depression. A distinctive sign of Cushing's syndrome is the appearance of stretch marks in the skin, as the skin becomes progressively thinner. Another distinctive sign is a moon face shown in the section *Introduction to the Endocrine System*, in which fat deposits give the face a rounded appearance. Treatment of Cushing's syndrome depends on its cause and may include surgery to remove a tumor or medications to suppress the activity of the adrenal glands.

### ADRENAL HYPOSECRETION: ADDISON'S DISEASE



Figure **8.6.5**: Hyperpigmentation of the skin is a characteristic sign of Addison's disease. The photo on the left shows the dark skin pigmentation of an Addison's patient before treatment. The photo on the right shows the same patient after treatment.

Hyposecretion of the glucocorticoid hormone cortisol leads to a disorder named **Addison's disease**. There may also be hyposecretion of mineralocorticoids with this disorder. Addison's disease is generally an autoimmune disorder, in which the immune system produces abnormal antibodies that attack cells of the adrenal cortex. Untreated infections, especially of tuberculosis, may also damage the adrenal cortex and cause Addison's disease. A third possible cause is the decreased output of ACTH by the pituitary gland, generally due to a pituitary tumor. A distinctive sign of Addison's disease is hyperpigmentation of the skin (Figure **8.6.5**). Other symptoms tend to be nonspecific and include excessive fatigue. Addison's disease is generally treated with replacement hormones in pill form.

## FEATURE: MY HUMAN BODY



Figure **8.6.6**: Base Jump

Does just looking at this photo cause you to break out in a cold sweat and experience heart palpitations? Imagine how scary it would be to fling yourself backward off a tall building like the BASE jumper in the photo. There would be very little time to use a parachute to slow your fall before you hit the ground. BASE jumping is called the most dangerous sport on Earth. In fact, it is so dangerous that it is outlawed in some places.

People who participate in such dangerous activities as BASE jumping are likely to be adrenaline "junkies." They are addicted to the adrenaline rush and euphoria, or "high," it causes when their fight-or-flight response is triggered by danger. Why does adrenaline have this effect? Adrenaline is closely related to dopamine, a chemical messenger in the brain that plays a major role in pleasure and addiction.

Adrenaline addicts don't have to participate in BASE jumping or other dangerous sports to get an adrenaline rush. They might choose a dangerous occupation such as firefighting, participate in risky behaviors such as reckless driving or bank robbing, or just pick fights with other people. They might even create their own stress by always taking on too much work or delaying projects until close to their deadline.

While some excitement in one's life is generally a good thing, always putting oneself in danger or constantly being under stress are obviously not good things. If you think you might be an adrenaline addict, note that there are healthier ways to experience a hormonal "high." Running, biking, or participating in some other form of vigorous aerobic exercise causes the pituitary gland and hypothalamus to produce opiate-like endorphins, leading to a so-called "runner's high." Like the euphoric feeling adrenaline causes, a runner's high may last for hours.

## REVIEW

1. Describe the structure and location of the adrenal glands.
2. Compare and contrast the adrenal cortex and adrenal medulla.
3. Identify the three layers of the adrenal cortex and the type of hormones each layer produces.
4. Give an example of each type of corticosteroid and state its function.
5. Explain how the production of glucocorticoids is regulated.
6. What is a catecholamine? Give an example of a catecholamine and state its function.
7. Compare and contrast Cushing's syndrome and Addison's disease.
8. Cortisol is a type of:
   A. Corticosteroid
   B. Mineralocorticoid
   C. Glucocorticoid
   D. A and C
9. *True or False.* The adrenal glands help regulate the body's stress response and reproductive functions.
10. *True or False.* The left adrenal gland produces steroid hormones, while the right adrenal gland produces non-steroid hormones.
11. Would it help to give someone with Cushing's syndrome more ACTH? Explain your answer.
12. What are two ways in which the nervous system (which includes the brain, spinal cord, and nerves) controls the adrenal gland?
13. If the level of cortisol rises too high, the amount of CRH secreted will normally:
    A. not change
    B. become excessively high
    C. become slightly higher

D. decrease

14. Noradrenaline is also called:

    A. norepinephrine
    B. adrenaline
    C. adrenocorticotropin
    D. glucocorticoid

15. Explain why a pituitary tumor can cause either hypersecretion or hyposecretion of cortisol.

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# 8.7: PANCREAS

## A SHOT IN THE ARM

Giving yourself an injection can be difficult, but for someone with diabetes, it may be a matter of life or death. The person in the photo has diabetes and is injecting himself with insulin, the hormone that helps control the level of glucose in the blood. Insulin is produced by the pancreas.



Figure **8.7.1**: Insulin Application

## INTRODUCTION TO THE PANCREAS

The **pancreas** is a large gland located in the upper left abdomen behind the stomach, as shown in the figure below. The pancreas is about 15 centimeters (6 in.) long; and it has a flat, oblong shape. Structurally, the pancreas is divided into a head, body, and tail. Functionally, the pancreas serves as both an endocrine gland and an exocrine gland.

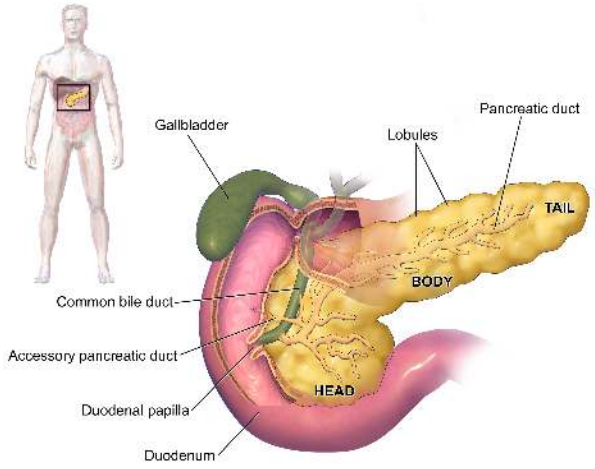



Figure **8.7.2**: The pancreas is located behind the stomach and near the upper part of the small intestine (duodenum). Its main parts are tail, body, and head. Its ducts carry digestive enzymes into the small intestine. The endocrine hormones it produces are secreted into the blood.

- As an endocrine gland, the pancreas is part of the endocrine system. As such, it releases hormones, such as insulin, directly into the bloodstream for transport to cells throughout the body.
- As an exocrine gland, the pancreas is part of the digestive system. As such, it releases digestive enzymes into ducts that carry the enzymes to the gastrointestinal tract where they assist with digestion. In this concept, the focus is on the pancreas as an endocrine gland. You can read about the pancreas as an exocrine gland in the chapter *Digestive System*.

## THE PANCREAS AS AN ENDOCRINE GLAND

The tissues within the pancreas that have an endocrine role exist as clusters of cells called **pancreatic islets.** They are also called the islets of Langerhans. In Figure **8.7.3**, you can see pancreatic tissue, including islets. There are approximately 3 million pancreatic islets, and they are crisscrossed by a dense network of capillaries. The capillaries are lined by layers of islet cells that have direct contact with the blood vessels, into which they secrete their endocrine hormones.

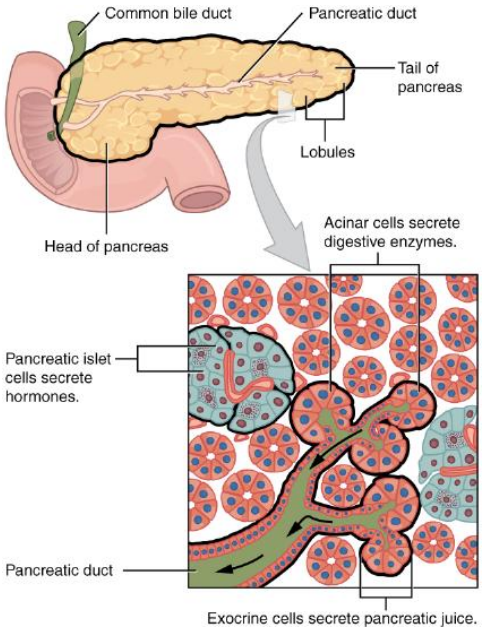



Figure **8.7.3**: Anatomy of the pancreas. The inset diagram shows pancreatic islet cells that produce endocrine hormones. It also shows the cells (called acinar cells) that secrete exocrine substances involved in digestion into pancreatic ducts.

The pancreatic islets consist of four main types of cells, each of which secretes a different endocrine hormone. However, all of the hormones produced by the pancreatic islets play crucial roles in glucose metabolism and the regulation of blood glucose levels, among other functions.

1. Islet cells called alpha (α) cells secrete the hormone glucagon. The function of glucagon is to increase the level of glucose in the blood. It does this by stimulating the liver to convert stored glycogen into glucose, which is released into the bloodstream.
2. Islet cells called beta (β) cells secrete the hormone insulin. The function of insulin is to decrease the level of glucose in the blood. It does this by promoting the absorption of glucose from the blood into fat, liver, and skeletal muscle cells. In these tissues, the absorbed glucose is converted into glycogen, fats (triglycerides), or both.
3. Islet cells called delta (δ) cells secrete the hormone **somatostatin.** This hormone is also called the growth hormone inhibiting hormone because it inhibits the anterior lobe of the pituitary gland from producing growth hormone. Somatostatin

also inhibits the secretion of pancreatic endocrine hormones and pancreatic exocrine enzymes.

4. Islet cells called gamma (γ) cells secrete the hormone pancreatic polypeptide. The function of pancreatic polypeptide is to help regulate the secretion of both endocrine and exocrine substances by the pancreas.

## DISORDERS OF THE PANCREAS

There are a variety of disorders that affect the pancreas. They include pancreatitis, pancreatic cancer, and diabetes mellitus.

### PANCREATITIS

**Pancreatitis** is inflammation of the pancreas. It has a variety of possible causes including gallstones, chronic alcohol use, infections such as measles or mumps, genetic causes, and certain medications. Pancreatitis occurs when digestive enzymes produced by the pancreas damage the gland's tissues, which causes problems with fat digestion. The disorder is usually associated with intense pain in the central abdomen, and the pain may radiate to the back. Yellowing of the skin and whites of the eyes (Figure **8.7.4**), which is called jaundice, is a common sign of pancreatitis. People with pancreatitis may also have pale stools and dark urine. Treatment of pancreatitis includes administering drugs to manage pain and addressing the underlying cause of the disease, for example, by removing gallstones.



Figure **8.7.4**: Jaundice, or yellowing of the skin and whites of the eyes, is a common sign of pancreatitis.

### PANCREATIC CANCER

There are several different types of pancreatic cancer that may affect either the endocrine or the exocrine tissues of the gland. Cancers affecting the endocrine tissues are all relatively rare. However, their incidence has been rising sharply. It is unclear to what extent this reflects increased detection, especially through medical imaging techniques. Unfortunately, pancreatic cancer is usually diagnosed at a relatively late stage when it is too late for surgery, which is the only way to cure the disorder. In the United States, pancreatic cancer is the fourth most common cause of death due to cancer.

Pancreatic cancer is rare before the age of 40 and occurs most often after the age of 60. Factors that increase the risk of developing pancreatic cancer include smoking, chronic pancreatitis, and diabetes. About one in four cases of pancreatic cancer are attributable to smoking. Certain rare genetic conditions are also risk factors for pancreatic cancer.

### DIABETES MELLITUS

By far the most common type of pancreatic disorder is diabetes mellitus, more commonly called simply diabetes. There are many different types of diabetes, but diabetes mellitus is the most common. It occurs in two major types, type 1 diabetes and type 2 diabetes. The two types have different causes and may also have different treatments, but they generally produce the same initial symptoms, which include excessive urination and thirst. These symptoms occur because the kidneys excrete more urine in an attempt to rid the blood of excess glucose, and loss of water in urine stimulates greater thirst. Other signs and symptoms of diabetes are listed in Figure **8.7.5**.

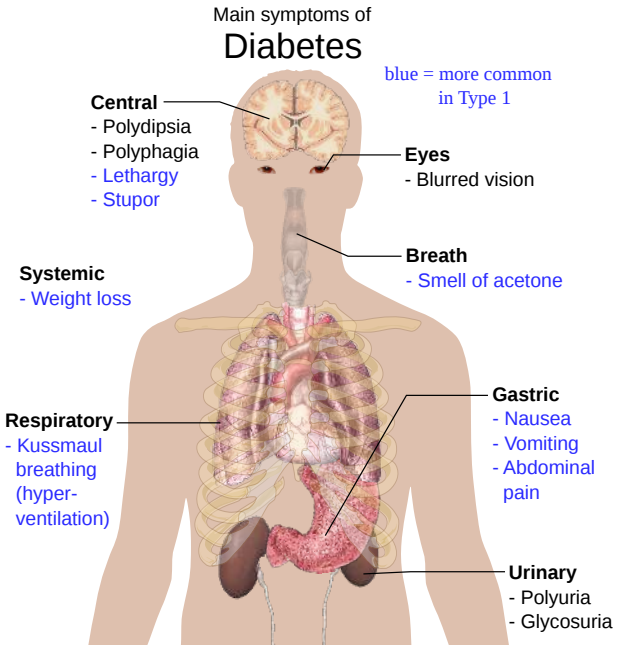



Figure **8.7.5**: Diabetes can affect many systems of the body. The symptoms shared by both type 1 and type 2 diabetes, such as blurred vision, polyuria, glycosuria, polydipsia, and polyphagia are listed in black, and the symptoms more common in type 1 diabetes, such as the smell of acetone, nausea, vomiting, abdominal pain, lethargy, stupor, weight loss, and hyperventilation are listed in blue.

When diabetes is not well controlled, it is likely to have several serious long-term consequences. Most of these consequences are due to damage to small blood vessels because of high blood levels of glucose. Damage to blood vessels, in turn, may lead to an increased risk of coronary artery disease and stroke. Damage to blood vessels in the retina of the eye can result in gradual vision loss and blindness. Damage to blood vessels in the kidneys can lead to chronic kidney disease, sometimes requiring dialysis or a kidney transplant. Long-term consequences of diabetes may also include damage to the nerves of the body, known as diabetic neuropathy. In fact, this is the most common complication of diabetes. Symptoms of diabetic neuropathy may include numbness, tingling, and pain in the extremities.

#### *TYPE 1 DIABETES*

**Type 1 diabetes** is a chronic autoimmune disorder in which the immune system attacks the insulin-secreting beta cells of the

pancreas. As a result, people with type 1 diabetes lack the insulin needed to keep blood glucose levels within the normal range. Type 1 diabetes may develop in people of any age but is most often diagnosed before adulthood. For type 1 diabetics, insulin injections are critical for survival.

### *TYPE 2 DIABETES*

**Type 2 diabetes** is the single most common form of diabetes. The cause of high blood glucose in this form of diabetes usually includes a combination of insulin resistance and impaired insulin secretion. Both genetic and environmental factors play roles in the development of type 2 diabetes. Management of type 2 diabetes includes changes in diet and physical activity, which may increase insulin sensitivity and help reduce blood glucose levels to normal ranges. Medications may also be used as part of the treatment, as may insulin injections.

### FEATURE: HUMAN BIOLOGY IN THE NEWS

Some patients with type 1 diabetes have been given pancreatic islet cells transplants from other human donors. If the transplanted cells are not rejected by the recipient's immune system, they can cure the patient of diabetes. However, only about 1,000 such surgeries have been performed over the past 10 years because of a shortage of appropriate human donors.

In June of 2016, a research team led by Dr. David K.C. Cooper at the Thomas E. Starzl Transplantation Institute in Pittsburgh, Pennsylvania, reported on their work developing pig islet cells for transplant into human diabetes patients. The researchers genetically engineered the pig islet cells to be protected from the human immune response. As a result, patients receiving transplanted cells would require only minimal suppression of their immune system after the surgery. The pig islet cells would also be less likely to transmit pathogenic agents because the animals could be raised in a controlled environment.

The researchers have successfully transplanted the pig islet cells into monkey models of type 1 diabetes. As of June 2016, the scientists were looking for funding to undertake clinical trials in humans with type 1 diabetes. Dr. Cooper predicted then that if the human trials go as well as expected, the pig islet cells could be available for curing patients in as little as two years.

## REVIEW

1. Describe the structure and location of the pancreas.
2. Distinguish between the endocrine and exocrine functions of the pancreas.
3. Identify the four types of pancreatic islet cells and the endocrine hormone each type of cell produces.
4. What is pancreatitis? What are the possible causes and effects of pancreatitis?
5. Describe the incidence, prognosis, and risk factors of cancer of the endocrine tissues of the pancreas.
6. Compare and contrast type 1 and type 2 diabetes.
7. If the alpha islet cells of the pancreas were damaged to the point that they no longer functioned, how would this affect blood glucose levels? Would the administration of insulin be more likely to help or hurt the condition? Explain your answer.
8. Explain how the pancreas is able to regulate the production of its own endocrine hormones, to some extent.
9. True or False. The pancreas is part of both the digestive system and the endocrine system.
10. Give an example of how the pancreas can regulate the production of hormones from the pituitary gland.
11. Which is the most common form of diabetes mellitus?
12. Explain why diabetes causes excessive thirst.
13. Damage to _____ is the underlying cause of many of the long-term consequences of diabetes.

    A. the adrenal gland
    B. gamma islet cells
    C. blood vessels
    D. the pituitary gland

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# 8.8: CASE STUDY CONCLUSION- HORMONAL AND CHAPTER SUMMARY

## CASE STUDY CONCLUSION: HORMONAL HAVOC

Gabrielle, who you read about in the beginning of this chapter, has polycystic ovary syndrome (PCOS). PCOS is named for the multiple fluid-filled sacs, or cysts, that are present in the ovaries of women with this syndrome. You can see these cysts in the illustration above, which compares a normal ovary with a polycystic ovary. The cysts result from follicles in the ovary that did not properly produce and release an egg. Mature eggs are normally released from follicles monthly during the process of ovulation, but in PCOS this often does not occur. Ovarian cysts can be common and do not necessarily mean that a woman has PCOS, but the presence of multiple ovarian cysts plus other telltale signs and symptoms may cause her physician suspect PCOS.

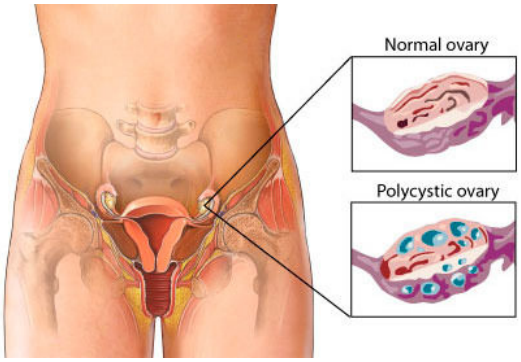



Figure **8.8.1**: Polycystic Ovary

Gabrielle's symptoms of PCOS included irregular menstrual periods, weight gain, acne, and excess facial hair. There are many other symptoms of PCOS that women can experience, such as male-pattern baldness, pelvic pain, and depression, among others. As you may recall, Gabrielle also had some abnormal blood test results, such as high levels of androgens and blood glucose. These can also be indications of PCOS.

As you have learned, androgens are a term for male sex hormones, but females also normally produce androgens, albeit to a lesser extent than males. In women with PCOS, the level of androgens is abnormally high. These androgens include testosterone, which is produced by the ovaries, and DHEA, which is produced by the adrenal glands. This increase in androgens can have a "masculinizing" effect on women, including an increase in facial and body hair, male-pattern baldness, and interference with the menstrual cycle by preventing ovulation. Androgens also can cause weight gain and acne — two of the other common symptoms of PCOS.

In addition to hypersecretion of androgens, PCOS often causes high blood glucose as a result of insulin resistance. As you have learned, insulin is a hormone secreted by the pancreas that works in conjunction with other pancreatic hormones (such as glucagon) to regulate the level of blood glucose. What is another disease involving insulin resistance? If you answered type 2 diabetes, you are correct! In fact, women with PCOS are at a high risk of developing type 2 diabetes because of their resistance to insulin. More than 50 percent of women with PCOS will develop diabetes or pre-diabetes before they are 40 years old.

Besides diabetes, women with PCOS have a higher chance of developing fertility problems, heart disease, sleep apnea (briefly stopping breathing during sleep), and uterine cancer, among other diseases and disorders. There is hope, however. Lifestyle modifications and medicines not only can help women cope with the symptoms of PCOS, but may also reduce the risk of some of the possible long-term consequences by lowering blood sugar and androgen levels. For instance, eating a healthy diet and exercising regularly can help women with PCOS lose weight. This can help lower blood glucose levels, improve insulin functioning, and can even make the menstrual cycle more regular. Medications such as birth control pills and anti-androgens can help restore a more regular menstrual cycle and reduce facial and body hair and acne. The diabetes medication metformin can be used to treat several of the symptoms of PCOS, and even may prevent type 2 diabetes, by improving insulin functioning and lowering testosterone. Finally, women with PCOS who are trying to conceive may be helped with fertility medications that stimulate ovulation.

The underlying cause of PCOS is not definitively known, although it is thought that both genetic and environmental factors play a role. PCOS tends to run in families, and women with a sister with PCOS are twice as likely to also have it. Researchers think that the insulin resistance seen in PCOS may cause an increase in androgens, illustrating how hormonal systems can influence each other.

As you have seen throughout this chapter, endocrine hormones can have a wide variety of effects on the body, including the regulation of metabolism, reproductive functions, homeostasis of different ions and molecules, and mediating responses to stressful situations. Different hormones have different effects, but even a single hormone can have multiple effects. Hormones travel throughout the bloodstream and affect any cells that have the appropriate receptors for them, known as target cells. Many hormones have target cells in multiple types of organs and tissues, or they regulate molecules, such as blood glucose, that affect many organ systems. These are some of the reasons why changes in the normal level of an endocrine hormone — either hypersecretion or hyposecretion — can result in a wide variety of symptoms, such as is seen in Cushing's syndrome, diabetes, and PCOS. By understanding what goes wrong in these disorders, you can better appreciate how important the endocrine system is for regulating the many diverse functions of the human body.

## CHAPTER SUMMARY

In this chapter, you learned about the glands and hormones of the endocrine system, their functions, how they are regulated, and some diseases and disorders of the endocrine system. Specifically, you learned that:

- The endocrine system is a system of glands that release chemical messenger molecules called hormones into the bloodstream. Other glands, called exocrine glands, release substances onto nearby body surfaces through ducts.
- Endocrine hormones travel more slowly than nerve impulses, which are the body's other way of sending messages. However, the effects of endocrine hormones may be much longer lasting.
- The pituitary gland is the master gland of the endocrine system. Most of the hormones it produces control other endocrine glands. These glands include the thyroid gland, parathyroid glands, pineal gland, pancreas, adrenal glands, gonads (testes and ovaries), and thymus gland.
- Diseases of the endocrine system are relatively common. An endocrine disease usually involves hypersecretion or hyposecretion of a hormone. Hypersecretion is frequently caused by a tumor. Hyposecretion is often caused by the destruction of hormone-secreting cells by the body's own immune system.
- Endocrine hormones travel throughout the body but affect only certain cells, called target cells, which have receptors specific to particular hormones.
- Steroid hormones such as estrogen are endocrine hormones made of lipids that cross plasma membranes and bind to receptors inside target cells. The hormone-receptor complexes then move into the nucleus where they influence gene expression.
- Non-steroid hormones such as insulin are endocrine hormones made of amino acids that bind to receptors on the surface of target cells. This activates an enzyme in the plasma membrane, and the enzyme controls a second messenger molecule, which influences cell processes.
- Most endocrine hormones are controlled by negative feedback loops in which rising levels of hormone feedback to stop its own production — and vice-versa. For example, a negative feedback loop controls the production of thyroid hormones. The loop includes the hypothalamus, pituitary gland, and thyroid gland.
- Only a few endocrine hormones are controlled by positive feedback loops in which rising levels of hormone feedback to stimulate continued production of the hormone. Prolactin, the pituitary hormone that stimulates milk production by mammary glands, is controlled by a positive feedback loop. The loop includes the nipples, hypothalamus, pituitary gland, and mammary glands.
- The pituitary gland is at the base of the brain, where it is connected to the hypothalamus by nerves and capillaries. It has an anterior (front) lobe that synthesizes and secretes pituitary hormones and a posterior (back) lobe that stores and secretes hormones from the hypothalamus.
    - Hormones synthesized and secreted by the anterior pituitary include growth hormone, which stimulates cell growth throughout the body, and thyroid stimulating hormone (TSH), which stimulates the thyroid gland to secrete its hormones.
    - Hypothalamic hormones stored and secreted by the posterior pituitary include vasopressin, which helps maintain homeostasis in body water; and oxytocin, which stimulates uterine contractions during birth and the letdown of milk during lactation.
- The thyroid gland is a large endocrine gland in the front of the neck. It is composed mainly of clusters of cells called follicles, which are specialized to absorb iodine and use it to make thyroid hormones. Parafollicular cells among the follicles synthesize the hormone calcitonin.
    - The thyroid hormones thyroxine (T4) and triiodothyronine (T3) cross cell membranes and regulate gene expression to control the rate of metabolism in cells body-wide, among other functions. The production of T4 and T3 is regulated by thyroid stimulating hormone (TSH) from the pituitary, which is regulated, in turn, by thyrotropin-releasing hormone (TRH) from the hypothalamus.
    - Calcitonin helps regulate blood calcium levels by stimulating the movement of calcium into bone. It works in conjunction with parathyroid hormone to maintain calcium homeostasis.
    - Abnormal secretion of thyroid hormones may occur for a variety of reasons and may lead to the development of a goiter. The most common cause of hyperthyroidism is Graves' disease, an autoimmune disorder. Iodine deficiency is a common cause of hypothyroidism worldwide. In the United States, the most common cause of hypothyroidism is Hashimoto's thyroiditis, another autoimmune disorder. Hypothyroidism in pregnant women may cause permanent cognitive deficits in children.
- The adrenal glands are endocrine glands that produce a variety of hormones. The two adrenal glands are located on both sides of the body, just above the kidneys. Each gland has two layers: an outer layer called the adrenal cortex and an inner layer called the adrenal medulla.
    - The adrenal cortex produces steroid hormones called by the general term corticosteroids, of which there are three types: mineralocorticoids such as aldosterone, which helps control electrolyte balance; glucocorticoids such as cortisol, which helps control the rate of metabolism and suppresses the immune system; and androgens such as DHEA, which is converted to sex hormones in the gonads.
    - The adrenal medulla produces non-steroid catecholamine hormones including adrenaline and noradrenaline. These hormones stimulate the fight-or-flight response.
    - Disorders of the adrenal glands generally include either hypersecretion or hyposecretion of adrenal hormones. The cause may be a problem with the adrenal glands or with the pituitary gland, which controls adrenal cortex hormone production. Examples include Cushing's syndrome, in which there is hypersecretion of cortisol; and Addison's disease, in which there is hyposecretion of cortisol and mineralocorticoids.
- The pancreas is a gland located in the upper left abdomen behind the stomach that functions as both an endocrine gland and an exocrine gland. As an endocrine gland, the pancreas releases

hormones, such as insulin, directly into the bloodstream. As an exocrine gland, the pancreas releases digestive enzymes into ducts that carry them to the gastrointestinal tract.

- Tissues in the pancreas that have an endocrine role exist as clusters of cells called pancreatic islets. The islets consist of four main types of cells, each of which secretes a different endocrine hormone. Alpha (α) cells secrete glucagon, beta (β) cells secrete insulin, delta (δ) cells secrete somatostatin, and gamma (γ) cells secrete pancreatic polypeptide.
- The endocrine hormones secreted by the pancreatic islets all play a role, either directly or indirectly, in glucose metabolism and homeostasis of blood glucose levels. For example, insulin stimulates the uptake of glucose by cells and decreases the level of glucose in the blood, whereas glucagon stimulates the conversion of glycogen to glucose and increases the level of glucose in the blood.
- Disorders of the pancreas include pancreatitis, pancreatic cancer, and diabetes mellitus. Pancreatitis is a painful inflammation of the pancreas that has many possible causes. Pancreatic cancer of the endocrine tissues is rare but increasing in frequency. It is generally discovered too late to cure surgically. Smoking is a major risk factor for pancreatic cancer.
- Diabetes mellitus is the most common type of pancreatic disorder. In diabetes, the inadequate activity of insulin results in high blood levels of glucose. Type 1 diabetes is a chronic autoimmune disorder in which the immune system attacks the insulin-secreting beta cells of the pancreas. Type 2 diabetes is usually caused by a combination of insulin resistance and impaired insulin secretion due to a variety of environmental and genetic factors.

## CHAPTER SUMMARY REVIEW

1. The pituitary gland is considered the master gland of the endocrine system because its hormones control other endocrine glands. For each of the glands below, describe one way in which it is controlled by the pituitary gland.
   A. The thyroid gland
   B. The adrenal gland
   C. The gonads (ovaries and testes)
2. What is the name of the main brain structure that secretes hormones that control the pituitary gland?
3. Define hyposecretion and give an example of an endocrine disorder involving hyposecretion. Be sure to include the name of the hormone involved.
4. Define hypersecretion and give an example of an endocrine disorder involving hypersecretion. Be sure to include the name of the hormone involved.
5. Which hormone plays a role in regulating metabolism in some way?
   A. Cortisol
   B. Thyroid hormone
   C. Glucagon
   D. All of the above
6. Which endocrine gland plays an important role in the fight-or-flight response?
7. *True or False*. Sex hormones, such as androgens, are only produced by the gonads.
8. *True or False*. Estrogen can travel to the nucleus of a cell.
9. Explain why non-steroid hormones typically require the activation of second messenger molecules to have their effects, instead of directly affecting intracellular processes themselves.
10. Explain what it means that endocrine hormones are “chemical messengers.”
11. If you were a physician, and a patient came to you complaining of excessive thirst and urination, what endocrine disorder might you suspect the patient has?
    A. In order to diagnose this disorder, what would you want to check for in the patient’s blood? Explain your answer.
12. Pancreatic islet cells all produce:
    A. Insulin
    B. Glucagon
    C. Endocrine hormones
    D. Digestive enzymes
13. Give one example of negative feedback in the endocrine system.
14. Explain the circumstances in which organs and hormones in a negative feedback loop can actually increase the level of a hormone.
15. *True or False*. The hormone vasopressin is synthesized by the hypothalamus.
16. *True or False*. Like most other hormones, prolactin is regulated by a negative feedback loop.
17. Identify the gland that secretes each of the following hormones:
    A. Melatonin
    B. Growth hormone
    C. Thyroid stimulating hormone
    D. Aldosterone
18. A goiter is an enlargement of which structure?
19. Explain why giving iodine can treat some cases of hypothyroidism, but it is not usually helpful when someone has hypothyroidism due to Hashimoto’s thyroiditis.
20. For each disease below, identify the hormone involved and whether the problem involves hyposecretion or hypersecretion of this hormone.
    A. Addison’s disease
    B. Graves’ disease
    C. Cushing’s syndrome
    D. Type 1 diabetes
21. What is an example of a disease that is due to hormone resistance?
22. *True or False*. Adrenaline is an exocrine hormone.
23. Steroid hormones:
    A. always increase muscle mass

B. are fat soluble
C. bind to receptors on the plasma membrane
D. include insulin

24. Explain generally how autoimmune disorders can disrupt the endocrine system, and give one example.

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# CHAPTER OVERVIEW

## 9: BLOOD AND THE CARDIOVASCULAR SYSTEM

This chapter provides a detailed description of the heart, blood vessels, and blood. It explains how they function together to transport substances throughout the body and maintain homeostasis. The chapter also describes several diseases of the cardiovascular system and lifestyle choices that can help prevent most of them.


9.1: Case Study- Your Body's Transportation System

9.2: Introduction to the Cardiovascular System

9.3: Heart

9.4: Blood Vessels

9.5: Blood

9.6: Blood Types

9.7: Cardiovascular Disease

9.8: Case Study Conclusion- Flight and Chapter Summary


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# 9.1: CASE STUDY- YOUR BODY'S TRANSPORTATION SYSTEM

## CASE STUDY: FLIGHT RISK

Nineteen-year-old Antônio is about to take his first plane flight. Shortly after he boards the plane and sits down, a man in his late sixties sits next to him in the aisle seat. About half an hour after the plane takes off, the pilot announces that she is turning the seat belt light off and that "it is now safe to move about the cabin."



Figure **9.1.1**: Airplane aisle

The man in the aisle seat, who has introduced himself to Antônio as Ahaya, immediately unbuckles his seat belt and paces up and down the aisle a few times before returning to his seat. After about forty-five minutes, Ahaya gets up again, walks some more, then sits back down and does some foot and leg exercises. After the third time, Ahaya gets up and paces the aisles, Antônio asks him whether he is walking so much to accumulate steps on a pedometer or fitness tracking device. Ahaya laughs and says no, he is trying to do something even more important for his health—prevent a blood clot from forming in his legs.

Ahaya explains that he has a chronic condition called heart failure. Although it sounds scary, his condition is currently well-managed and he is able to lead a relatively normal lifestyle. However, it does put him at risk of developing other serious health conditions such as deep vein thrombosis (DVT), which is when a blood clot occurs in the deep veins, usually in the legs. Air travel, or other situations where a person has to sit for a long period of time, increases the risk of DVT. Ahaya's doctor said that he was healthy enough to fly, but that he should walk frequently and do leg exercises to help avoid a blood clot.

As you read this chapter, you will learn about the heart, blood vessels, and blood that make up the cardiovascular system, as well as disorders of the cardiovascular system such as heart failure. At the end of the chapter, you will learn more about why DVT occurs, why Ahaya has to take extra precautions when he flies, and what can be done to lower the risk of DVT and its potentially deadly consequences.

## CHAPTER OVERVIEW: CARDIOVASCULAR SYSTEM

In this chapter, you will learn about the cardiovascular system, which transports substances throughout the body. Specifically, you will learn about:

- The major components of the cardiovascular system: the heart, blood vessels, and blood.
- The functions of the cardiovascular system, including transporting needed substances such as oxygen and nutrients to the cells of the body and picking up waste products.
- How blood is oxygenated through the pulmonary circulation, which transports blood between the heart and lungs.
- How blood is circulated throughout the body through the systemic circulation.
- The components of blood, including plasma, red blood cells, white blood cells, and platelets, and their specific functions.
- Types of blood vessels, including arteries, veins, and capillaries, and their functions, similarities, and differences.
- The structure of the heart, how it pumps blood, and how contractions of the heart are controlled.
- What blood pressure is and how it is regulated.
- Blood types: A, B, AB, and O
- Blood disorders, including anemia, HIV, and leukemia.
- Cardiovascular diseases including heart attack, stroke, and angina, and the risk factors and precursors, such as high blood pressure and atherosclerosis, which contribute to them.

As you read the chapter, think about the following questions:

1. What is heart failure? How do you think it increases the risk of DVT?
2. What is a blood clot? What are the possible health consequences of blood clots?
3. Why do you think sitting for long periods of time increases the risk of DVT and why does walking and exercising the legs help reduce this risk?

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# 9.2: INTRODUCTION TO THE CARDIOVASCULAR SYSTEM

## ANT HILL OR PLUMBING SYSTEM?

What do you think Figure **9.2.1** shows? Does it show a maze of underground passageways in an anthill? A network of interconnected pipes in a complex plumbing system? The picture actually shows something that, like ant tunnels and plumbing pipes, functions as a transportation system. It shows a network of blood vessels. Blood vessels are part of the cardiovascular system.

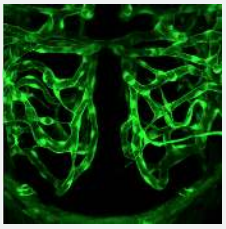


Figure **9.2.1**: Blood Vessels

## WHAT IS THE CARDIOVASCULAR SYSTEM?

The **cardiovascular system**, also called the circulatory system, is the organ system that transports materials to and from all the cells of the body. The materials carried by the cardiovascular system include oxygen from the lungs, nutrients from the digestive system, hormones from glands of the endocrine system, and waste materials from cells throughout the body. Transport of these and many other materials is necessary to maintain homeostasis of the body. The main components of the cardiovascular system are the heart, blood vessels, and blood. Each of these components is shown in Figure **9.2.2** and introduced in the text.

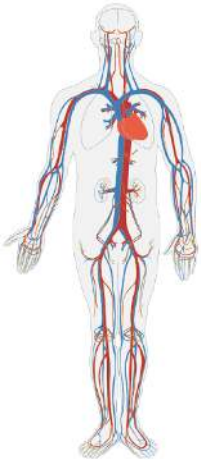


Figure **9.2.2**: This simplified drawing of the cardiovascular system shows its main structures. The heart is shown in the chest in red. Blood vessels called arteries are also shown in red, and blood vessels called veins are shown in blue.

## HEART

The heart is a muscular organ in the chest. It consists mainly of cardiac muscle tissue and pumps blood through blood vessels by repeated, rhythmic contractions. As shown in Figure **9.2.3**, the heart has four inner chambers: a right atrium and ventricle and a left atrium and ventricle. On each side of the heart, blood is pumped from the atrium to the ventricle below it and from the ventricle out of the heart. The heart also contains several valves that allow blood to flow only in the proper direction through the heart.

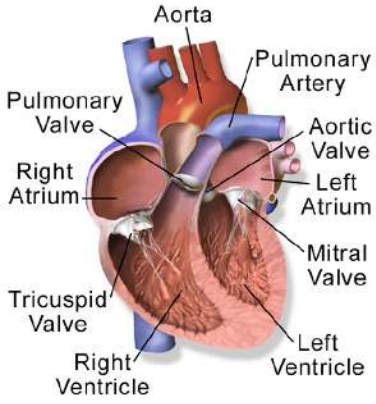



Figure **9.2.3**: The right side of the heart includes the right atrium and right ventricle. The left side includes the left atrium and left ventricle. The valves between the chambers and the major vessels are also visible

Unlike skeletal muscle, cardiac muscle routinely contracts without stimulation by the nervous system. Specialized cardiac muscle cells send out electrical impulses that stimulate the contractions. As a result, the atria and ventricles normally contract with just the right timing to keep blood pumping efficiently through the heart.

## BLOOD VESSELS

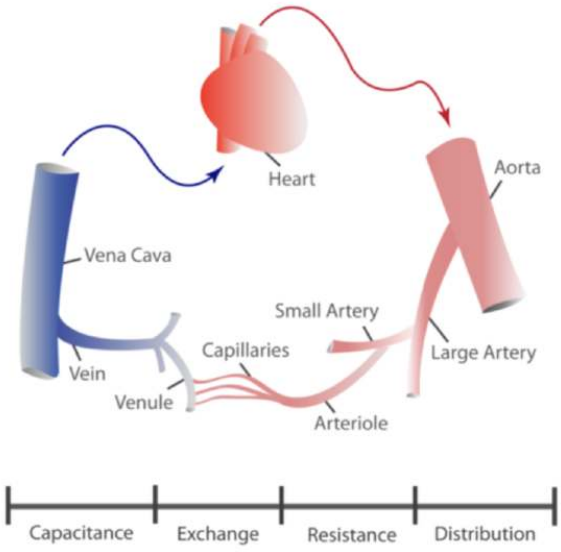



Figure **9.2.4**: This diagram represents the structure and functions of the different types of blood vessels in the cardiovascular system. Arteries carry blood from the heart and to capillaries. Veins carry blood from the capillaries back to the heart.

The blood vessels of the cardiovascular system are like a network of interconnected, one-way roads that range from superhighways to back alleys. Like a network of roads, the blood vessels have the job of allowing the transport of materials from one place to another. There are three major types of blood vessels: arteries, veins, and capillaries. They are illustrated in Figure 9.2.4.

- Arteries are blood vessels that carry blood away from the heart (except for the arteries that actually supply blood to the heart muscle). Most arteries carry oxygen-rich blood, and one of their main functions is distributing oxygen to tissues throughout the body. The smallest arteries are called arterioles.
- Veins are blood vessels that carry blood toward the heart. Most veins carry deoxygenated blood. The smallest veins are called venules.
- Capillaries are the smallest blood vessels. They connect arterioles and venules. As they pass through tissues, they exchange substances including oxygen with cells.

## TWO CIRCULATIONS

Cells throughout the body need a constant supply of oxygen. They get oxygen from capillaries in the systemic circulation. The systemic circulation is just one of two interconnected circulations that make up the human cardiovascular system. The other circulation is the pulmonary system. This is where the blood picks up oxygen to carry to cells. It takes blood about 20 seconds to make one complete transit through both circulations.

### PULMONARY CIRCULATION

The **pulmonary circulation** involves only the heart and lungs and the major blood vessels that connect them. It is illustrated in Figure 9.2.5. Blood moves through the pulmonary circulation from the heart to the lungs, and back to the heart again, becoming oxygenated in the process. Specifically, the right ventricle of the heart pumps deoxygenated blood into the right and left pulmonary arteries. These arteries carry the blood to the right and left lungs, respectively. Oxygenated blood then returns from the right and left lungs through the two right and two left pulmonary veins. All four pulmonary veins enter the left atrium of the heart.

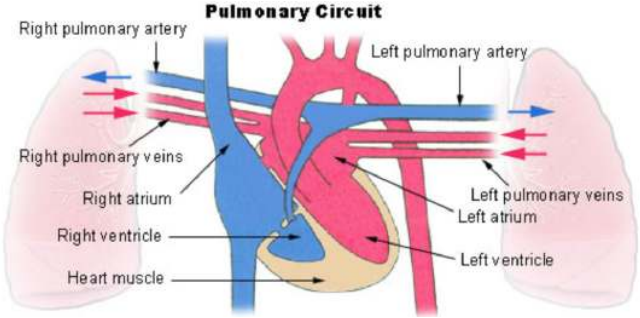



Figure 9.2.5: This diagram shows the heart, lungs, and major vessels that make up the pulmonary circulation. The colored arrows indicate the direction of blood flow. Oxygenated blood (in red) flows from the lungs to the left side of the heart. Deoxygenated blood (in blue) flows from the right side of the heart to the lungs.

What happens to the blood while it is in the lungs? It passes through increasingly smaller arteries and finally through capillary networks surrounding the alveoli (Figure 9.2.6). This is where gas exchange takes place. The deoxygenated blood in the capillaries picks up oxygen from the alveoli and gives up carbon dioxide to the alveoli. As a result, the blood returning to the heart in the pulmonary veins is almost completely saturated with oxygen.

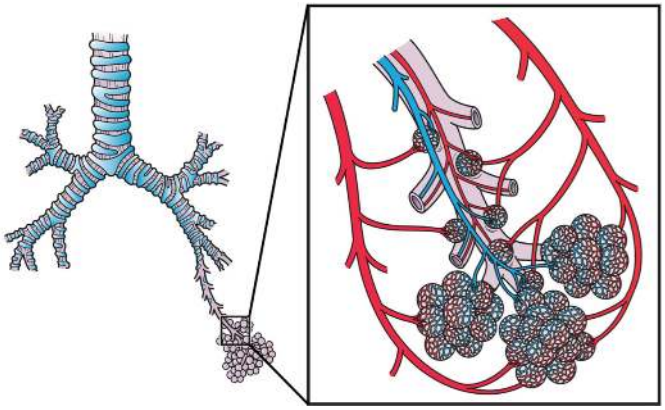


Figure 9.2.6: This diagram illustrates clusters of alveoli in the lungs where gas exchange takes place with blood in capillaries as it passes through the pulmonary circulation.

### SYSTEMIC CIRCULATION

The oxygenated blood that enters the left atrium of the heart in the pulmonary circulation then passes into the **systemic circulation.** This is the part of the cardiovascular system that transports blood to and from all of the tissues of the body to provide oxygen and nutrients and pick up wastes. It consists of the heart and blood vessels that supply the metabolic needs of all the cells in the body, including those of the heart and lungs.

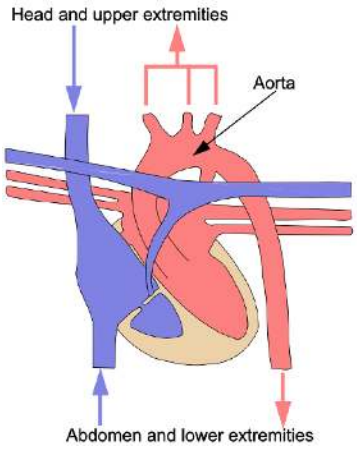



Figure 9.2.7: The systemic circulation includes the aorta (red), which carries oxygenated blood away from the heart to the rest of the body; and the inferior and superior venae cavae (blue), which return deoxygenated blood to the heart from the body. The colored arrows in the diagram indicate the direction of blood flow, red for oxygenated and blue for deoxygenated.

As shown in Figure 9.2.7, in the systemic circulation, the left atrium pumps oxygenated blood to the left ventricle, which pumps the blood directly into the aorta, the body's largest artery. Major arteries branching off the aorta carry the blood to the head and upper

extremities. The aorta continues down through the abdomen and carries blood to the abdomen and lower extremities. The blood then returns to the heart through the network of increasingly larger veins of the systemic circulation. All of the returning blood eventually collects in the superior vena cava (upper body) and inferior vena cava (lower body), which empty directly into the right atrium of the heart.

## BLOOD

Blood is a fluid connective tissue that circulates throughout the body in blood vessels by the pumping action of the heart. Blood carries oxygen and nutrients to all the body's cells, and it carries carbon dioxide and other wastes away from the cells to be excreted. Blood also transports many other substances, defends the body against infection, repairs body tissues, and controls the body's pH, among other functions.

The fluid part of blood is called plasma. It is a yellowish, watery liquid that contains many dissolved substances and blood cells. Types of blood cells in plasma include red blood cells, white blood cells, and platelets, all of which are illustrated in Figure **9.2.8** and explained in the text.

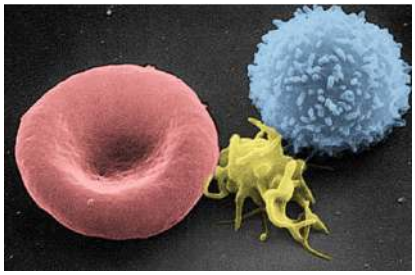


Figure **9.2.8**: The three types of cells in the blood are pictured here: red blood cell (left), platelet (center), and white blood cell (right).

- Red blood cells have the main function of carrying oxygen in the blood. Red blood cells consist mostly of hemoglobin, a protein containing iron that binds with oxygen.
- White blood cells are far fewer in number than red blood cells. They defend the body in various ways. For example, white blood cells called phagocytes swallow and destroy pathogens, dead cells, and other debris in the blood.
- Platelets are cell fragments involved in blood clotting. They stick to tears in blood vessels and to each other, forming a plug at the site of injury. They also release chemicals that are needed for clotting to occur.

## REVIEW

1. What is the cardiovascular system? What are its main components?
2. Describe the heart and how it functions.
3. List the three major types of blood vessels and their basic functions.
4. Compare and contrast the pulmonary and systemic circulations.
5. What is blood? What are its chief constituents?
6. *True or False.* The circulatory system brings blood to and from the body, while the cardiovascular system brings blood to and from the lungs only.
7. *True or False.* Arteries carry mainly oxygenated blood.
8. Name three different types of substances that are transported by the cardiovascular system.
9. Describe where and how the pulmonary and systemic circulation systems meet.
10. Which of the following carries blood to the lungs? Choose all that apply.

    A. Left pulmonary artery

    B. Left pulmonary vein

    C. Right pulmonary artery

    D. Right pulmonary vein

11. Put the following structures in order of how blood flows from the heart out to the body and back again.

    capillaries; venules; aorta; veins; arteries

12. Explain why the heart and lungs need blood from the systemic circulation.
13. *Choose one.* Blood vessels carrying deoxygenated blood from the body back to the heart get increasingly (larger/smaller).
14. Blood becomes oxygenated in the lungs through gas exchange into:

    A. Arterioles

    B. Capillaries

    C. Venules

    D. Bronchioles

15. Which type of blood cell carries oxygen?

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# 9.3: HEART

## LUB DUB

Lub dub, lub dub, lub dub... That's how the sound of a beating heart is typically described. In a normal, healthy heart, those are the only two sounds that should be audible when listening to the heart through a stethoscope. If a physician assistant hears something different from the normal lub dub sounds, it's a sign of a possible heart abnormality. What causes the heart to produce the characteristic lub dub sounds? Read on to find out.



Figure **9.3.1**: Listening to a heartbeat

The **heart** is a muscular organ behind the sternum (breastbone), slightly to the left of the center of the chest. A normal adult heart is about the size of a fist. The function of the heart is to pump blood through the blood vessels of the cardiovascular system. The continuous flow of blood through the system is necessary to provide all the cells of the body with oxygen and nutrients and to remove their metabolic wastes.

## STRUCTURE OF THE HEART

The heart has a thick muscular wall that consists of several layers of tissue. Internally, the heart is divided into four chambers through which blood flows. Blood flows in just one direction through the chambers due to heart valves.

### HEART WALL

As shown in Figure **9.3.2**, the wall of the heart is made up of three layers, called the endocardium, myocardium, and pericardium.

- The endocardium is the innermost layer of the heart wall. It is made up primarily of simple epithelial cells. It covers the heart chambers and valves. A thin layer of connective tissue joins the endocardium to the myocardium.
- The myocardium is the middle and thickest layer of the heart wall. It consists of cardiac muscle surrounded by a framework of collagen. There are two types of cardiac muscle cells in the myocardium: cardiomyocytes, which have the ability to contract easily; and pacemaker cells, which conduct electrical impulses that cause the cardiomyocytes to contract. About 99 percent of cardiac muscle cells are cardiomyocytes, and the remaining 1 percent are pacemaker cells. The myocardium is supplied with blood vessels and nerve fibers via the pericardium.
- The epicardium is the third layer which is a part of the pericardium, a protective sac that encloses and protects the heart. The pericardium consists of two membranes (visceral pericardium called epicardium and parietal pericardium), between which there is a fluid-filled cavity. The fluid helps to cushion the heart and also lubricates its outer surface.

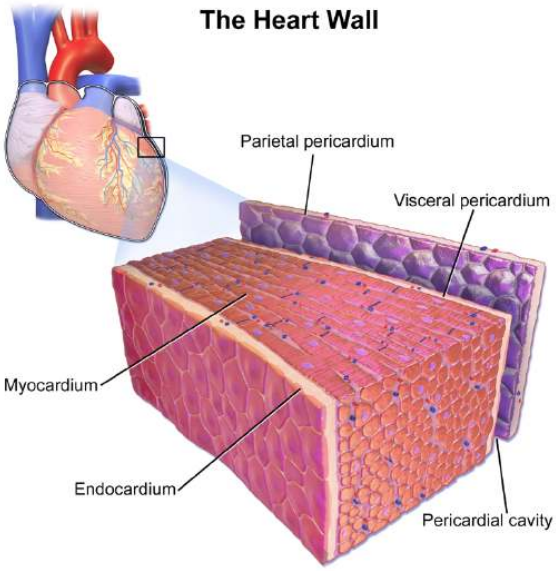



Figure **9.3.2**: The wall of the heart is made up mainly of the myocardium, which consists largely of cardiac muscle.

### HEART CHAMBERS

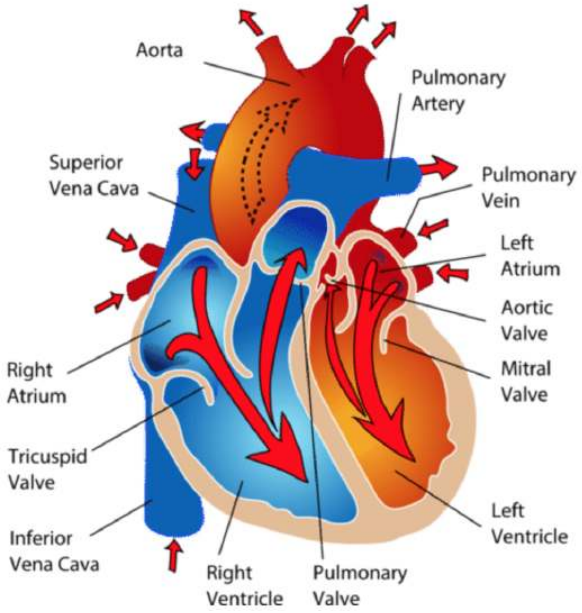



Figure **9.3.3**: This cross-sectional diagram of the heart shows its four chambers and four valves. The red arrows indicate the direction of blood flow through the heart chambers.

As shown in Figure **9.3.3**, the four chambers of the heart include two upper chambers called **atria (singular, atrium**) and two lower chambers called ventricles. The atria are also referred to as receiving chambers because blood coming into the heart first enters these two chambers. The right atrium receives blood from the upper and lower body through the superior vena cava and inferior vena cava, respectively; and the left atrium receives blood from the lungs through the pulmonary veins. The **ventricles** are also referred to as discharging chambers because the blood leaving the heart passes out through these two chambers. The right ventricle discharges blood to the lungs through the pulmonary artery, and the left ventricle discharges blood to the rest of the body through the aorta. The four chambers are separated from each other by dense connective tissue consisting mainly of collagen.

### HEART VALVES

Figure **9.3.3** also shows the location of the four valves of the heart. The heart valves allow blood to flow from the atria to the ventricles and from the ventricles to the pulmonary artery and aorta. The valves are constructed in such a way that blood can flow through them in only one direction, thus preventing the backflow of blood. The four valves are the:

1. tricuspid valve, which allows blood to flow from the right atrium to the right ventricle.
2. the mitral valve, which allows blood to flow from the left atrium to the left ventricle.
3. pulmonary valve, which allows blood to flow from the right ventricle to the pulmonary artery.
4. the aortic valve, which allows blood to flow from the left ventricle to the aorta.

The tricuspid and mitral valves are also called atrioventricular (or AV) valves because they are found between the atrium and the ventricle. The pulmonary and aortic valves are also called semilunar valves because they are shaped like half-moons.

## CORONARY CIRCULATION

The cardiomyocytes of the muscular walls of the heart are very active cells because they are responsible for the constant beating of the heart. These cells need a continuous supply of oxygen and nutrients. The carbon dioxide and waste products they produce also must be continuously removed. The blood vessels that carry blood to and from the heart muscle cells make up the coronary circulation. Note that the blood vessels of the coronary circulation supply heart tissues with blood and are different from the blood vessels that carry blood to and from the chambers of the heart as part of the general circulation. **Coronary arteries** supply oxygen-rich blood to the heart muscle cells. Coronary veins remove deoxygenated blood from the heart muscle cells.

- There are two coronary arteries: a right coronary artery that supplies the right side of the heart and a left coronary artery that supplies the left side of the heart. These arteries branch repeatedly into smaller and smaller arteries and finally into capillaries, which exchange gases, nutrients, and waste products with cardiomyocytes.
- At the back of the heart, small cardiac veins drain into larger veins and finally into the great cardiac vein, which empties into the right atrium. At the front of the heart, small cardiac veins drain directly into the right atrium.

## BLOOD CIRCULATION THROUGH THE HEART

Figure **9.3.4** shows how blood circulates through the chambers of the heart. The right atrium collects blood from two large veins, the superior vena cava (from the upper body) and the inferior vena cava (from the lower body). The blood that collects in the right atrium is pumped through the tricuspid valve into the right ventricle. From the right ventricle, the blood is pumped through the pulmonary valve into the pulmonary artery. The pulmonary artery carries the blood to the lungs, where it enters the pulmonary circulation, gives up carbon dioxide, and picks up oxygen. The oxygenated blood travels back from the lungs through the pulmonary veins (of which there are four) and enters the left atrium of the heart. From the left atrium, the blood is pumped through the mitral valve into the left ventricle. From the left ventricle, the blood is pumped through the aortic valve into the aorta, which subsequently branches into smaller arteries that carry the blood throughout the rest of the body. After passing through capillaries and exchanging substances with cells, the blood returns to the right atrium via the superior vena cava and inferior vena cava, and the process begins anew.

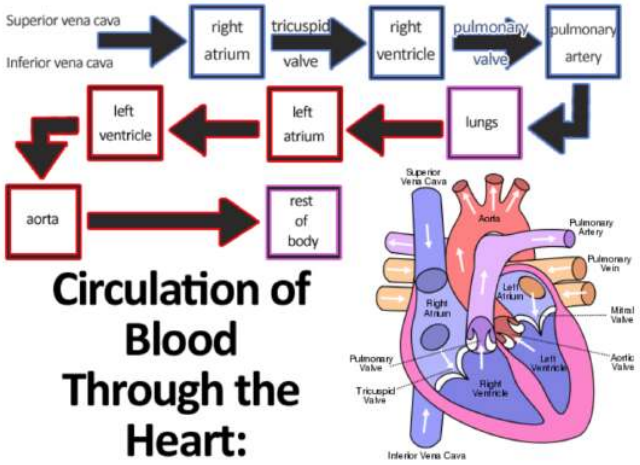



Figure **9.3.4**: The flow chart in this diagram summarizes the pathway blood takes as it flows into, through, and out of the heart. Trace the path of blood flow in the diagram of the heart as you follow it through the flow chart.

## CARDIAC CYCLE

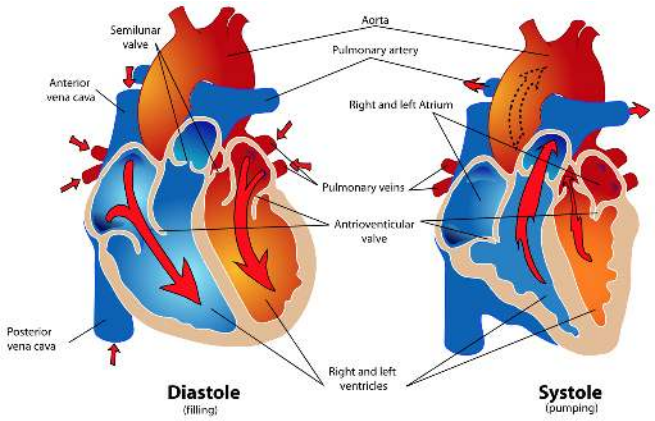



Figure **9.3.5**: Diastole is referred to as the filling stage because this is when the ventricles fill with blood. Systole is referred to as the pumping stage because this is when the ventricles pump blood out of the heart.

The cardiac cycle refers to a single complete heartbeat, which includes one iteration of the lub and dub sounds heard through a stethoscope. During the cardiac cycle, the atria and ventricles work in a coordinated fashion so that blood is pumped efficiently through and out of the heart. The cardiac cycle includes two parts, called diastole and systole, which are illustrated in Figure **9.3.5**.

- During **diastole,** the atria contract and pump blood into the ventricles, while the ventricles relax and fill with blood from the atria.
- During **systole,** the atria relax and collect blood from the lungs and body, while the ventricles contract and pump blood out of the heart.

## ELECTRICAL STIMULATION OF THE HEART

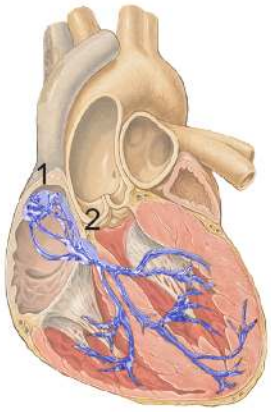



Figure **9.3.6**: In this drawing of the heart, the numbers refer to (1) the sinoatrial node and (2) the atrioventricular node. The blue lines in the drawing indicate the path of transmission of electrical signals through the heart.

The normal, rhythmical beating of the heart is called **sinus rhythm.** It is established by the heart's **pacemaker** cells, which are located in an area of the heart called the sinoatrial node (Figure **9.3.6**). The pacemaker cells create electrical signals by the movement of electrolytes (sodium, potassium, and calcium ions) into and out of the cells. For each cardiac cycle, an electrical signal rapidly travels first from the sinoatrial node to the right and left atria so they contract together. Then the signal travels to another node, called the atrioventricular node (also shown in Figure **9.3.6**), and from there to the right and left ventricles, which also contract together, just a split second after the atria contract.

The normal sinus rhythm of the heart is influenced by the autonomic nervous system through sympathetic and parasympathetic nerves. These nerves arise from two paired cardiovascular centers in the medulla of the brainstem. The parasympathetic nerves act to decrease the heart rate, and the sympathetic nerves act to increase the heart rate. Parasympathetic input normally predominates. Without it, the pacemaker cells of the heart would generate a resting heart rate of about 100 beats per minute, instead of a normal resting heart rate of about 72 beats per minute. The cardiovascular centers receive input from receptors throughout the body and act through the sympathetic nerves to increase the heart rate as needed. For example, increased physical activity is detected by receptors in muscles, joints, and tendons. These receptors send nerve impulses to the cardiovascular centers, causing sympathetic nerves to increase the heart rate. This allows more blood to flow to the muscles.

Besides the autonomic nervous system, other factors can also affect the heart rate. For example, thyroid hormones and adrenal hormones such as epinephrine can stimulate the heart to beat faster. The heart rate also increases when blood pressure drops or the body is dehydrated or overheated. On the other hand, cooling of the body and relaxation, among other factors, can contribute to a decrease in the heart rate.

### FEATURE: HUMAN BIOLOGY IN THE NEWS

When a patient's heart is too diseased or damaged to sustain life, a heart transplant is likely to be the only long-term solution. The first successful heart transplant was undertaken in South Africa in 1967. For the past two decades in the United States, about 2,400 hearts were transplanted each year. The problem is that far too few hearts are available for transplant, and many patients die each year waiting for a life-saving heart to become available.

Hearts for transplant have to be used within four hours of the death of the donor. In addition, hearts can only come from brain-dead individuals whose hearts are removed while they are still healthy. Then the hearts are placed on ice inside picnic coolers to be transported to a waiting recipient. The four-hour window means that traffic jams, bad weather, or other unforeseen delays often result in a heart being in less than optimal condition by the time it arrives at its destination. Unfortunately, there is no way to know if the heart will start up again after it is transplanted until it is actually placed in the recipient's body. In up to seven percent of cases, a transplanted heart does not work and has to be removed.

A medical device company in Massachusetts named TransMedic was featured in many news stories when it developed the Organ Care System, commonly referred to as "heart in a box." The system takes a new approach to maintain

donated hearts until they are transplanted. The box is heated and contains a device that pumps oxygenated blood through the heart while it is being transported to the recipient. This extends the time up to 12 hours that the heart can remain healthy and usable. It also allows the heart to be monitored so it is kept in optimal condition while it is on the route. The end result, ideally, is that the recipient gets a healthier heart with less chance of failure of the new organ and a lower risk of death.

As of mid-2016, the heart-in-a-box system had already been used for several successful heart transplants in other countries. At that time, the system was also undergoing clinical trials in the United States to assess its effectiveness in promoting positive recipient outcomes. Developers of the heart-in-a-box predict that the system could increase the number of usable donor hearts by as much as 30 percent, thus greatly increasing the number of patients who are saved from death due to heart failure.

## REVIEW

1. What is the heart, where is located, and what is its function?
2. Outline the structure of the heart.
3. Describe the coronary circulation.
4. Summarize how blood flows into, through, and out of the heart.
5. Define the cardiac cycle, and identify its two parts.
6. Explain what controls the beating of the heart.
7. a. What are the two types of cardiac muscle cells in the myocardium?

   b. What are the differences between these two types of cells?
8. Match each of the three layers of the walls of the heart (endocardium, myocardium, and pericardium) with the description that best matches it below.

   a. Protects the heart

   b. Covers the heart valves

   c. Responsible for the beating of the heart
9. Is the blood flowing through the mitral valve oxygenated or deoxygenated? Explain your reasoning.
10. *True or False.* The coronary arteries carry blood to the heart.
11. *True or False.* Systole is when the heart is contracting, diastole is when the heart is fully relaxed.
12. Explain why the blood from the cardiac veins empties into the right atrium of the heart. Focus on function rather than anatomy in your answer.

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# 9.4: BLOOD VESSELS

## BULGING VEINS

Why do bodybuilders have such prominent veins? Bulging muscles push surface veins closer to the skin. Couple that with a virtual lack of subcutaneous fat, and you have bulging veins as well as bulging muscles. Veins are one of three major types of blood vessels in the cardiovascular system.



Figure **9.4.1**: 2012 Hong Kong Bodybuilding Championship participant

## TYPES OF BLOOD VESSELS

**Blood vessels** are part of the cardiovascular system that transports blood throughout the human body. There are three major types of blood vessels: veins, arteries, and capillaries.

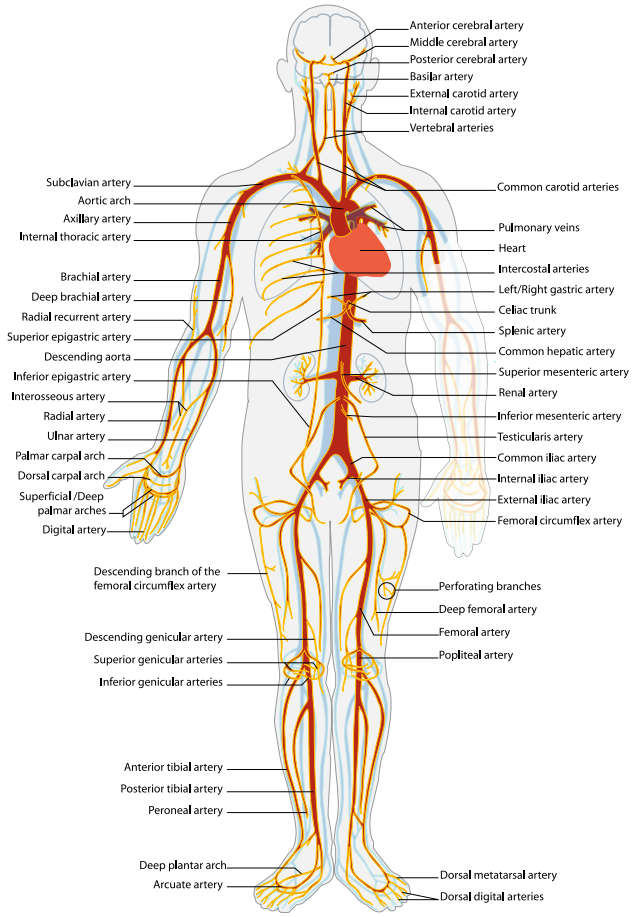



Figure **9.4.2**: This figure shows the heart and the major arteries of the cardiovascular system. The pulmonary veins are included in the diagram because, like arteries, they carry oxygenated blood.

**Arteries** are defined as blood vessels that carry blood away from the heart. Blood flows through arteries largely because it is under pressure from the pumping action of the heart. It should be noted that coronary arteries, which supply heart muscle cells with blood, travel toward the heart but not as part of the blood flow that travels through the chambers of the heart. Most arteries, including coronary arteries, carry oxygenated blood, but there are a few exceptions, most notably the pulmonary artery. This artery carries deoxygenated blood from the heart to the lungs, where it picks up oxygen and releases carbon dioxide. In virtually all other arteries, the hemoglobin in red blood cells is highly saturated with oxygen (95-100 percent). These arteries distribute oxygenated blood to tissues throughout the body.

The largest artery in the body is the aorta, which is connected to the heart and extends down into the abdomen (Figure **9.4.2**). The aorta has high-pressure, oxygenated blood pumped directly into it from the left ventricle of the heart. The aorta has many branches, and the branches subdivide repeatedly, with the subdivisions growing smaller and smaller in diameter. The smallest arteries are called arterioles.

## VEINS

**Veins** are defined as blood vessels that carry blood toward the heart. Blood traveling through veins is not under pressure from the beating heart. It gets help moving along by the squeezing action of skeletal muscles, for example, when you walk or breathe. It is also prevented from flowing backward by valves in the larger veins, as illustrated in Figure **9.4.3**. Veins are called capacitance blood vessels because the majority (about 60 percent) of the body's total volume of blood is contained within veins.

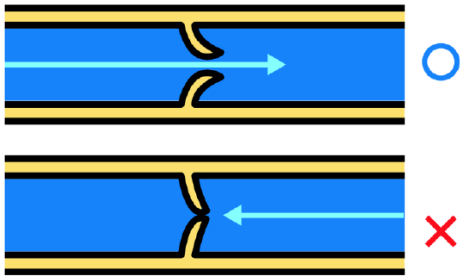


Figure **9.4.3**: The two flaps that make up a venous valve can open in just one direction, so blood can flow in only one direction through the vein.

Most veins carry deoxygenated blood, but there are a few exceptions, including the four pulmonary veins. These veins carry oxygenated blood from the lungs to the heart, which then pumps the blood to the rest of the body. In virtually all other veins, hemoglobin is relatively unsaturated with oxygen (about 75 percent).

The two largest veins in the body are the **superior vena cava**, which carries blood from the upper body directly to the right atrium of the heart, and the **inferior vena cava**, which carries blood from the lower body directly to the right atrium. The inferior vena cava is labeled in the figure below. The superior vena cava is not labeled in Figure **9.4.4** but is clearly visible entering the right atrium of the heart. Like arteries, veins form a complex, branching system of larger and smaller vessels. The smallest veins are called venules. They receive blood from capillaries and transport it to larger veins. Each venule receives blood from multiple capillaries.

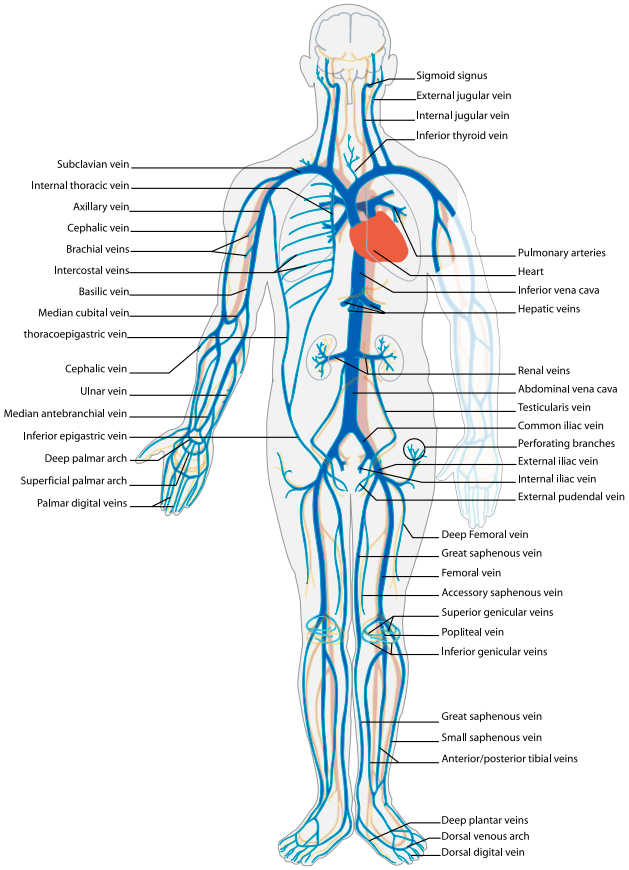



Figure **9.4.4**: This diagram shows the heart and major veins of the cardiovascular system. The pulmonary arteries are included in the diagram because, like veins, they carry deoxygenated blood.

## CAPILLARIES

**Capillaries** are the smallest blood vessels in the cardiovascular system. They are so small that only one red blood cell at a time can squeeze through a capillary, and then only if the red blood cell deforms. Capillaries connect arterioles and venules, as shown in Figure **9.4.5**. Capillaries generally form a branching network of vessels, called a capillary bed, that provides a large surface area for the exchange of substances between the blood and surrounding tissues.

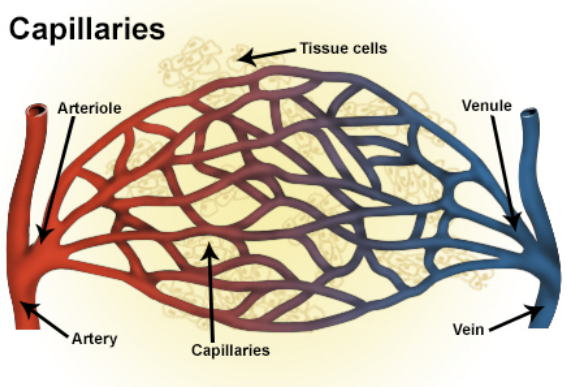



Figure **9.4.5**: Capillaries form beds of tiny blood vessels that exchange substances with the cells of tissues.

## STRUCTURE OF BLOOD VESSELS

All blood vessels are basically hollow tubes with an internal space, called a lumen, through which blood flows. The lumen of an artery is shown in cross-section in the photomicrograph below. The width of blood vessels varies, but they all have a lumen. The walls of blood vessels differ depending on the type of vessel. In general, arteries and veins are more similar to one another than capillaries in the structure of their walls.

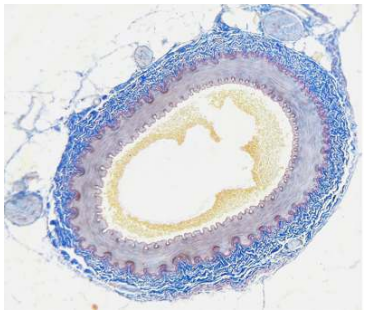


Figure **9.4.6**: The lumen is the white space in the center of this cross-sectional slice of an artery. You can see that the walls of the artery have multiple layers.

## WALLS OF ARTERIES AND VEINS

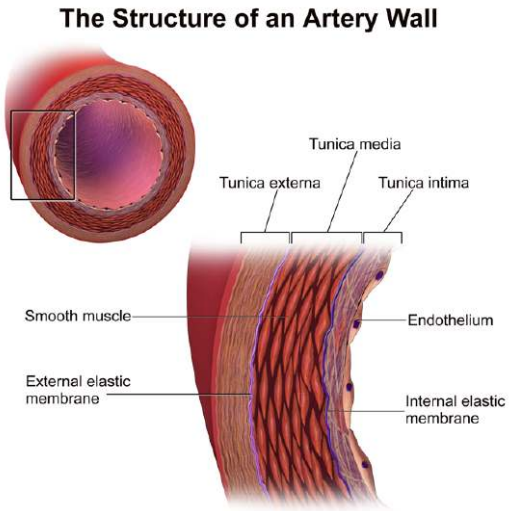



Figure **9.4.7**: The wall of an artery is made of three layers: tunica intima, tunica media, and tunica externa. A vein has the same three layers as the artery shown here, but the middle layer (tunica media) of a vein is thinner and lacks smooth muscle tissue.

The walls of both arteries and veins have three layers: the tunica intima, tunica media, and tunica adventitia. You can see the three layers for an artery in Figure **9.4.7**.

1. The tunica intima is the inner layer of arteries and veins. It is also the thinnest layer, consisting of a single layer of endothelial cells surrounded by a thin layer of connective tissues. It reduces friction between the blood and the inside of the blood vessel walls.
2. The tunica media is the middle layer of arteries and veins. In arteries, this is the thickest layer. It consists mainly of elastic fibers and connective tissues. In arteries, this is the thickest layer because it also contains smooth muscle tissues, which control the diameter of the vessels.
3. The tunica externa (also called tunica adventitia) is the outer layer of arteries and veins. It consists of connective tissue and also contains nerves. In veins, this is the thickest layer. In general, the tunica externa protects and strengthens vessels and attaches them to surrounding structures.

### CAPILLARY WALLS

The walls of capillaries consist of little more than a single layer of epithelial cells. Being just one cell thick, the walls are well suited for the exchange of substances between the blood inside them and the cells of surrounding tissues. Substances including water, oxygen, glucose, and other nutrients as well as waste products such as carbon dioxide can pass quickly and easily through the extremely thin walls of capillaries.

### BLOOD PRESSURE

The blood in arteries is normally under pressure because of the beating of the heart. The pressure is highest when the heart contracts and pumps out blood, and lowest when the heart relaxes and refills with blood. (You can feel this variation in pressure in your wrist or neck when you count your pulse.) **Blood pressure** is a measure of

the force that blood exerts on the walls of arteries. It is generally measured in millimeters of mercury (mm Hg) and expressed as a double number: a higher number for systolic pressure when the ventricles contract; and a lower number for diastolic pressure when the ventricles relax. Normal blood pressure is generally defined as less than 120 mm Hg (systolic)/80 mm Hg (diastolic) when measured in the arm at the level of the heart. It decreases as blood flows farther away from the heart and into smaller arteries.

As arteries grow smaller, there is increasing resistance to blood flow through them because of the friction of the blood against the arterial walls. This resistance restricts blood flow so less blood reaches smaller, downstream vessels, thus reducing blood pressure before the blood flows into the tiniest vessels, the capillaries. Without this reduction in blood pressure, capillaries would not be able to withstand the pressure of the blood without bursting. By the time blood flows through the veins, it is under very little pressure. The pressure of blood against the walls of veins is always about the same and normally no more than 10 mm Hg.

## VASOCONSTRICTION AND VASODILATION

Smooth muscles in the walls of arteries can contract or relax to cause vasoconstriction (narrowing of the lumen of blood vessels) or vasodilation (widening of the lumen of blood vessels). This allows the arteries — especially the arterioles — to contract or relax as needed to help regulate blood pressure. In this regard, the arterioles act like an adjustable nozzle on a garden hose. When they narrow, the increased friction with the arterial walls causes less blood to flow downstream from the narrowing, resulting in a drop in blood pressure. These actions are controlled by the autonomic nervous system in response to pressure-sensitive sensory receptors in the walls of larger arteries.

Arteries can also dilate or constrict to help regulate body temperature by allowing more or less blood to flow from the warm body core to the body's surface. In addition, vasoconstriction and vasodilation play roles in the fight-or-flight response, under the control of the sympathetic nervous system. For example, vasodilation allows more blood to flow to skeletal muscles and vasoconstriction reduces blood flow to digestive organs.

### FEATURE: MY HUMAN BODY

The lumpy appearance of this man's leg is caused by *varicose veins*. Do you have varicose veins? If you do, you may wonder whether they are a sign of a significant health problem. You may also wonder whether you should have them treated, and if so, what treatments are available. As is usually the case, when it comes to your health, "knowledge is power."



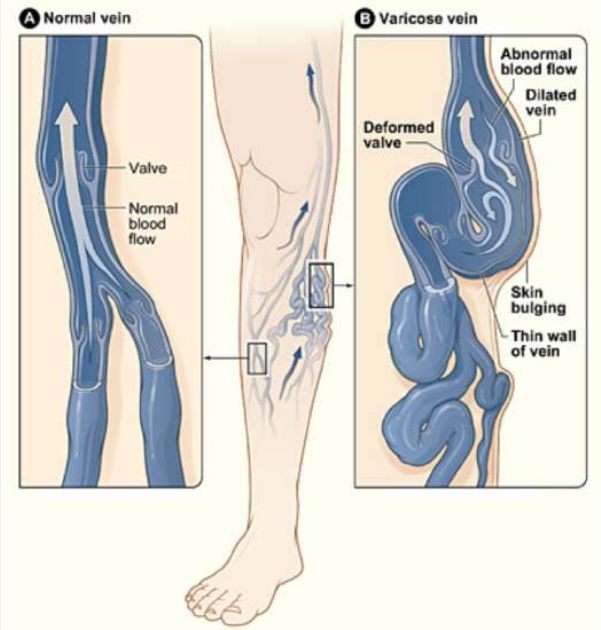



Figure **9.4.8**: Varicose veins form when a deformed valve allows blood to pool creating a bulge in the vein.

First, the "back story:" varicose veins are veins that have become enlarged and twisted because their valves have become ineffective (see Figure **9.4.8**). As a consequence, blood pools in the veins and stretches them out. Varicose veins occur most frequently in the superficial veins of the legs, but they may also occur in other parts of the body. They are most common in older adults, females, and people who have a family history of the condition. Obesity and pregnancy also increase the risk of developing varicose veins. A job that requires standing for long periods of time, chronic constipation, and long-term alcohol consumption are additional risk factors.

Varicose veins usually are not serious. In many people, they are only a cosmetic issue. However, in severe cases, varicose veins may cause pain and other problems. For example, the affected leg(s) may feel heavy and achy, especially after long periods of standing. Ankles may become swollen by the end of the day. Minor injuries may bleed more than normal. The skin over varicosity may become red, dry, and itchy. In very severe cases, skin ulcers may develop.

If you are concerned about varicose veins, call them to the attention of your doctor, who can determine the best course of action for your case. There are many potential treatments for varicose veins. Some of the treatments have potential adverse side effects; and with many of the treatments, varicose veins

may return. Which treatment is best for a given patient depends in part on the severity of the condition.

- If varicose veins are not serious, then conservative treatment options may be recommended. These include avoiding standing or sitting for long periods, frequently elevating the legs, and wearing graduated compression stockings.
- For more serious cases, less conservative but non-surgical options may be advised. These include sclerotherapy, in which medicine is injected into the veins to make them shrink. Another non-surgical approach is endovenous thermal ablation. In this type of treatment, laser light, radio-frequency energy, or steam is used to heat the walls of the veins, causing them to shrink and collapse.
- For the most serious cases, surgery may be the best option. The most invasive surgery is vein stripping, in which all or part of the main trunk of a vein is tied off and removed from the leg while the patient is under general anesthesia. In a less invasive surgery, called ambulatory phlebectomy, short segments of a vein are removed through tiny incisions under local anesthesia.

## REVIEW

1. What are the blood vessels? Name the three major types of blood vessels.
2. Describe arteries. Identify the largest artery in the body.
3. How are veins defined? What are the two largest veins in the body?
4. Compare and contrast how blood moves through arteries and veins.
5. What are capillaries, and what is their function?
6. Compare and contrast the structure of the walls of arteries, veins, and capillaries.
7. What is blood pressure, and how is it expressed? What blood pressure is considered normal?
8. Identify the functions of vasoconstriction and vasodilation of arteries.
9. Does the blood in most veins have any oxygen at all? Explain your answer.
10. *True or False.* Only one red blood cell can pass through the lumen of a capillary at a given time.
11. *True or False.* The pulmonary artery carries oxygenated blood.
12. Which tissue in blood vessels is responsible for vasodilation and vasoconstriction? Where is it located?
13. The blood pressure at the arterioles is generally _____ the blood pressure at the aorta.
    A. lower than
    B. higher than
    C. the same as
    D. not related to
14. Explain why it is important that the walls of capillaries are very thin.
15. Most of the blood in the body is in the:
    A. Capillaries
    B. Arteries
    C. Heart
    D. Veins

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# 9.5: BLOOD

## VAMPIRES

From Bram Stoker's famous novel about Count Dracula to the campy TV series *Buffy the Vampire Slayer*, fantasies featuring vampires, like the one in Figure **9.5.1**, have been popular for decades. In fact, vampires are found in centuries-old myths from many cultures. In such myths, vampires are generally described as creatures that drink blood, preferably of the human variety, for sustenance. Dracula, for example, is based on Eastern European folklore about a human who attains immortality (and eternal damnation) by drinking the blood of others.



Figure **9.5.1**: Dracula

## FUNCTIONS OF BLOOD

Blood performs many important functions in the body. Major functions of blood include:

- supplying tissues with oxygen, which is needed by all cells for aerobic cellular respiration.
- supplying cells with nutrients, including glucose, amino acids, and fatty acids.
- removing metabolic wastes from cells, including carbon dioxide, urea, and lactic acid.
- helping to defend the body from pathogens and other foreign substances.
- forming clots to seal broken blood vessels and stop bleeding.
- transporting hormones and other messenger molecules.
- regulating the pH of the body, which must be kept within a narrow range (7.35 to 7.45).
- helping to regulate body temperature (through vasoconstriction and vasodilation).

## WHAT IS BLOOD?

**Blood** is a fluid connective tissue that circulates throughout the body through blood vessels of the cardiovascular system. What makes blood so special that it features in widespread myths? Although blood accounts for less than 10 percent of human body weight, it is quite literally the elixir of life. As blood travels through the vessels of the cardiovascular system, it delivers vital substances such as nutrients and oxygen to all of the cells and carries away their metabolic wastes. It is no exaggeration to say that without blood, cells could not survive. Indeed, without the oxygen carried in the blood, cells of the brain start to die within just a matter of minutes.

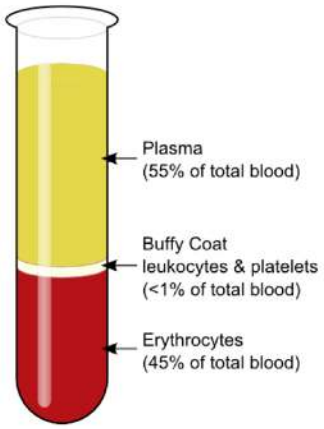



Figure **9.5.2**: If blood is centrifuged (spun at high speed), it separates into its major components based on density, as shown here: plasma, leukocytes (white blood cells) and platelets, and erythrocytes (red blood cells). Plasma makes up about 55% of the blood. Leukocytes and platelets make up less than 1%. Erythrocytes make up about 45%.

The average adult body contains between 4.7 and 5.7 liters (5-6 quarts) of blood. More than half of that amount is fluid. Most of the rest of that amount consists of cells. The relative amounts of the various components in the blood are illustrated in Figure **9.5.2**. The components are also described in the text.

## BLOOD PLASMA

**Plasma** is the liquid component of human blood and makes up about 55 percent of blood by volume. It is about 92 percent water and contains many dissolved substances. Most of these substances are proteins, but plasma also contains trace amounts of glucose, mineral ions, hormones, carbon dioxide, and other substances.

## FORMED ELEMENTS

The formed elements in the blood include red blood cells, white blood cells, and platelets. These different types of elements are pictured in Figure **9.5.3** and described in the sections that follow.

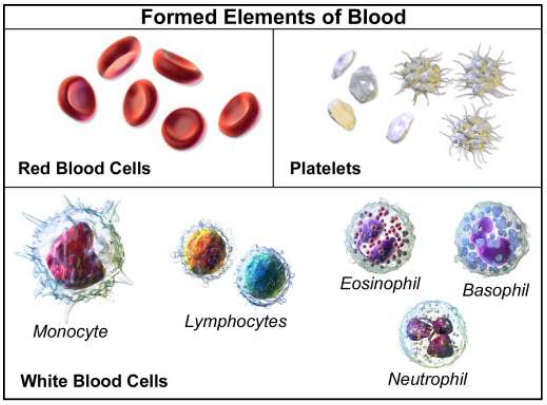



Figure **9.5.3**: Highly magnified blood cells in this image include donut-shaped red blood cells, rough-surfaced white blood cells, and small disc-shaped platelets.

# RED BLOOD CELLS

The most numerous cells in the blood are **red blood cells,** also called erythrocytes. One microliter of blood contains between 4.2 and 6.1 million red blood cells, and red blood cells make up about a quarter of all the cells in the human body. The cytoplasm of a mature red blood cell is almost completely filled with hemoglobin, the iron-containing protein that binds with oxygen and gives the cell its red color. Mature red blood cells lack a cell nucleus and most organelles in order to provide maximum space for hemoglobin. They are little more than sacks of hemoglobin.

Red blood cells also carry proteins called antigens that determine blood type. Blood type is a genetic characteristic. The best known human blood type systems are the ABO and Rhesus systems. These are described in the next section.

## WHITE BLOOD CELLS (WBC)

**White blood cells** are cells in the blood that defend the body against invading microorganisms and other threats. There are far fewer white blood cells (also called leukocytes) than red blood cells in the blood. There are normally only about 1,000 to 11,000 white blood cells per microliter of blood. Unlike red blood cells, white blood cells have a nucleus. White blood cells are part of the body's immune system. They destroy and remove old or abnormal cells and cellular debris, as well as attack pathogens and foreign substances. There are two categories of WBCs, granulocytes (contain visible granules in the cytoplasm) and agranulocytes (do not contain granules). The Granulocytes include neutrophils, eosinophils, and basophils. The agranulocytes include lymphocytes and monocytes. The five types differ in their specific immune functions. The relative percent and functions of WBCs are summarized in Table **9.5.1**:

Table **9.5.1**: Major Types of White Blood Cells

| Type of Leukocyte | Percent of All Leukocytes | Main Function(s) |
|---|---|---|
| Neutrophil | 62 | Phagocytize (engulf and destroy) bacteria and fungi in the blood |
| Eosinophil | 2 | Attack and kill large parasites; carry out allergic responses |
| Basophil | <1 | Release histamines in inflammatory responses |
| Lymphocyte | 30 | Attack and destroy virus-infected and tumor cells; create lasting immunity to specific pathogens |
| Monocyte | 5 | Phagocytize pathogens and debris in tissues |

## PLATELETS

**Platelets,** also called thrombocytes, are actually cell fragments. Like red blood cells, they lack a nucleus and are more numerous than white blood cells. There are about 150,000 to 400,000 platelets per microliter of blood.

The main function of platelets is blood clotting or **coagulation.** This is the process by which blood changes from a liquid to a gel, forming a plug in a damaged blood vessel. If blood clotting is successful, it results in hemostasis, which is the cessation of blood loss from the damaged vessel. A blood clot consists of both platelets and proteins, especially the protein fibrin. You can see a scanning electron microscope micrograph of a blood clot in Figure **9.5.4**.

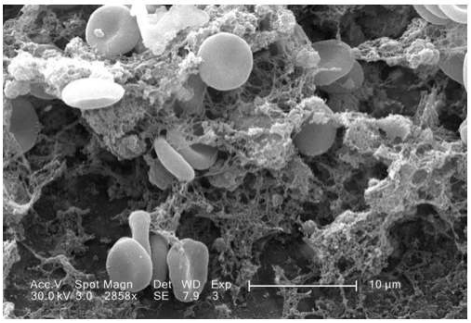



Figure **9.5.4**: Red blood cells become trapped in a coagulating clot so they cannot escape through a break in a blood vessel.

Coagulation begins almost instantly after an injury to the endothelium of a blood vessel occurs. Platelets become activated and change their shape from spherical to star-shaped, as shown in Figure **9.5.5**. This helps them aggregate with one another at the site of injury to start forming a plug in the vessel wall. Activated platelets also release substances into the blood that activate additional platelets and start a sequence of reactions leading to fibrin formation. Strands of fibrin crisscross the platelet plug and strengthen it, much as rebar strengthens concrete.

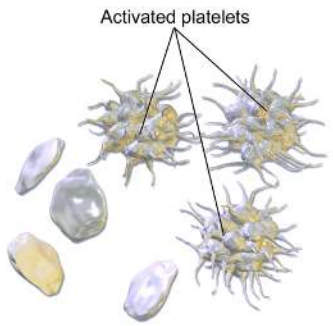



Figure 9.5.5: The shape of platelets after they are activated helps them to stick together and form a plug for a damaged blood vessel.

## FORMATION AND DEGRADATION OF BLOOD CELLS

Blood is considered to be a connective tissue because blood cells form inside bones. All three types of blood cells are made in the red marrow of bones in a process called hematopoiesis. The formation of blood cells occurs by the proliferation of stem cells in the marrow. These stem cells are self-renewing: when they divide, some of the daughter cells remain stem cells, so the pool of stem cells is not used up. Other daughter cells follow various pathways to differentiate into a variety of types of blood cells. Once the cells have differentiated, they cannot divide to form copies of themselves.

Eventually, blood cells die and must be replaced through the formation of new blood cells from proliferating stem cells. After blood cells die, the dead cells are phagocytized (engulfed and destroyed) by white blood cells and removed from the circulation. This most often takes place in the spleen and liver.

## BLOOD DISORDERS

Many human disorders primarily affect the blood. They include cancers, genetic disorders, poisoning by toxins, infections, and nutritional deficiencies.

- **Leukemia** is a group of cancers of the blood-forming tissues in the bone marrow. It is the most common type of cancer in children, although most cases occur in adults. Leukemia is generally characterized by large numbers of abnormal white blood cells. Symptoms may include excessive bleeding and bruising, fatigue, fever, and an increased risk of infections. Leukemia is thought to be caused by a combination of genetic and environmental factors.
- **Hemophilia** refers to any of several genetic disorders that cause dysfunction in the blood clotting process. People with hemophilia are prone to potentially uncontrollable bleeding even with otherwise inconsequential injuries. They also commonly suffer bleeding into the spaces between joints, which can cause crippling.
- Carbon monoxide poisoning occurs when inhaled carbon monoxide (for example, in fumes from a faulty home furnace) binds irreversibly to the hemoglobin in red blood cells. As a result, oxygen cannot bind to the red cells for transport throughout the body, and this can quickly lead to suffocation. Carbon monoxide is extremely dangerous because it is colorless and odorless so it cannot be detected in the air by human senses.
- HIV is a virus that infects certain types of white blood cells and interferes with the body's ability to defend itself from pathogens and other causes of illness. HIV infection may eventually lead to AIDS or acquired immunodeficiency syndrome. AIDS is characterized by rare infections and cancers that people with a healthy immune system almost never acquire.

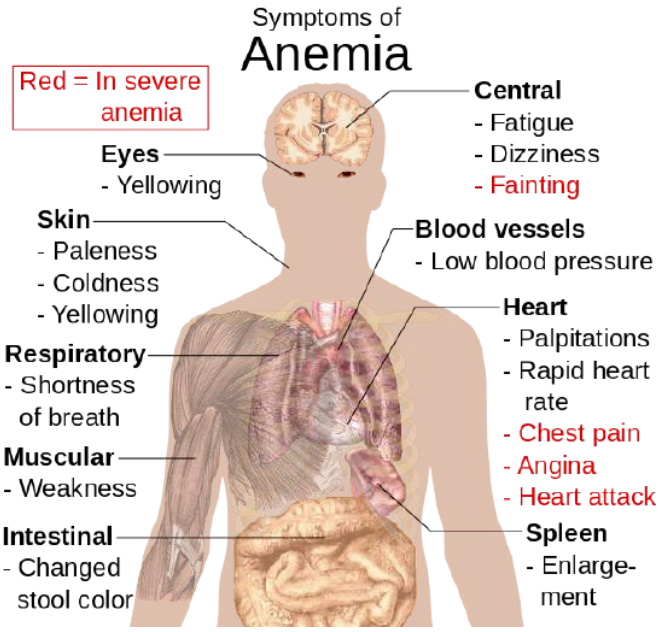



Figure **9.5.6**: Anemia has wide-ranging effects on the human body because oxygen is essential for the normal functioning of cells in every organ system. The most severe symptoms include fainting, chest pain, angina, and heart attack.

- **Anemia** is a disorder in which the blood has an inadequate volume of red blood cells. This reduces the amount of oxygen that the blood can carry and may cause weakness and fatigue. These and other signs and symptoms of anemia are shown in the figure below. Anemia has many possible causes, including excessive bleeding, inherited disorders such as sickle cell hemoglobin, or nutritional deficiencies (iron, folate, or B12). Severe anemia may require transfusions of donated blood.

## FEATURE: MYTH VS. REALITY

Donating blood saves lives. In fact, with each blood donation, as many as three lives may be saved. The feeling that comes from knowing you have saved lives is well worth the short amount of time it takes to make a blood donation. Nonetheless, only a minority of potential donors actually donate blood. There are many myths about blood donation that contribute to the small percentage of donors. Knowing the facts may reaffirm your decision to donate if you are already a donor. If you aren't a donor already, getting the facts may help you decide to become one.

**Myth:** Your blood might become contaminated with an infection during the donation.

**Reality:** There is no risk of contamination because only single-use, disposable catheters, tubing, and other equipment are used to collect blood for a donation.

**Myth:** You are too old (or too young) to donate blood.

**Reality**: There is no upper age limit on donating blood as long as you are healthy. The lower age limit is 16 years.

**Myth:** You can't donate blood if you have high blood pressure.

**Reality:** As long as your blood pressure is below 180/100 at the time of donation, you can give blood. Even if you take blood pressure medication to keep your blood pressure below this level, you can donate.

**Myth:** You can't give blood if you have high cholesterol.

**Reality:** Having high cholesterol does not affect your ability to donate blood. Taking cholesterol-lowering medication also does not disqualify you.

**Myth:** You can't donate blood if you have had a flu shot.

**Reality:** Having a flu shot has no effect on your ability to donate blood. You can even donate on the same day that you receive a flu shot.

**Myth:** You can't donate blood if you take medication.

**Reality:** As long as you are healthy, in most cases taking medication does not preclude you from donating blood.

**Myth:** Your blood isn't needed if it's a common blood type.

**Reality:** All types of blood are in constant demand.

## REVIEW

1. What is blood? Why is blood considered to be a connective tissue?
2. Identify four physiological roles of blood in the body.
3. Describe plasma and its components.
4. Identify red blood cells and their major function.
5. What are white blood cells? Which body system besides the cardiovascular system includes white blood cells?
6. Explain how platelets cause coagulation.
7. Summarize the formation and degradation of blood cells.
8. Identify three disorders of the blood.
9. For each of the descriptions below, choose the blood cell that best fits the description. Blood cells: red blood cells; white blood cells; platelets

    A. Has a nucleus
    B. Responsible for blood clotting
    C. Carbon monoxide binds to a protein in these cells

10. What is another name for erythrocytes? What is another name for leukocytes?
11. *True or False.* Plasma refers to the cytoplasm within blood cells.
12. *True or False.* Platelets are cell fragments.

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# 9.6: BLOOD TYPES

## GIVING THE GIFT OF LIFE

Did you ever donate blood as the individual in Figure **9.6.1** is doing? If you did, then you probably know that your blood type is an important factor in blood transfusions. People vary in the type of blood they inherit, and this determines which type(s) of blood they can safely receive in a transfusion. Do you know your blood type?



Figure **9.6.1**: Donating Blood

## WHAT ARE BLOOD TYPES?

**Blood type** (or blood group) is a genetic characteristic associated with the presence or absence of certain molecules, called antigens, on the surface of red blood cells. These molecules may help maintain the integrity of the cell membrane, act as receptors, or have other biological functions. A **blood group system** refers to all of the gene(s), alleles, and possible genotypes and phenotypes that exist for a particular set of blood type antigens. Human blood group systems include the well-known ABO and Rhesus (Rh) systems, as well as at least 33 others that are less well known.

### ANTIGENS AND ANTIBODIES

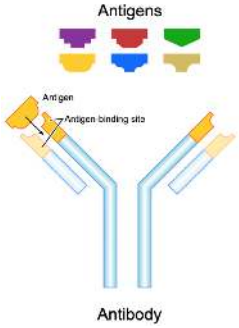



Figure **9.6.2**: Model of antigen and matching antibody

**Antigens** such as those on the red blood cells are molecules that the immune system identifies as either self (produced by your own body) or non-self (not produced by your own body). Blood group antigens may be proteins, carbohydrates, glycoproteins (proteins attached to chains of sugars), or glycolipids (lipids attached to chains of sugars), depending on the particular blood group system. If antigens are identified as nonself, the immune system responds by forming antibodies that are specific to the non-self antigens. **Antibodies** are large, Y-shaped proteins produced by the immune system that recognize and bind to non-self antigens. The analogy of a lock and key is often used to represent how an antibody and antigen fit together, as shown in Figure **9.6.2**. When antibodies bind to antigens, it marks them for destruction by other immune system cells. Nonself antigens may enter your body on pathogens such as bacteria or viruses, on foods, or on red blood cells in a blood transfusion from someone with a different blood type than your own. The last way is virtually impossible nowadays because of effective blood typing and screening protocols.

### GENETICS OF BLOOD TYPE

An individual's blood type depends on which alleles for a blood group system were inherited from their parents. Generally, blood type is controlled by alleles for a single gene or for two or more very closely linked genes. Closely linked genes are almost always inherited together because there is little or no recombination between them. Like other genetic traits, a person's blood type is generally fixed for life, but there are rare instances in which blood type can change. This could happen, for example, if an individual receives a bone marrow transplant to treat a disease such as leukemia. If the bone marrow comes from a donor who has a different blood type, the patient's blood type may eventually convert to the donor's blood type because red blood cells are produced in the bone marrow.

## ABO BLOOD GROUP SYSTEM

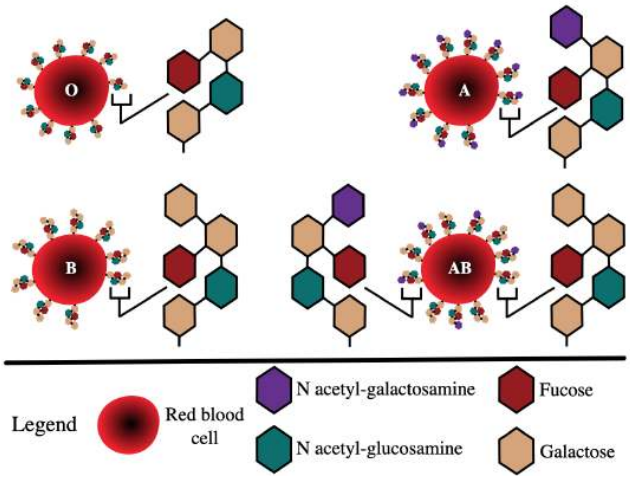



Figure **9.6.3**: ABO antigen molecules

The **ABO blood group system** is the best known human blood group system. Antigens in this system are glycoproteins. These antigen compounds are shown in Figure **9.6.3**. There are four common blood types for the ABO system:

1. Type A, in which only the A antigen is present
2. Type B, in which only the B antigen is present

3. Type AB, in which both the A and B antigens are present
4. Type O, in which neither the A nor the B antigen is present

## GENETICS OF THE ABO SYSTEM

The ABO blood group system is controlled by a single gene on chromosome 9. There are three common alleles for the gene, often represented by the letters $I^A$ (or A), $I^B$ (or B), and i (or O). With three alleles, there are six possible genotypes for the ABO blood group. However, alleles $I^A$ and $I^B$ are both dominant to allele i and codominant to each other. This results in just four possible phenotypes (blood types) for the ABO system. These genotypes and phenotypes are shown in Table **9.6.1**.

Table **9.6.1**: **ABO Blood Group System**

| Genotype | Phenotype (Blood Type, or Group) |
|---|---|
| $I^Ai$ | A |
| $I^AI^A$ | A |
| $I^AI^B$ | AB |
| $I^Bi$ | B |
| $I^BI^B$ | B |
| $ii$ | O |

The diagram in Figure **9.6.4** shows an example of how ABO blood type is inherited. In this particular example, the father has blood type A (genotype AO) and the mother has blood type B (genotype BO). This mating type can produce children with each of the four possible ABO phenotypes, although in any given family not all phenotypes may be present in the children.

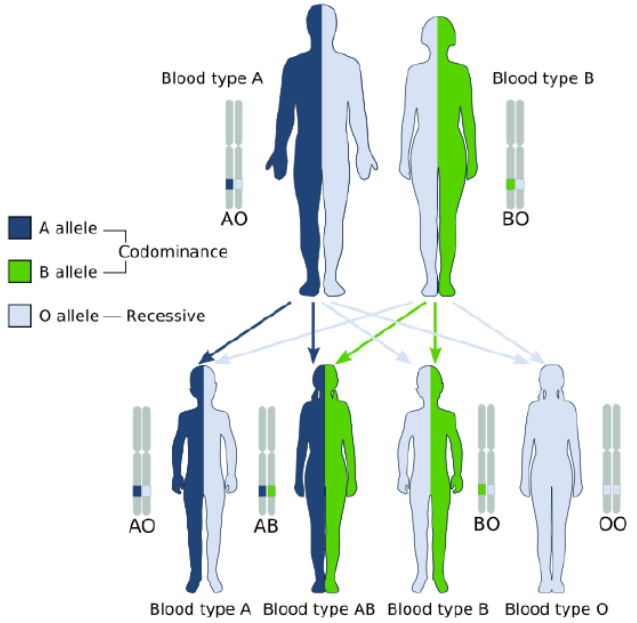



Figure **9.6.4**: Example of ABO blood group inheritance. A male who is type A (genotype of AO) and a female who is type B (genotype BO) can have children with blood types: A, AB, B, and O.

## MEDICAL SIGNIFICANCE OF ABO BLOOD TYPE

The ABO system is the most important blood group system in blood transfusions. If red blood cells containing a particular ABO antigen are transfused into a person who lacks that antigen, the person's immune system will recognize the antigen on the red blood cells as non-self. Antibodies specific to that antigen will attack the red blood cells, causing them to agglutinate, or clump and break apart. If a unit of incompatible blood were to be accidentally transfused into a patient, a severe reaction (called acute hemolytic transfusion reaction) is likely to occur in which many red blood cells are destroyed. This may result in kidney failure, shock, and even death. Fortunately, such medical accidents virtually never occur today.

ABO antibodies are likely to already be present in a recipient's blood for antigens that the person lacks. These antibodies are produced in the first years of life by sensitization to similar antigens commonly occurring in the environment. Anti-A antibodies are thought to originate from an immune response to an antigen on the influenza virus, and anti-B antibodies are thought to originate from an immune response to an antigen found on bacteria such as *E. coli*. Once the antibodies have been produced, they circulate in the plasma. The relationship between ABO red blood cell antigens and plasma antibodies is shown in Table **9.6.2**.

Table **9.6.2**: The antibodies that circulate in the plasma are for different antigens than those on red blood cells, which are recognized as self-antigens.

| Blood group | A | B | AB | O |
|---|---|---|---|---|
| Antibodies in plasma | Anti-B | Anti-A | None | Anti-A and Anti-B |
| Antigens on the red blood cell | A antigen | B antigen | A and B antigen | None |

Which blood types are compatible and which are not? Type O blood contains both anti-A and anti-B antibodies, so people with type O blood can only receive type O blood. However, they can donate blood to people of any ABO blood type. That's why individuals with type O blood are called **universal donors.** Type AB blood contains neither anti-A nor anti-B antibodies, so people with type AB blood can receive blood from people of any ABO blood type. That's why individuals with type AB blood are called **universal recipients.** However, they can donate blood only to people who also have type AB blood. These and other relationships between blood types of donors and recipients are summarized in Figure **9.6.5**.

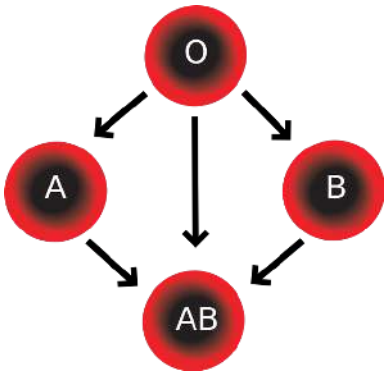



Figure **9.6.5**: You can always donate blood to someone who has the same blood type as yours, but you may or may not be able to donate to people who have other blood types, as indicated in this diagram.

ABO blood type antigens are found not only on red blood cells but also on platelets, in other body fluids such as tears and urine, and on cells of other types of tissues. Blood type compatibility is important to consider for successful organ transplantation. If a transplanted organ has nonself antigens for ABO, it may be attacked by antibodies and rejected by the body.

## RHESUS BLOOD GROUP SYSTEM

Another well-known blood group system is the **Rhesus (Rh) blood group system**. The Rhesus system has dozens of different antigens but only five main antigens (named D, C, c, E, and e). The major Rhesus antigen is the D antigen. People with the D antigen are called Rh-positive (Rh+), and people who lack the D antigen are called Rh-negative (Rh-). Rhesus antigens are thought to play a role in transporting ions across cell membranes by acting as channel proteins.

The Rhesus blood group system is controlled by two linked genes on chromosome 1. One gene, called RHD, produces a single antigen, antigen D. The other gene, called RHCE, produces the other four relatively common Rhesus antigens (C, c, E, and e), depending on which alleles for this gene are inherited.

### RHESUS BLOOD GROUP AND TRANSFUSIONS

After the ABO system, the Rhesus system is the second most important blood group system in blood transfusions. The D antigen is the one most likely to provoke an immune response in people who lack the antigen. People who have the D antigen (Rh+) can be safely transfused with either Rh+ or Rh- blood, whereas people who lack the D antigen (Rh-) can be safely transfused only with Rh- blood.

Unlike anti-A and anti-B antibodies to ABO antigens, anti-D antibodies for the Rhesus system are not usually produced by sensitization to environmental substances. However, people who lack the D antigen (Rh-) may produce anti-D antibodies if exposed to Rh+ blood. This may happen accidentally in a blood transfusion, although this is extremely unlikely today. It may also happen during pregnancy with an Rh+ fetus if some of the fetal blood cells pass into the mother's blood circulation.

### HEMOLYTIC DISEASE OF THE NEWBORN

If a woman who is Rh- is carrying an Rh+ fetus, the fetus may be at risk. This is especially likely if the mother has formed anti-D antibodies during a prior pregnancy because of a mixing of maternal and fetal blood during childbirth. Unlike antibodies against ABO antigens, antibodies against the Rhesus D antigen can cross the placenta and enter the blood of the fetus. This may cause **hemolytic disease of the newborn (HDN)**, also called erythroblastosis fetalis, an illness in which fetal red blood cells are destroyed by maternal antibodies, causing anemia. This illness may range from mild to severe. If it is severe, it may cause brain damage and is sometimes fatal for the fetus or newborn. Fortunately, HDN can be prevented by preventing the formation of anti-D antibodies in the Rh- mother. This is achieved through an injection into the mother of a medication called Rho(D) immune globulin.

## FEATURE: MYTH VS. REALITY

**Myth:** Your nutritional needs can be determined by your ABO blood type. Knowing your blood type allows you to choose the appropriate foods that will help you lose weight, increase your energy, and live a longer, healthier life.

**Reality:** This idea was proposed in 1996 in a *New York Times* bestseller *Eat Right for Your Type*, by Peter D'Adamo, a naturopath. Naturopathy is a method of treating disorders that involve the use of herbs, sunlight, fresh air, and other natural substances. Some medical doctors consider naturopathy a pseudoscience. A major scientific review of the blood type diet could find no evidence to support it. In one study, adults eating the diet designed for blood type A showed improved health, but this occurred in everyone regardless of their blood type. Because the blood type diet is based solely on blood type, it fails to account for other factors that might require dietary adjustments or restrictions. For example, people with diabetes but different blood types would follow different diets, and one or both of the diets might conflict with standard diabetes dietary recommendations and be dangerous.

**Myth:** ABO blood type is associated with certain personality traits. For example, people with blood type A are patient and responsible but may also be stubborn and tense, whereas people with blood type B are energetic and creative but may also be irresponsible and unforgiving. In selecting a spouse, both your own and your potential mate's blood type should be taken into account to ensure the compatibility of your personality.

**Reality:** The belief that blood type is correlated with personality is widely held in Japan and other East Asian countries (the Japanese booth pictured below offers fortunes based on blood type). The idea was originally introduced in the 1920s in a study commissioned by the Japanese government but later shown to have no scientific support. The idea was revived in the 1970s by a Japanese broadcaster who wrote popular books about it. There is no scientific basis for the idea, and it is generally dismissed as pseudoscience by the scientific community. Nonetheless, it remains popular in East Asian countries, like astrology in many other countries.

## REVIEW

1. Define blood type and blood group system.
2. Explain the relationship between antigens and antibodies.
3. Identify the alleles, genotypes, and phenotypes in the ABO blood group system.
4. Discuss the medical significance of the ABO blood group system.
5. Give examples of how different ABO blood types vary in their susceptibility to diseases.
6. Describe the Rhesus blood group system.
7. Relate Rhesus blood groups to blood transfusions.
8. What causes hemolytic disease of the newborn?

9. A woman is blood type O and Rh- and her husband is blood type AB and Rh+. Answer the following questions about this couple and their offspring.

   a. What are the possible genotypes of their offspring in terms of ABO blood group?

   b. What are the possible phenotypes of their offspring in terms of ABO blood group?

   c. Can the woman donate blood to her husband? Explain your answer.

   d. Can the man donate blood to his wife? Explain your answer.

10. *True or False.* The D antigen is part of the ABO blood group system.
11. Explain why hemolytic disease of the newborn may be more likely to occur in a second pregnancy than in a first.

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# 9.7: CARDIOVASCULAR DISEASE

## HEART ATTACK ON A PLATE

Eating this greasy cheeseburger smothered in bacon may not literally cause a heart attack. However, regularly eating high-fat, low-fiber foods such as this may increase the risk of a heart attack or other type of cardiovascular disease. In fact, unhealthy lifestyle choices such as this may account for as many as 90 percent of cases of cardiovascular disease.



Figure **9.7.1**: Bacon Cheeseburger

## WHAT IS CARDIOVASCULAR DISEASE?

**Cardiovascular disease** is a class of diseases that involve the cardiovascular system. They include diseases of the coronary arteries that supply the heart muscle with oxygen and nutrients; diseases of arteries such as the carotid artery that provide blood flow to the brain; and diseases of the peripheral arteries that carry blood throughout the body. Worldwide, cardiovascular disease is the leading cause of death, causing about a third of all deaths each year.

Most cases of the cardiovascular disease occur in people over the age of 60, with disease onset typically being about a decade earlier in males than females. The LGBT (lesbian, gay, bisexual, and transgender) community belongs to almost every race, ethnicity, religion, age, and socioeconomic group. The LGBT youth are at a higher risk for cardiovascular diseases, obesity, anxiety, and depression as compared to the general population. LGBT youth receive poor quality of care due to stigma, lack of healthcare providers' awareness, and insensitivity to the unique needs of this community. Young LGBT individuals find it difficult to report their sexual identity to their clinicians. Some clinicians are not well trained in addressing the concerns of members of this community.

You can't control your age or sex, but you can control other factors that increase the risk of cardiovascular disease. Not smoking, maintaining a healthy weight, eating a healthy diet, taking medications as needed to control diabetes and cholesterol, and getting regular exercise are all ways to prevent cardiovascular disease or keep it from progressing. It should be noted that high blood lipid levels are definitely risk factors for cardiovascular disease. High levels of cholesterol in the diet do not appear to lead directly to high levels of cholesterol in the blood. Clearly, cardiovascular disease is multifactorial in terms of its causes.

## PRECURSORS OF CARDIOVASCULAR DISEASE

There are two very common conditions that are precursors to virtually all cases of cardiovascular disease: hypertension (hypertension) and atherosclerosis (hardening of blood wall). Both conditions affect the arteries and their ability to maintain normal blood flow.

### HYPERTENSION

**Hypertension** is a chronic medical condition in which the blood pressure in the arteries is persistently elevated, as defined in Table **9.7.1**. Hypertension usually does not cause symptoms, so more than half of the people with high blood pressure are unaware of their condition. Hypertension is typically diagnosed when blood pressure is routinely measured during a medical visit for some other health problem.

Table **9.7.1**: Classification of Blood Pressure (in Adults)

| Category | Systolic (mm Hg) | Diastolic (mm Hg) |
|---|---|---|
| Normal blood pressure | 90-119 | 60-79 |
| Prehypertension | 120-139 | 80-89 |
| Hypertension | 140 or higher | 90 or higher |

High blood pressure is classified as either primary or secondary high blood pressure. At least 90% of cases are primary high blood pressure, which is caused by some combination of genetic and lifestyle factors. Numerous genes have been identified as having small effects on blood pressure. Lifestyle factors that increase the risk of high blood pressure include excess dietary salt and alcohol consumption in addition to the risk factors for cardiovascular disease stated above. Secondary high blood pressure, which makes up the remaining 10% of cases of hypertension, is attributable to chronic kidney disease or an endocrine disorder such as Cushing's disease.

Treating hypertension is important for reducing the risk of all types of cardiovascular disease, especially stroke. These and other complications of persistent high blood pressure are shown in Figure **9.7.2**. Lifestyle changes, such as reducing salt intake and adopting a healthier diet may be all that is needed to lower blood pressure to the normal range. In many cases, however, medications are also required.

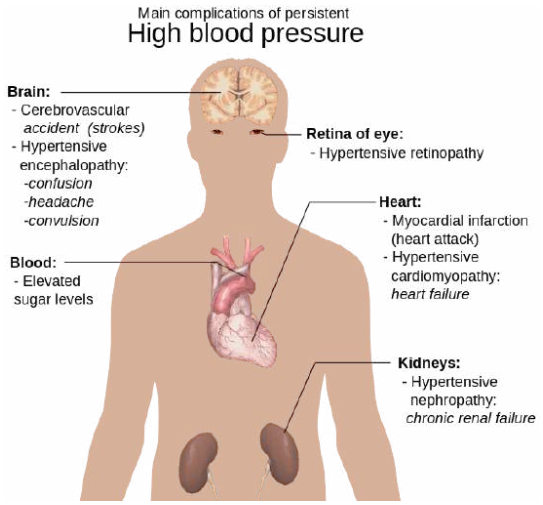



Figure **9.7.2**: If high blood pressure is not brought under control, it can eventually cause hypertensive retinopathy, myocardial infarction, heart failure, nephropathy, stokes, confusion, headache, convulsion, and elevated sugar levels.

## ATHEROSCLEROSIS

**Atherosclerosis** is a condition in which artery walls thicken and stiffen as a result of the buildup of plaques inside the arteries. Plaques consist of white blood cells, cholesterol, and other fats. Typically, there is also a proliferation of smooth muscle cells that make the plaque fibrous as well as fatty. Over time, the plaques may harden with the addition of calcium crystals. This reduces the elasticity of the artery walls. As plaques increase in size, the artery walls dilate to compensate so blood flow is not affected. Eventually, however, the lumen of the arteries is likely to become so narrowed by plaque buildup that blood flow is reduced or even blocked entirely. Figure **9.7.3** illustrates the formation of a plaque in a coronary artery.

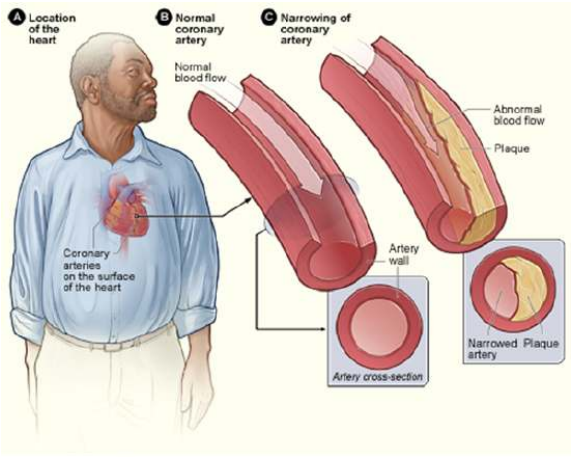



Figure **9.7.3**: Plaque accumulation in a coronary artery may reduce blood flow to cardiac muscle cells.

In most people, plaques start to form in arteries during childhood and progress throughout life. Individuals may develop just a few plaques or dozens of them. Plaques typically remain asymptomatic for decades. Signs and symptoms appear only after there is severe narrowing (stenosis) or complete blockage of arteries. As plaques increase in size and interfere with blood flow, they commonly lead to the formation of blood clots. These may plug arteries at the site of the plaque or travel elsewhere in the circulation. Sometimes plaques rupture or become detached from an arterial wall and become lodged in a smaller, downstream artery. Blockage of arteries by plaques or clots may cause a heart attack, stroke, or other potentially life-threatening cardiovascular events. If blood flow to the kidneys is affected, it may lead to chronic kidney disease.

The process in which plaques form is not yet fully understood, but it is thought that it begins when low-density lipoproteins (LDLs) accumulate inside endothelial cells in artery walls, causing inflammation. The inflammation attracts white blood cells that start to form a plaque. Continued inflammation and a cascade of other immune responses cause the plaque to keep growing. Risk factors for the development of atherosclerosis include hypertension, high cholesterol (especially LDL cholesterol), diabetes, and smoking. The chance of developing atherosclerosis also increases with age, male sex, and a family history of cardiovascular disease.

Treatment of atherosclerosis often includes both lifestyle changes and medications to lower cholesterol, control blood pressure, and reduce the risk of blood clot formation. In extreme cases or when other treatments are inadequate, surgery may be recommended. Surgery may involve the placement of stents in arteries to keep them open and improve blood flow or the use of grafts to divert blood flow around blocked arteries.

## CORONARY ARTERY DISEASE

**Coronary artery diseases** are a group of diseases that result from atherosclerosis of coronary arteries. Treatment of the diseases mainly involves treating underlying atherosclerosis. Two of the most common coronary artery diseases are angina and myocardial infarction.

### ANGINA

**Angina** is chest pain or pressure that occurs when heart muscle cells do not receive adequate blood flow and become starved of oxygen (a condition called ischemia). It is illustrated in Figure **9.7.4**. There may also be a pain in the back, neck, shoulders, or jaw; and in some cases, the pain may be accompanied by shortness of breath, sweating, or nausea. The main goals of the treatment of angina are relieving the symptoms and slowing the progression of underlying atherosclerosis.

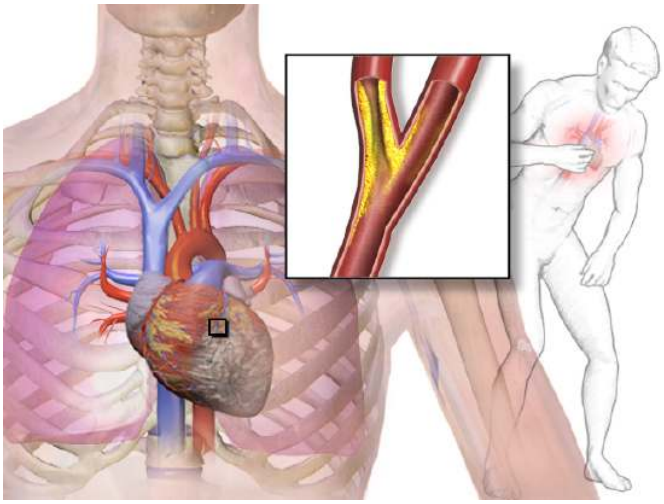


Figure **9.7.4**: Angina is a pain in the chest due to reduced blood flow in coronary arteries so the heart muscle does not receive adequate oxygen.

Angina may be classified as either stable angina or unstable angina:

- Stable angina is angina in which pain is precipitated by exertion (say, from brisk walking or running) and improves quickly with rest or the administration of nitroglycerin, which dilates coronary arteries and improves blood flow. Stable angina may develop into unstable angina.
- Unstable angina is angina in which pain occurs during rest, lasts more than 15 minutes, and is of new onset. This type of angina is more dangerous and may be a sign of an imminent heart attack. It requires urgent medical attention.

### MYOCARDIAL INFARCTION

A **myocardial infarction (MI)**, commonly known as a heart attack, occurs when blood flow stops to a part of the heart causing damage to the heart muscle and the death of myocardial cells. An MI usually occurs because of complete blockage of a coronary artery, often due to a blood clot or the rupture of a plaque (Figure **9.7.5**). An MI typically causes chest pain and pressure, among other possible symptoms, but at least one-quarter of MIs do not cause any symptoms.

In the worst case, an MI may cause sudden death. Even if the patient survives, an MI often causes permanent damage to the heart. This puts the heart at risk of heart arrhythmias, heart failure, and cardiac arrest.

- Heart arrhythmias are abnormal heart rhythms, which are potentially life-threatening. Heart arrhythmias often can be interrupted with a cardiac defibrillator, which delivers an electrical shock to the heart, in effect “rebooting” it.
- Heart failure occurs when the pumping action of the heart is impaired so tissues do not get adequate oxygen. This is a chronic condition that tends to get worse over time, although it can be managed with medications.
- Cardiac arrest occurs when the heart no longer pumps blood or pumps blood so poorly that vital organs can no longer function. This is a medical emergency requiring immediate intervention.

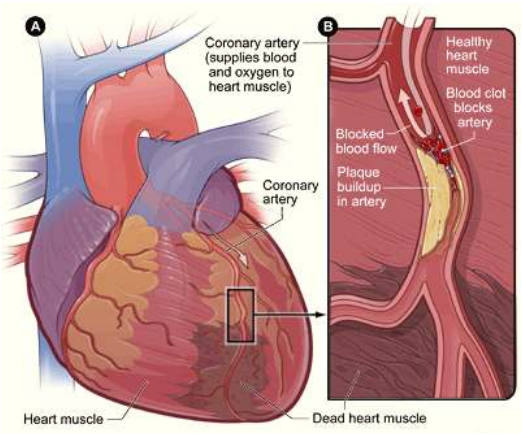



Figure **9.7.5**: A myocardial infarction occurs when cardiac muscle cells die due to blockage of a coronary artery.

## OTHER CARDIOVASCULAR DISEASES

Hypertension and atherosclerosis often cause other cardiovascular diseases. These commonly include stroke and peripheral artery disease.

### STROKE

A **stroke,** also known as a cerebrovascular accident or brain attack, occurs when blocked or broken arteries in the brain result in the death of brain cells. There are two main types of stroke: ischemic stroke and hemorrhagic stroke. Ischemic storke is illustrated in Figure **9.7.6**.

1. An ischemic stroke occurs when an embolus (blood clot) breaks off from a plaque or forms in the heart because of arrhythmia and travels to the brain where it becomes lodged in an artery. This blocks blood flow to the part of the brain that is served by arteries downstream from the blockage. Lack of oxygen causes the death of brain cells. Treatment with a clot-busting drug within a few hours of the stroke may prevent permanent damage. Almost 90 percent of strokes are ischemic strokes.
2. A hemorrhagic stroke occurs when an artery in the brain ruptures and causes bleeding in the brain. This deprives downstream tissues of adequate blood flow and also puts pressure on brain tissue. Both factors can lead to the death of brain cells. Surgery to temporarily open the cranium may be required to relieve the pressure. Only about 10 percent of strokes are hemorrhagic strokes, but they are more likely to be fatal than ischemic strokes.

In both types of stroke, the part of the brain that is damaged loses is the ability to function normally. Signs and symptoms of stroke may include an inability to move, feel, or see on one side of the body; problems understanding speech or difficulty speaking; memory problems; confusion; and dizziness. Hemorrhagic strokes may also cause a severe headache. The symptoms of a stroke usually occur within seconds or minutes of the brain injury. Depending on the severity of the stroke and how quickly treatment is provided, the symptoms may be temporary or permanent. If the symptoms of a stroke go away on their own in less than an hour or two, the stroke is

called a transient ischemic attack. Stroke is the leading cause of disability in the United States, but rehabilitation with physical, occupational, speech, or other types of therapy may significantly improve functioning.

The main risk factor for stroke is high blood pressure. Therefore, keeping blood pressure within the normal range, whether with lifestyle changes or medications, is the best way to reduce the risk of stroke. Another possible cause of stroke is the use of illicit drugs such as amphetamines or cocaine. Having had a stroke in the past greatly increases one's risk of future strokes. Men are also more likely than women to have strokes.

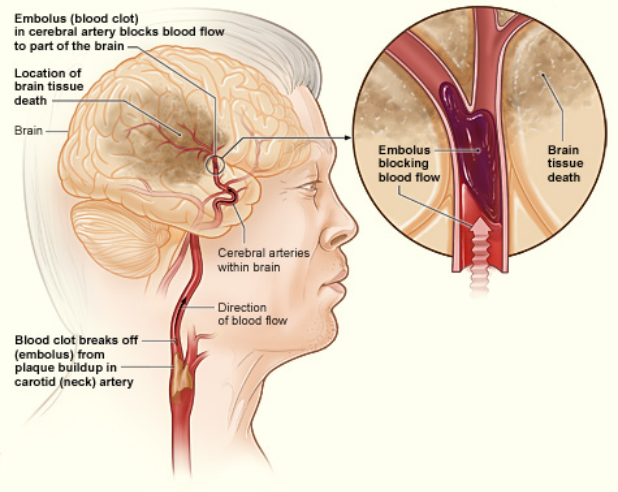



Figure **9.7.6**: In an ischemic stroke, brain cells die due to a blocked artery in the brain. The blockage happens when a blood clot breaks from a buildup in the carotid artery and blocks blood flow to part of the brain. As a result, the brain tissue dies. The traveling clot is called embolus.

## PERIPHERAL ARTERY DISEASE

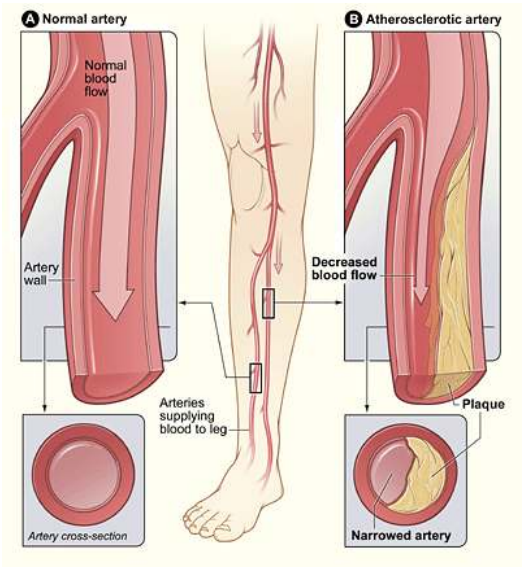



Figure **9.7.7**: Peripheral artery disease (PAD) develops when plaque accumulates in the wall of the leg artery. PAD typically causes pain and other symptoms because of decreased blood flow in the leg or other areas of the body served by peripheral arteries.

**Peripheral artery disease (PAD)** is the narrowing of the arteries other than those that supply the heart or brain due to atherosclerosis. Figure **9.7.7** shows how the PAD occurs. PAD most commonly affects the legs, but other arteries may also be involved. The classic symptom is leg pain when walking, which usually resolves with rest. This symptom is known as intermittent claudication. Other symptoms may include skin ulcers, bluish skin, cold skin, or poor nail and hair growth in the affected leg(s). However, up to half of all cases of PAD do not have any symptoms.

The main risk factor for PAD is smoking. Other risk factors include diabetes, high blood pressure, and high blood cholesterol. The underlying mechanism is usually atherosclerosis. PAD is typically diagnosed when blood pressure readings taken at the ankle are lower than blood pressure readings taken at the upper arm. It is important to diagnose PAD and treat underlying atherosclerosis because people with this disorder have a four to five times higher risk of myocardial infarction or stroke. Surgery to expand the affected arteries or to graft vessels in order to bypass blockages may be recommended in some cases.

### FEATURE: MY HUMAN BODY

You read in this concept about the many dangers of hypertension. Do you know whether you have hypertension? The only way to know for sure is to have your blood pressure measured. Measuring blood pressure is quick and painless, but several measurements are needed to accurately diagnose hypertension. Some people have what is called "white coat disease." Their blood pressure rises just because they are being examined by a physician (in a white coat). Blood pressure also fluctuates from time to time due to factors such as hydration, stress, and time of day. Repeatedly measuring and recording your own blood pressure at home can provide your doctor with valuable diagnostic data. Digital blood pressure monitors for home use, like the one pictured in Figure **9.7.8**, are relatively inexpensive, easy to use, and available at most pharmacies.




Figure **9.7.8**: This personal blood pressure monitor is worn on the wrist.

## REVIEW

1. What is cardiovascular disease? How much mortality do cardiovascular diseases cause?
2. List risk factors for cardiovascular disease.
3. What is hypertension?

4. Define atherosclerosis.
5. What is coronary artery disease?
6. Identify two specific coronary artery diseases.
7. Explain how a stroke occurs and how it affects the patient.
8. Describe the cause of peripheral artery disease.
9. What are two cardiovascular diseases that can be caused by atherosclerosis? Explain specifically how atherosclerosis contributes to each of them.
10. *True or False.* A heart attack is the same thing as cardiac arrest.
11. *True or False.* Plaques in arteries can cause blood clots.
12. What are the similarities between angina and ischemic stroke?
13. How can kidney disease be caused by problems in the cardiovascular system?
14. In peripheral artery disease, the blood pressure at the ankle is typically _____ the blood pressure at the upper arm.

    A. erratic compared to B. the same as

    C. higher than D. lower than
15. Name three components of the plaque that can build up in arteries.

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# 9.8: CASE STUDY CONCLUSION- FLIGHT AND CHAPTER SUMMARY

## CASE STUDY CONCLUSION: FLIGHT RISK

At the beginning of this chapter, you learned about Antônio and Ahaya, who met while sitting next to each other on a plane. During the flight, Ahaya got up to take frequent walks and was doing leg exercises to try to avoid the medical condition depicted in Figure **9.8.1**—**deep vein thrombosis** (DVT). DVT occurs when a blood clot forms in a deep vein, usually in the leg. It can be very dangerous—even deadly.

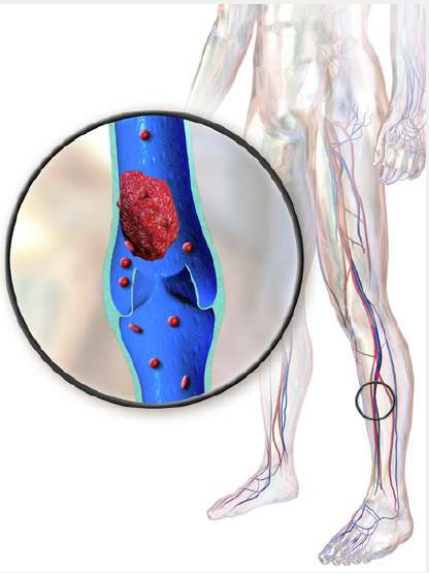


Figure **9.8.1**: Illustration of a blood clot in a deep vein in the leg, which is called deep vein thrombosis (DVT).

As you learned in this chapter, a blood clot is an aggregation of platelets and proteins. Blood clots are helpful to prevent blood loss when a blood vessel is damaged. But in some situations, they can be extremely dangerous. For example, blood clots can cause heart attacks or strokes by blocking the flow of blood to the heart or brain, respectively.

When DVT occurs, one of the major risks is pulmonary embolism (PE). PE is when the blood clot breaks off, travels through the blood vessels, and lodges in a pulmonary artery, like the blood clot shown in Figure **9.8.2**. Recall what the pulmonary arteries do: they carry deoxygenated blood from the heart to the lungs, where the blood picks up oxygen and releases carbon dioxide due to gas exchange between the capillaries and the alveoli of the lungs. Imagine what would happen if this flow of blood to the lungs was partially or completely blocked by a blood clot. Depending on the size of the blood clot and where it is lodged, a PE can cause a variety of serious consequences ranging from lung damage to instant death, because of the disruption of the pulmonary circulation.

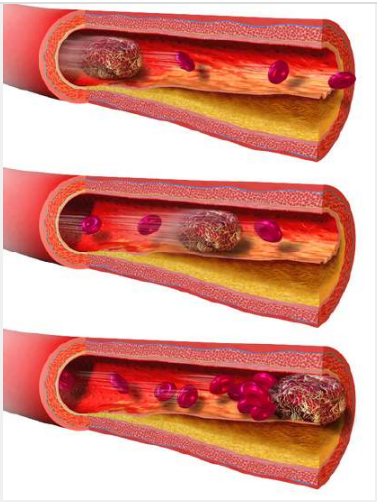


Figure **9.8.2**: Illustration of how a moving blood clot can get stuck in a blood vessel. When this occurs in a pulmonary artery, it is called a pulmonary embolism (PE).

Ahaya has a higher risk of DVT and its consequences because he has heart failure. As you have learned, heart failure is a chronic condition in which the pumping action of the heart is impaired. One reason that heart failure is thought to increase the risk of DVT is that the blood is not being pushed strongly enough through the cardiovascular system, allowing blood clots to form more easily.

Ahaya needs to be particularly concerned about DVT while on a long plane flight. Why do you think this is? Think about how blood flows through arteries and veins. Blood is pushed through arteries mainly due to the pumping action of the heart. Veins, on the other hand, rely on the movement of the surrounding skeletal muscles to help push blood through them. Sitting still for long periods of time in cramped quarters, such as on a plane, can cause blood to pool in the deep veins of the legs. This can lead to the formation of a blood clot.

## CHAPTER SUMMARY

In this chapter, you learned about the structure, functions, and disorders of the cardiovascular system. Specifically, you learned that:

- The cardiovascular system is the organ system that transports materials to and from all the cells of the body. The main components of the cardiovascular system are the heart, blood vessels, and blood.
- The cardiovascular system has two interconnected circulations. The pulmonary circulation carries blood between the heart and lungs, where blood is oxygenated. The systemic circulation carries blood between the heart and the rest of the body, where it delivers oxygen.
- The heart is a muscular organ in the chest that consists mainly of cardiac muscle and pumps blood through blood vessels by repeated, rhythmic contractions.

- The wall of the heart consists of three layers. The middle layer, the myocardium, is the thickest layer and consists mainly of cardiac muscle.
- The interior of the heart consists of four chambers, with an upper atrium and lower ventricle on each side of the heart. Blood enters the heart through the atria, which pump it to the ventricles. Then the ventricles pump blood out of the heart. Four valves in the heart keep blood flowing in the correct direction and prevent backflow.
- Deoxygenated blood flows into the right atrium through veins from the upper and lower body (superior and inferior vena cava, respectively), and oxygenated blood flows into the left atrium through four pulmonary veins from the lungs. Each atrium pumps the blood to the ventricle below it. From the right ventricle, deoxygenated blood is pumped to the lungs through the two pulmonary arteries. From the left ventricle, oxygenated blood is pumped to the rest of the body through the aorta.
- The coronary circulation consists of blood vessels that carry blood to and from the heart muscle cells. There are two coronary arteries that supply the two sides of the heart with oxygenated blood. Cardiac veins drain deoxygenated blood back into the heart.
- The cardiac cycle refers to a single complete heartbeat. It includes diastole when the atria contract; and systole when the ventricles contract.
- The normal, rhythmic beating of the heart is called sinus rhythm. It is established by the heart's pacemaker cells in the sinoatrial node. Electrical signals from the pacemaker cells travel to the atria and cause them to contract. Then the signals travel to the atrioventricular node and from there to the ventricles, causing them to contract. Electrical stimulation from the autonomic nervous system and hormones from the endocrine system can also influence heartbeat.

- Blood vessels carry blood throughout the body. Major types of blood vessels are arteries, veins, and capillaries.
  - Arteries are blood vessels that usually carry blood away from the heart (except for coronary arteries that supply the heart muscle with blood). Most arteries carry oxygenated blood. The largest artery is the aorta, which is connected to the heart and extends into the abdomen. Blood moves through arteries due to pressure from the beating of the heart.
  - Veins are blood vessels that usually carry blood toward the heart. Most veins carry deoxygenated blood. The largest veins are the superior and inferior venae cavae. Blood moves through veins by the squeezing action of surrounding skeletal muscles. Valves in veins prevent the backflow of blood.
  - Capillaries are the smallest blood vessels. They connect arterioles and venules. They form capillary beds where substances are exchanged between the blood and surrounding tissues.
  - The walls of arteries and veins have three layers. The middle layer is thickest in arteries, in which it contains smooth muscle tissue that controls the diameter of the vessels. The outer layer is thickest in veins and consists mainly of connective tissue. The walls of capillaries consist of little more than a single layer of epithelial cells.
  - Blood pressure is a measure of the force that blood exerts on the walls of arteries. It is expressed as a double number, with the higher number representing systolic pressure when the ventricles contract and the lower number representing diastolic pressure when the ventricles relax. Normal blood pressure is generally defined as a pressure of 120/80 mm Hg or less.
  - Vasoconstriction (narrowing) and vasodilation (widening) of arteries can occur to help regulate blood pressure or body temperature or to change blood flow as part of the fight-or-flight response.
- Blood is a fluid connective tissue that circulates throughout the body in blood vessels. Blood supplies tissues with oxygen and nutrients and removes their metabolic wastes. Blood helps defend the body from pathogens and other threats, transports hormones and other substances, and helps to keep the body's pH and temperature in homeostasis. Blood consists of a liquid part, called plasma, and cells, including red blood cells, white blood cells, and platelets.
  - Plasma makes up more than half of blood by volume. It consists of water and many dissolved substances. Blood also contains blood cells and platelets.
  - Red blood cells are the most numerous cells in the blood and consist mostly of hemoglobin, which carries oxygen. Red blood cells also carry antigens that determine blood types. White blood cells are less numerous than red blood cells and are part of the body's immune system. They protect the body from abnormal cells, microorganisms, and other harmful substances. There are several different types of white blood cells that differ in their specific immune functions.
  - Platelets are cell fragments that play important roles in blood clotting or coagulation. They stick together at breaks in blood vessels to form a clot and stimulate the production of fibrin, which strengthens the clot.
  - All blood cells form by the proliferation of stem cells in red bone marrow in a process called hematopoiesis. When blood cells die, they are phagocytized by white blood cells and removed from circulation.
  - Disorders of the blood include leukemia, which is a cancer of the bone-forming cells; hemophilia, which is any of several genetic blood-clotting disorders; carbon monoxide poisoning, which prevents red blood cells from binding with oxygen and causes suffocation; HIV infection, which destroys certain white blood cells and can cause AIDS; and anemia, in which there are not enough red blood cells to carry adequate oxygen to body tissues.
- Blood type (or blood group) is a genetic characteristic associated with the presence or absence of antigens on the surface of red blood cells. A blood group system refers to all of the gene(s),

alleles, and possible genotypes and phenotypes that exist for a particular set of blood type antigens.

- Cardiovascular disease is a class of diseases that involve the cardiovascular system. Worldwide, it is the leading cause of death. Most cases occur in people over age 60, and onset is typically about a decade earlier in males than females. Other risk factors include smoking, obesity, diabetes, high blood cholesterol, and lack of exercise.
- Antigens are molecules that the immune system identifies as either self or nonself. If antigens are identified as nonself, the immune system responds by forming antibodies that are specific to the nonself antigens, leading to the destruction of cells bearing the antigens.
- The ABO blood group system is a system of red blood cell antigens controlled by a single gene with three common alleles on chromosome 9. There are four possible ABO blood types: A, B, AB, and O. The ABO system is the most important blood group system in blood transfusions. People with type O blood are universal donors, and people with type AB blood are universal recipients.
- The Rhesus blood group system is a system of red blood cell antigens controlled by two genes with many alleles on chromosome 1. There are five common Rhesus antigens, of which antigen D is most significant. Individuals who have antigen D are called Rh+, and individuals who lack antigen D are called Rh-. Rh- mothers of Rh+ fetuses may produce antibodies against the D antigen in the fetal blood, causing hemolytic disease of the newborn (HDN).

- Two common conditions that lead to most cases of cardiovascular disease are hypertension and atherosclerosis. Hypertension is blood pressure that is persistently at or above 140/90 mm Hg. Atherosclerosis is a buildup of fatty, fibrous plaques in arteries that may reduce or block blood flow. Treating these conditions is important for preventing cardiovascular disease.
  - Coronary artery disease is a group of diseases that result from atherosclerosis of coronary arteries. Two of the most common are angina and myocardial infarction (heart attack). In angina, cardiac cells receive inadequate oxygen, which causes chest pain. In a heart attack, cardiac cells die because blood flow to part of the heart is blocked. A heart attack may cause death or lead to heart arrhythmias, heart failure, or cardiac arrest.
  - A stroke occurs when blocked or broken arteries in the brain result in the death of brain cells. This may occur when an artery is blocked by a clot or plaque or when an artery ruptures and bleeds in the brain. In both cases, part of the brain is damaged and functions such as speech and controlled movements may be impaired, either temporarily or permanently.
  - Peripheral artery disease occurs when atherosclerosis narrows peripheral arteries, usually in the legs, often causing pain when walking. It is important to diagnose this disease so underlying atherosclerosis can be treated before it causes a heart attack or stroke.

In this chapter, you learned that the cardiovascular system carries nutrients to the cells of the body. Read the next chapter about the Digestive System to learn about how your body transforms your meals into the nutrients that cells need to function.

## CHAPTER SUMMARY REVIEW QUESTIONS

1. Alex goes to the doctor and learns that his blood pressure is 135/90 mm Hg. Answer the following questions about his blood pressure.
   A. Is this normal blood pressure? Why or why not?
   B. Which number refers to the systolic pressure and which number refers to the diastolic pressure?
   C. Describe what the atria and ventricles of Alex's heart are doing when the pressure is at 135 mm Hg.
   D. Alex's doctor would like him to lower his blood pressure. Why do you think he would like Alex to do this and what are some ways in which he may be able to lower his blood pressure?
2. What are the three functions of the cardiovascular system?
3. What is the watery part of the blood called?
4. Which are the chambers of the heart that receive blood? Which are the chambers of the heart that pump blood out of the heart?
5. Which chambers of the heart contain deoxygenated blood?
   A. Right and left atria
   B. Right and left ventricles
   C. Right atrium and right ventricle
   D. Left atrium and left ventricle
6. What are two different places in the cardiovascular system where valves are located?
7. Valves prevent blood from flowing backward in the cardiovascular system. Why do you think this is important?
8. Explain how pacemaker cells in the heart work together with the nervous system to regulate the beating of the heart.
9. *True or False.* Red marrow is the source of white blood cells.
10. *True or False.* Plaques that build up in arteries are made completely of fats.
11. The aorta is:
    A. An artery
    B. A chamber of the heart
    C. A vein
    D. A valve
12. Compare the coronary arteries, pulmonary arteries, and arteries elsewhere in the body in terms of their target tissues (i.e. where they bring blood to) and whether they are carrying oxygenated or deoxygenated blood.
13. The superior vena cava empties into which structure of the heart? The inferior vena cava empties into which structure of the heart?
    A. right atrium; left atrium
    B. right atrium; right atrium

C. right atrium; right ventricle
D. right ventricle; left ventricle

14. Venules receive blood from what?
15. Define blood type and blood group system. Explain the relationship between antigens and antibodies.
16. Identify the alleles, genotypes, and phenotypes in the ABO blood group system.
17. Discuss the medical significance of the ABO blood group system.
18. Give examples of how different ABO blood types vary in their susceptibility to diseases.
19. Describe the Rhesus blood group system.
20. Relate Rhesus blood groups to blood transfusions.
21. What causes hemolytic disease of the newborn?
22. A woman is blood type O and Rh- and her husband is blood type AB and Rh+. Answer the following questions about this couple and their offspring.
    A. What are the possible genotypes of their offspring in terms of ABO blood group?
    B. What are the possible phenotypes of their offspring in terms of ABO blood group?
    C. Can the woman donate blood to her husband? Explain your answer.
    D. Can the man donate blood to his wife? Explain your answer.
23. *True or False.* The D antigen is part of the ABO blood group system.
24. Explain why hemolytic disease of the newborn may be more likely to occur in a second pregnancy than in a first.
25. Anemia causes weakness and fatigue due to a reduction in the amount of oxygen that gets to the cells of the body. Explain how oxygen is transported to the cells of the body and which blood cells are affected in anemia.
26. What are the two conditions that are precursors to virtually all cases of cardiovascular disease?
27. What is another name for a heart attack?
    A. Heart arrhythmia
    B. Myocardial infarction
    C. Angina
    D. Heart failure
28. *True or False.* Strokes can be due to a blood clot or to a broken artery.
29. *True or False.* After an injury to a blood vessel, platelets respond by losing their nuclei.
30. What are the main differences between coronary circulation, pulmonary circulation, and systemic circulation?
31. Define the term *sinus rhythm.*
32. Which is generally a more serious and immediately life-threatening condition: heart failure or cardiac arrest? Explain your answer.
33. Match each of the following descriptions to the disease or disorder from the list below that *best* matches it. Use each disease or disorder only once. Diseases and disorders: hypertension; atherosclerosis; coronary artery disease; peripheral artery disease
    A. Blood flow to the muscle cells of the heart is impaired.
    B. Blood pressure is too high.
    C. Arteries in the legs specifically become more narrow.
    D. Plaque builds up in arteries (in general).

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## ATTRIBUTIONS


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# CHAPTER OVERVIEW

## 10: THE LYMPHATIC AND IMMUNE SYSTEMS

This chapter outlines the layered responses of the human immune system, including both innate and adaptive immune responses. It also describes the structures and functions of the lymphatic system, with a focus on its roles in host defense. In addition, the chapter examines three different types of immune system disorders.


10.1: Case Study- Your Defense System

10.2: Introduction to the Immune System

10.3: Lymphatic System

10.4: Innate Immune System

10.5: Adaptive Immune System

10.6: Disorders of the Immune System

10.7: Human Microbiome

10.8: Case Study Conclusion- Lymphoma and Chapter Summary


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# 10.1: CASE STUDY- YOUR DEFENSE SYSTEM

## CASE STUDY: DEFENDING YOUR DEFENSES

Twenty-six-year-old Wei isn't feeling well. Wei uses he/him/his pronouns. He is more tired than usual, dragging through his workdays despite going to bed earlier and napping on the weekends. He doesn't have much of an appetite and has started losing weight. When he presses on the side of his neck, like the doctor is doing in Figure 10.1.1, he notices an unusual lump.



Figure 10.1.1: Palpating lymph nodes

Wei goes to his doctor, who performs a physical exam and determines that the lump is a swollen lymph node. Lymph nodes are part of the immune system, and they will often become enlarged when the body is fighting off an infection. Dr. Bouazizi thinks that the swollen lymph node and fatigue could be signs of a viral or bacterial infection, or indicate a type of cancer called lymphoma. However, an infection is a more likely cause, particularly in a young person like Wei. Dr. Bouazizi prescribes an antibiotic in case Wei has a bacterial infection and advises him to return in a few weeks if his lymph node does not shrink or if he is not feeling better.

Wei returns a few weeks later. He is not feeling better and his lymph node is still enlarged. Dr. Bouazizi is concerned and orders a biopsy of the enlarged lymph node. A lymph node biopsy for suspected lymphoma often involves the surgical removal of all or part of a lymph node, to determine whether the tissue contains cancerous cells.

The initial results of the biopsy indicate that Wei does have lymphoma. Although lymphoma is more common in older people, young adults and even children can get this disease. There are many types of lymphoma, with the two main types being Hodgkin and non-Hodgkin lymphoma. Non-Hodgkin lymphoma (NHL), in turn, has many subtypes depending on factors such as which cell types are affected. For instance, some subtypes of NHL affect immune system cells called B cells, while others affect different immune system cells called T cells.

Dr. Bouazizi explains to Wei that it is important to determine which type of lymphoma he has, in order to choose the best course of treatment. Wei's biopsied tissue will be further examined and tested to see which cell types are affected and which specific cell-surface proteins, called antigens, are present. This should help in identifying his specific type of lymphoma.

As you read this chapter, you will learn about the functions of the immune system, and the specific roles that its cells and organs—such as B and T cells and lymph nodes— play in defending the body. At the end of this chapter, you will learn what type of lymphoma Wei has and what some of his treatment options are, including treatments that make use of the biochemistry of the immune system to fight cancer with the immune system itself.

## CHAPTER OVERVIEW: IMMUNE SYSTEM

In this chapter, you will learn about the immune system—the system that defends the body against infections and other causes of disease such as cancerous cells. Specifically, you will learn about:

- How the immune system identifies normal cells of the body as "self" and pathogens and damaged cells as "non-self."
- The two major subsystems of the general immune system: the innate immune system, which provides a quick but non-specific response; and the adaptive immune system, which is slower but provides a specific response that often results in long-lasting immunity.
- The specialized immune system that protects the brain and spinal cord called the neuroimmune system.
- The organs, cells, and responses of the innate immune system, which include physical barriers such as skin and mucus, chemical and biological barriers, inflammation, activation of the complement system of molecules, and non-specific cellular responses such as phagocytosis.
- The lymphatic system—which includes white blood cells called lymphocytes; lymphatic vessels that transport a fluid called lymph; and organs such as the spleen, tonsils, and lymph nodes —and its important role in the adaptive immune system.
- Specific cells of the immune system and their functions, including B cells, T cells, plasma cells, and natural killer cells.
- How the adaptive immune system can generate specific and often long-lasting immunity against pathogens through the production of antibodies.
- How vaccines work to generate immunity.
- How cells in the immune system detect and kill cancerous cells.
- Some strategies that pathogens employ to evade the immune system.
- Disorders of the immune system, including allergies, autoimmune diseases (such as diabetes and multiple sclerosis), and immunodeficiency resulting from conditions such as HIV infection.

As you read the chapter, think about the following questions:

1. What are the functions of lymph nodes?
2. What are B and T cells and how do they relate to lymph nodes?
3. What are cell-surface antigens? How do they relate to the immune system and to cancer?

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# 10.2: INTRODUCTION TO THE IMMUNE SYSTEM

## WORM ATTACK!

Does this organism look like a space alien? A scary creature from a nightmare? In fact, it's a 1-cm long worm in the genus *Schistosoma*. It may invade and take up residence in the human body, causing a very serious illness known as schistosomiasis. The worm gains access to the human body while it is in a microscopic life stage. It enters through a hair follicle when the skin comes into contact with contaminated water. The worm then grows and matures inside the human organism, causing disease.



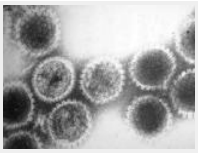
Figure **10.2.1**: Schistosome Parasite

## HOST VS. PATHOGEN

The *Schistosoma* worm has a parasitic relationship with humans. In this type of relationship, one organism, called the parasite, lives on or in another organism, called the host. The parasite always benefits from the relationship and the host is always harmed. The human host of the *Schistosoma* worm is clearly harmed by the parasite when it invades the host's tissues. The urinary tract or intestines may be infected, and signs and symptoms may include abdominal pain, diarrhea, bloody stool, or blood in the urine. Those who have been infected a long time may experience liver damage, kidney failure, infertility, or bladder cancer. In children, *Schistosoma* infection may cause poor growth and difficulty learning. Table **10.2.1** lists some of the microscopic pathogens, their images, description, and the diseases that they cause.

Like the Schistosoma worm, many other organisms can make us sick if they manage to enter our body. Any such agent that can cause disease is called a **pathogen**. Most pathogens are microorganisms, although some, such as the Schistosoma worm, are much larger. In addition to worms, common types of pathogens of human hosts include bacteria, viruses, fungi, and single-celled organisms called protists. You can see examples of each of these types of pathogens in Table **10.2.1**. Fortunately for us, our immune system is able to keep most potential pathogens out of the body or to quickly destroy them if they do manage to get in. When you read this chapter, you'll learn how your immune system usually keeps you safe from harm — including from scary creatures like the Schistosoma worm!

Table **10.2.1**: Types of Pathogens

| Type of Pathogen | Example and their Image | Description | Human Disease caused by pathogens of that type |
|---|---|---|---|
| **Bacteria** |  such as *Escherichia coli* | Single-celled organisms without a nucleus | Strep throat, staph infections, tuberculosis, food poisoning, tetanus, pneumonia, syphilis |
| **Viruses** |  such as Herpes simplex | Particles that reproduce by taking over living cells. | Common cold, flu, genital herpes, cold sores, measles, AIDS, genital warts, chickenpox, smallpox |
| **Fungi** |  such as *Trichophyton rubrum* | Organisms with a nucleus that grow as single cells or tread-like filaments | Ringworm, athlete's foot, tineas, candidiasis, histoplasmosis |
| **Protozoa** |  Such as *Giarida lamblia* | A single-celled organism with a nucleus | Malaria, Traveler's diarrhea, giardiasis, trypanosomiasis (sleeping sickness) |

## WHAT IS THE IMMUNE SYSTEM?

The **immune system** is a host defense system. It comprises many biological structures —ranging from individual white blood cells to entire organs — as well as many complex biological processes. The function of the immune system is to protect the host from pathogens and other causes of disease such as tumor cells. To function properly, the immune system must be able to detect a wide variety of pathogens. It also must be able to distinguish the cells of pathogens from the host's own cells and also to distinguish cancerous or damaged host cells from healthy cells. In humans and most other vertebrates, the immune system consists of layered defenses that have increased specificity for particular pathogens or tumor cells. The layered defenses of the human immune system are usually classified into two subsystems called the innate immune system and the adaptive immune system.

### INNATE IMMUNE SYSTEM

Any discussion of the innate immune response usually begins with the physical barriers that prevent pathogens from entering the body, destroy them after they enter, or flush them out before they can establish themselves in the hospitable environment of the body's soft tissues. Barrier defenses are part of the body's most basic defense mechanisms. The barrier defenses are not a response to infections, but they are continuously working to protect against a broad range of pathogens.

The **phagocytes** are the body's fast acting first line of immunological defense against organisms that have breached barrier defenses and have entered the vulnerable tissues of the body. For example, certain leukocytes (white blood cells) engulf and destroy pathogens they encounter in the process called phagocytosis. The body's response again a pathogen's breach is also called **Inflammation**. Phagocytosis and Inflammation will be discussed in detail in concept *Innate Immune System*.

### ADAPTIVE IMMUNE SYSTEM

The adaptive immune system is activated if pathogens successfully enter the body and manage to evade the general defenses of the innate immune system. An adaptive response is specific to the particular type of pathogen that has invaded the body or to cancerous cells. It takes longer to launch a specific attack, but once it is underway, its specificity makes it very effective. An adaptive response also usually leads to immunity. This is a state of resistance to a specific pathogen due to the ability of the adaptive immune system to "remember" the pathogen and immediately mount a strong attack tailored to that particular pathogen if it invades again in the future.

## SELF VS. NON-SELF

Both innate and adaptive immune responses depend on the ability of the immune system to distinguish between self and non-self molecules. Self molecules are those components of an organism's body that can be distinguished from foreign substances by the immune system. Virtually all body cells have surface proteins that are part of a complex called the **major histocompatibility complex (MHC)**. These proteins are one way the immune system recognizes body cells as self. Non-self proteins, in contrast, are recognized as foreign because they are different from self-proteins.

## ANTIGENS AND ANTIBODIES

Many non-self molecules comprise a class of compounds called antigens. Antigens, which are usually proteins, bind to specific receptors on immune system cells and elicit an adaptive immune response. Some adaptive immune system cells (B cells) respond to foreign antigens by producing antibodies. An antibody is a molecule that precisely matches and binds to a specific antigen. This may target the antigen (and the pathogen displaying it) for destruction by other immune cells.

Antigens on the surface of pathogens are how the adaptive immune system recognizes specific pathogens. Antigen specificity allows for the generation of responses tailored to the specific pathogen. It is also how the adaptive immune system "remembers" the same pathogen in the future.

## IMMUNE SURVEILLANCE

Another important role of the immune system is to identify and eliminate tumor cells. This is called **immune surveillance.** The transformed cells of tumors express antigens that are not found on normal body cells. The main response of the immune system to tumor cells is to destroy them. This is carried out primarily by aptly named killer T cells of the adaptive immune system.

## LYMPHATIC SYSTEM

The lymphatic system is a human organ system that is a vital part of the adaptive immune system. It is also part of the cardiovascular system and plays a major role in the digestive system (see the concept Lymphatic System).

### FEATURE: HUMAN BIOLOGY IN THE NEWS

"They'll have to rewrite the textbooks!"

That sort of response to scientific discovery is sure to attract media attention, and it did. It's what Kevin Lee, a neuroscientist at the University of Virginia, said in 2016 when his colleagues told him they had discovered human anatomical structures that had never before been detected. The structures were tiny lymphatic vessels in the meningeal layers surrounding the brain.

How these lymphatic vessels could have gone unnoticed when all human body systems have been studied so completely is amazing in its own right. The suggested implications of the discovery are equally amazing:

- The presence of these lymphatic vessels means that the brain is directly connected to the peripheral immune system, presumably allowing a close association between the human brain and human pathogens. This suggests an entirely new avenue by which humans and their pathogens may have influenced each other's evolution. The researchers speculate that our pathogens may have even influenced the evolution of our social behaviors.
- The researchers think there will also be many medical applications of their discovery. For example, the newly discovered lymphatic vessels may play a major role in neurological diseases that have an immune component, such as multiple sclerosis. The discovery might also affect how conditions such as autism spectrum disorders and schizophrenia are treated.

## REVIEW

1. What is a pathogen?
2. State the purpose of the immune system.
3. Compare and contrast the innate and adaptive immune systems.
4. Explain how the immune system distinguishes self molecules from non-self molecules.
5. What are antigens?
6. Define tumor surveillance.
7. Briefly describe the lymphatic system and its role in immune function.
8. Identify the neuroimmune system.
9. Which of the following is NOT a function of the immune system?

   A. Protecting the body against fungi

B. Protecting the body against bacteria
C. Protecting the body against cancerous cells
D. None of the above

10. What does it mean that the immune system is not just composed of organs?
11. What are the general relationships between the terms *lymphocytes*, *leukocytes*, and *white blood cells*?
12. *True or False.* Phagocytosis occurs in the innate immune system.
13. *True or False.* Major histocompatibility complex proteins are antibodies.
14. *True or False.* Only the adaptive immune response requires the ability to distinguish between self and non-self.
15. Why is the immune system considered to be "layered?"

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# 10.3: LYMPHATIC SYSTEM

## TONSILLITIS

The white patches on either side of the throat in this picture are signs of tonsillitis. The tonsils are small structures in the throat that are very common sites of infection. The white spots on the tonsils pictured here are evidence of infection. The patches consist of large amounts of dead bacteria, cellular debris, and white blood cells; in a word, pus. Children with recurrent tonsillitis may have their tonsils removed surgically to eliminate this type of infection. The tonsils are organs of the lymphatic system.



Figure **10.3.1**:Tonsilitis

## WHAT IS THE LYMPHATIC SYSTEM?

The **lymphatic system** is a collection of organs involved in the production, maturation, and harboring of white blood cells called lymphocytes. It also includes a network of vessels that transport or filter the fluid known as **lymph** in which lymphocytes circulate. Figure **10.3.2**shows major lymphatic vessels and other structures that make up the lymphatic system. Besides the tonsils, organs of the lymphatic system include the thymus, the spleen, and hundreds of lymph nodes that are distributed along the lymphatic vessels.

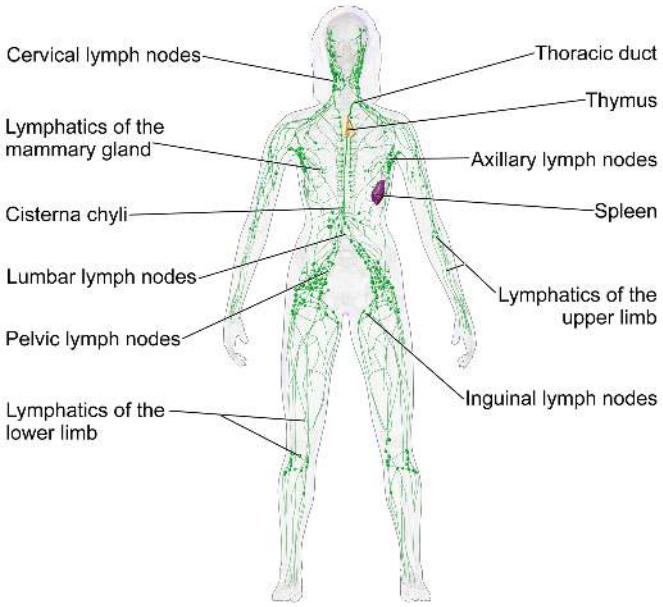



Figure **10.3.2**

: The lymphatic system includes the thymus, spleen, lymph vessels, and nodes.

The lymphatic vessels form a transportation network similar in many respects to the blood vessels of the cardiovascular system. However, unlike the cardiovascular system, the lymphatic system is not a closed system. Instead, lymphatic vessels carry lymph in a single direction, always toward the upper chest, where the lymph empties from lymphatic vessels into blood vessels.

## CARDIOVASCULAR FUNCTION OF THE LYMPHATIC SYSTEM

The return of lymph to the bloodstream is one of the major functions of the lymphatic system. When blood travels through capillaries of the cardiovascular system, it is under pressure, which forces some of the components of blood (such as water, oxygen, and nutrients) through the walls of the capillaries and into the tissue spaces between cells, forming tissue fluid, also called interstitial fluid (Figure **10.3.3**). Interstitial fluid bathes and nourishes cells and also absorbs their waste products. Much of the water from the interstitial fluid is reabsorbed into the capillary blood by osmosis. Most of the remaining fluid is absorbed by tiny lymphatic vessels called lymph capillaries. Once interstitial fluid enters the lymphatic vessels, it is called lymph. Lymph is very similar in composition to blood plasma. Besides water, lymph may contain proteins, waste products, cellular debris, and pathogens. It also contains numerous white blood cells, especially the subset of white blood cells known as lymphocytes. In fact, lymphocytes are the main cellular components of lymph.

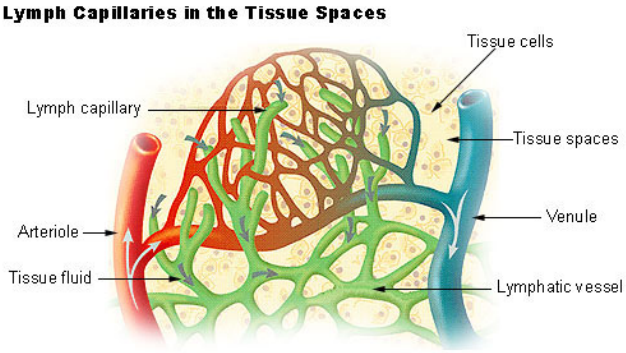



Figure **10.3.3**: Fluid and other substances in the blood are forced by blood pressure through the walls of capillaries and into the surrounding tissue spaces. Some of the tissue fluid is absorbed by tiny lymphatic vessels, forming lymph. The arrows show the direction of blood and lymph through the blood and lymphatic vessels.

The lymph that enters lymph capillaries in tissues is transported through the lymphatic vessel network to two large lymphatic ducts in the upper chest. From there, the lymph flows into two major veins (called subclavian veins) of the cardiovascular system. Unlike blood, lymph is not pumped through its network of vessels. Instead, lymph moves through lymphatic vessels via a combination of contractions of the vessels themselves and forces applied to the vessels externally by skeletal muscles. Lymphatic vessels also contain numerous valves that keep lymph flowing in just one direction, thereby preventing backflow.

## DIGESTIVE FUNCTION OF THE LYMPHATIC SYSTEM

Lymphatic vessels called lacteals (Figure **10.3.4**) are present in the lining of the gastrointestinal tract, mainly in the small intestine. Each tiny villus in the lining of the small intestine has an internal bed of capillaries and lacteals. The capillaries absorb most nutrients from the digestion of food into the blood. The lacteals absorb mainly fatty acids from lipid digestion into the lymph, forming a fatty-acid-enriched fluid called chyle. Vessels of the lymphatic network then transport chyle from the small intestine to the main lymphatic ducts in the chest from which it drains into the blood circulation. The nutrients in chyle then circulate in the blood to the liver, where they are processed along with the other nutrients that reach the liver directly via the bloodstream.

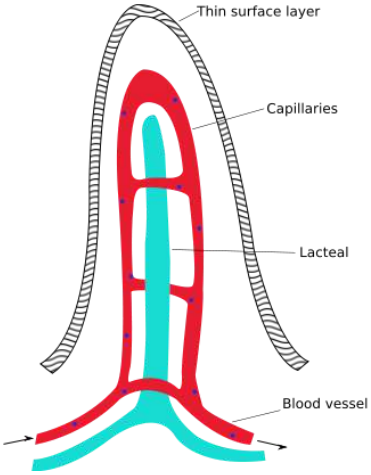



Figure **10.3.4**: Vessels called lacteals in the villi lining the small intestine are the main way that fatty acids from digestion are absorbed from the gastrointestinal tract. These nutrients eventually reach the blood circulation after traveling through the network of lymphatic vessels.

## IMMUNE FUNCTION OF THE LYMPHATIC SYSTEM

The primary function of the lymphatic system is host defense as part of the immune system. This function of the lymphatic system is centered on the production, maturation, and circulation of lymphocytes. **Lymphocytes** are leukocytes that are involved in the adaptive immune system. They are responsible for the recognition of, and tailored defense against, specific pathogens or tumor cells. Lymphocytes may also create a lasting memory of pathogens so they can be attacked quickly and strongly if they ever invade the body again. In this way, lymphocytes bring about long-lasting immunity to specific pathogens.

There are two major types of lymphocytes, called B cells and T cells, which are illustrated in Figure **10.3.5**. Both B cells and T cells are involved in the adaptive immune response, but they play different roles. You can learn more about their immune functions by reading the concept Adaptive Immune System.

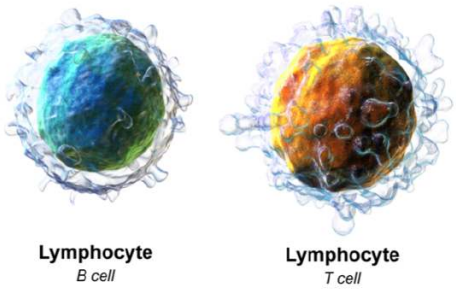



Figure **10.3.5**: Notice the large nucleus in the center of these relatively round cells.

## PRODUCTION AND MATURATION OF LYMPHOCYTES

Like all other types of blood cells, including red blood cells as well as leukocytes, both B cells and T cells are produced from stem cells in the red marrow inside bones. After lymphocytes first form, they must go through a complicated maturation process before they are ready to search for pathogens. In this maturation process, they "learn" to distinguish self from non-self. Only those lymphocytes that successfully complete this maturation process go on to actually fight infections by pathogens.

B cells mature in the bone marrow, which is why they are called B cells. After they mature and leave the bone marrow, they travel first to the circulatory system and then enter the lymphatic system to search for pathogens. T cells, on the other hand, mature in the thymus, which is why they are called T cells. The **thymus** is illustrated in Figure **10.3.6**. It is a small lymphatic organ in the chest that consists of an outer cortex and inner medulla, all surrounded by a fibrous capsule. After maturing in the thymus, T cells enter the rest of the lymphatic system to join B cells in the hunt for pathogens. The bone marrow and thymus are called primary lymphoid organs because of their role in the production and/or maturation of lymphocytes.

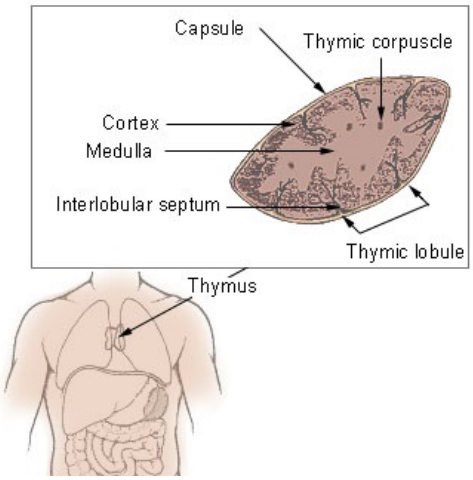



Figure **10.3.6**: The thymus (found in the chest) is an important organ of the lymphatic system because it is the location of T cell maturation.

## LYMPHOCYTES IN SECONDARY LYMPHOID ORGANS

The tonsils, spleen, and lymph nodes are referred to as secondary lymphoid organs. These organs do not produce or mature lymphocytes. Instead, they filter lymph and store lymphocytes. It is in these secondary lymphoid organs that pathogens (or their antigens) activate lymphocytes and initiate adaptive immune responses. Activation leads to the cloning of pathogen-specific lymphocytes, which then circulate between the lymphatic system and the blood, searching for and destroying their specific pathogens by producing antibodies against them.

### *TONSILS*

There are actually four pairs of human **tonsils.** Three of the four are shown in Figure 10.3.7. The fourth pair, called tubal tonsils, is located at the back of the nasopharynx. The palatine tonsils are the tonsils that are visible on either side of the throat. All four pairs of tonsils encircle a part of the anatomy where the respiratory and gastrointestinal tracts intersect and where pathogens have ready access to the body. This ring of tonsils is called **Waldeyer's ring**.

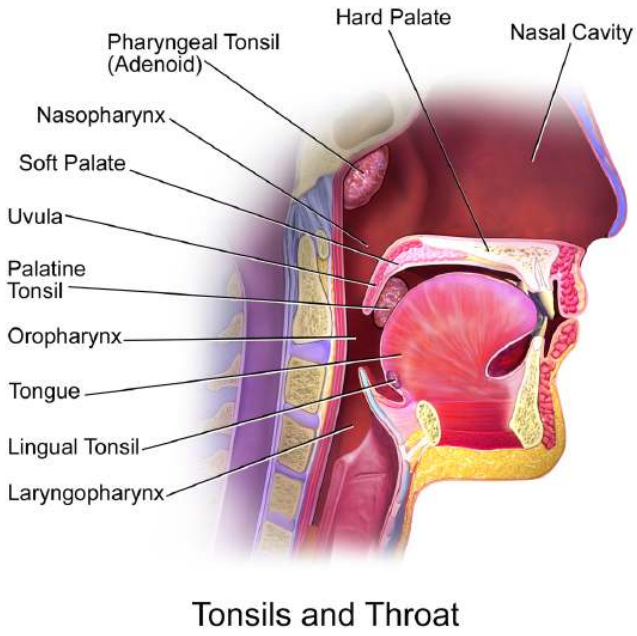



Figure **10.3.7**: Three of four pairs of human tonsils are shown in this figure. Lingual tonsils are below the tongue. Palatine tonsils are at the back of the mouth. Pharyngeal (adenoid) tonsils are in the back of the nasal cavity.

### *SPLEEN*

The spleen (Figure 10.3.8) is the largest of the secondary lymphoid organs and is centrally located in the body. Besides harboring lymphocytes and filtering lymph, the spleen also filters blood. Most dead or aged red blood cells are removed from the blood in the red pulp of the spleen. Lymph is filtered in the white pulp of the spleen. In the fetus, the spleen has the additional function of producing red blood cells. This function is taken over by bone marrow after birth.

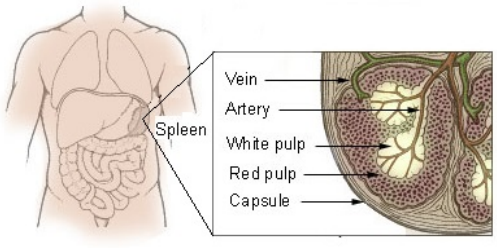



Figure **10.3.8**: The spleen (found behind the stomach) is a secondary lymphoid organ where pathogens are likely to encounter lymphocytes and trigger an adaptive immune response.

### *LYMPH NODES*

Each **lymph node** is a small but organized collection of lymphoid tissue (see green circular structures in Figure 10.3.1) that contains many lymphocytes. Lymph nodes are located at intervals along the lymphatic vessels, and lymph passes through them on their way back to the blood. There are at least 500 lymph nodes in the human body. Many of them are clustered at the base of the limbs and in the neck. Figure 10.3.9 shows the major lymph node concentrations. The figure includes the spleen and the region named Waldeyer's ring, consisting of the tonsils.

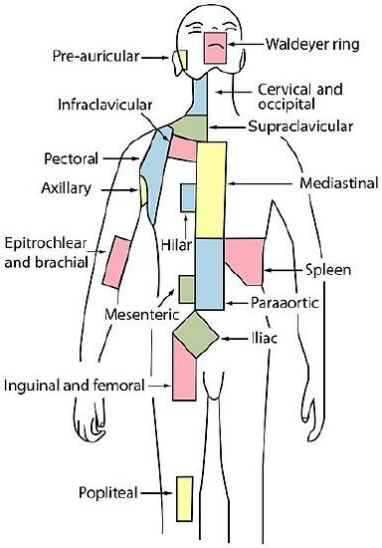



Figure **10.3.9**: In this diagram, lymph node regions are just shown for the left side of the body. The same regions are also found on the right side of the body.

### FEATURE: MYTH VS. REALITY

Lymph nodes near the surface of the body are obvious signs of immune system activity when they become enlarged and sometimes tender to the touch. Because it is easy to see and feel swollen lymph nodes, an individual can monitor his or her own health. It is important to be able to know the myths and realities of swollen lymph nodes.

**Myth:** You should see a doctor immediately whenever you have swollen lymph nodes.

**Reality:** Lymph nodes are constantly filtering lymph so it is expected that they will change in size with varying amounts of debris or pathogens that may be present. A minor, unnoticed infection may cause swollen lymph nodes that may last for a few weeks. Generally, lymph nodes that return to their normal size within three weeks are not a cause for concern.

**Myth:** Swollen lymph nodes mean you have a bacterial infection.

**Reality:** Although infection is the most common cause of swollen lymph nodes, not all infections are caused by bacteria. For example, mononucleosis commonly causes swollen lymph nodes, and it is caused by viruses. There are also other causes of swollen lymph nodes besides infections, such as cancer and certain medications.

**Myth:** A swollen lymph node means you have cancer.

**Reality:** Cancer is far less likely to be the cause of a swollen lymph node than is an infection.

**Myth:** Cancer in a lymph node always originates somewhere else. There is no cancer of the lymph nodes.

**Reality:** Cancers do commonly spread from their site of origin to nearby lymph nodes and then to other organs, but cancer may also originate in the lymph nodes. This type of cancer is called lymphoma.

## REVIEW

1. What is the lymphatic system?
2. Describe the composition of lymph.
3. Outline the cardiovascular function of the lymphatic system.
4. Describe the role of the lymphatic system in the absorption of nutrients from the digestive system.
5. Summarize the function of the lymphatic system in host defense.
6. Name primary lymphatic organs and their functions.
7. What are the secondary lymphatic organs? State their functions in the adaptive immune system.
8. How is interstitial fluid related to lymph?
9. B and T cells are types of:
   A. Leukocytes
   B. Lymphocytes
   C. White blood cells
   D. All of the above
10. For each of the following statements, indicate whether it applies to B cells, T cells, or both.
    A. These cells are born in the red bone marrow.
    B. These cells are part of the adaptive immune system.
    C. These cells mature in the bone marrow.
11. Explain the difference between lymphocyte maturation and lymphocyte activation.
12. *True or False*. The spleen produces lymphocytes.
13. *True or False*. Tonsils are glands that produce lymph.

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## ATTRIBUTIONS


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# 10.4: INNATE IMMUNE SYSTEM

**PAPER CUT**

It's just a paper cut, but the break in your skin could provide an easy way for pathogens to enter your body. If bacteria were to enter through the cut and infect the wound, your innate immune system would quickly respond with a dizzying array of general defenses.



Figure **10.4.1**: Papercut

The **innate immune system** is a subset of the human immune system that produces rapid but non-specific responses to pathogens. Innate responses are generic rather than tailored to a particular pathogen. Every pathogen that is encountered is responded to in the same general ways by the innate system. Although the innate immune system provides immediate and rapid defenses against pathogens, it does not confer long-lasting immunity to them. In most organisms, the innate immune system is the dominant system of host defense. Other than most vertebrates including humans, the innate immune system is the only system of host defense.

In humans, the innate immune system includes surface barriers, inflammation, the complement system, and a variety of cellular responses. Surface barriers of various types generally keep most pathogens out of the body. If these barriers fail, then other innate defenses are triggered. The triggering event is usually the identification of pathogens by pattern-recognition receptors on cells of the innate immune system. These receptors recognize molecules that are broadly shared by pathogens but distinguishable from host molecules. Alternatively, the other innate defenses may be triggered when damaged, injured, or stressed cells send out alarm signals, many of which are recognized by the same receptors as those that recognize pathogens.

## BARRIERS TO PATHOGENS

The body's first line of defense consists of three different types of barriers that keep most pathogens out of body tissues. The types of barriers are mechanical, chemical, and biological barriers.

### MECHANICAL BARRIERS

Mechanical barriers are the first line of defense against pathogens, and they physically block pathogens from entering the body. The skin is the most important mechanical barrier. In fact, it is the single most important defense the body has. The outer layer of skin, the epidermis, is tough and very difficult for pathogens to penetrate. It consists of dead cells that are constantly being shed from the body surface. This helps remove bacteria and other infectious agents that have adhered to the skin. The epidermis also lacks blood vessels and is usually lacking moisture, so it does not provide a suitable environment for most pathogens. Hair, which is an accessory organ of the skin, also helps to keep out pathogens. Hairs inside the nose may trap larger pathogens and other particles in the air before they can enter the airways of the respiratory system.

Mucous membranes provide a mechanical barrier to pathogens and other particles at body openings. These membranes also line the respiratory, gastrointestinal, urinary, and reproductive tracts. Mucous membranes secrete mucus, which is a slimy and somewhat sticky substance that traps pathogens. Many mucous membranes also have hair-like cilia that sweep mucus and trapped pathogens toward body openings where they can be removed from the body. When you sneeze or cough, mucus, and pathogens are mechanically ejected from the nose and throat, as you can see in the photo below. Other mechanical defenses include tears, which wash pathogens from the eyes, and urine, which flushes pathogens out of the urinary tract.



Figure **10.4.2**: A sneeze can expel many pathogens from the respiratory tract. That's why you should always cover your mouth and nose and when you sneeze.

### CHEMICAL BARRIERS

Chemical barriers also protect against infection by pathogens. They destroy pathogens on the outer body surface, at body openings, and on inner body linings. Sweat, mucus, tears, saliva, and breastmilk all contain antimicrobial substances, such as the enzyme lysozyme, that kill pathogens, especially bacteria. Sebaceous glands in the dermis of the skin secrete acids that form a very fine, slightly acidic film on the surface of the skin that acts as a barrier to bacteria, viruses, and other potential contaminants that might penetrate the skin. Urine and vaginal secretions are also too acidic for many pathogens to endure. Semen contains zinc, which most pathogens cannot tolerate, as well as defensins, which are antimicrobial proteins that act mainly by disrupting bacterial cell membranes. In the stomach, stomach acid and digestive enzymes called proteases, which break down proteins, kill most pathogens that enter the gastrointestinal tract in food or water.

### BIOLOGICAL BARRIERS

Biological barriers are living organisms that help protect the body from pathogens. Trillions of harmless bacteria normally live on the human skin and in the urinary, reproductive, and gastrointestinal tracts. These bacteria use up food and surface space that help prevent pathogenic bacteria from colonizing the body. Some of these harmless bacteria also secrete substances that change the conditions

of their environment, making it less hospitable to potentially harmful bacteria. For example, they may release toxins or change the pH. All of these effects of harmless bacteria reduce the chances that pathogenic microorganisms will be able to reach sufficient numbers to cause illness.

## INFLAMMATION

If pathogens manage to breach the barriers protecting the body, then one of the first active responses of the innate immune system kicks in. This response is **inflammation.** The main function of inflammation is to establish a physical barrier against the spread of infection. It also eliminates the initial cause of cell injury, clears out dead cells and tissues damaged from the original insult and the inflammatory process, and initiates tissue repair. Inflammation is often a response to infection by pathogens, but there are other possible causes, including burns, frostbite, and exposure to toxins.

The signs and symptoms of inflammation include redness, swelling, warmth, pain, and frequently some loss of function. These symptoms are caused by increased blood flow into infected tissue and a number of other processes, illustrated in Figure **10.4.3** and described below in the text.

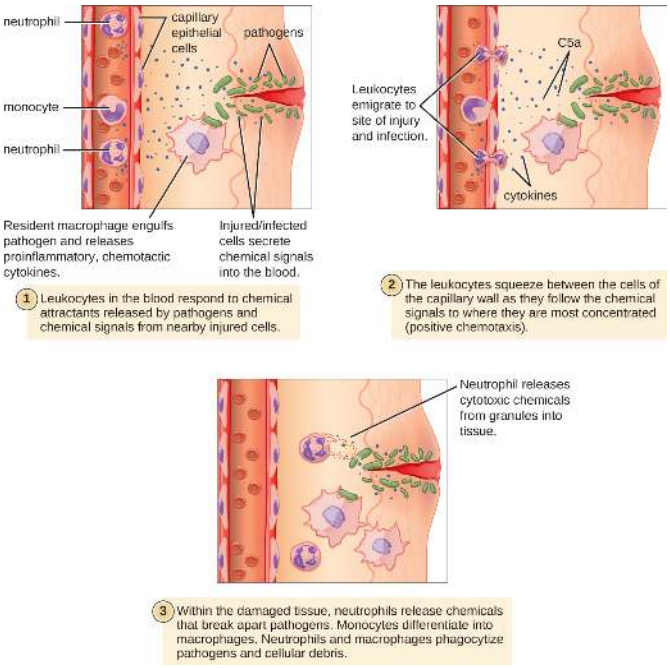



Figure **10.4.3**: This drawing shows what happens during the inflammatory response.

Inflammation is triggered by chemicals such as **cytokines** and **histamines,** which are released by injured or infected cells or by immune system cells such as macrophages (described in Figure **10.4.5**) that are already present in tissues. These chemicals cause capillaries to dilate and become leaky, increasing blood flow to the infected area and allowing blood to enter the tissues. Pathogen-destroying leukocytes, complement proteins, and tissue-repairing proteins migrate into tissue spaces from the bloodstream to attack pathogens and repair their damage. Cytokines also promote chemotaxis, which is migration to the site of infection by leukocytes that destroy pathogens. Some cytokines have anti-viral, antifungal, and antibacterial effects, such as shutting down protein synthesis in host cells, which viruses need in order to survive and replicate.

## COMPLEMENT SYSTEM

The **complement system** is a complex biochemical mechanism named for its ability to "complement" the killing of pathogens directly by creating holes in the body of the pathogen and by assisting antibodies. Antibodies are produced as part of an adaptive immune response. The complement system consists of more than two dozen proteins that are normally found in the blood and synthesized in the liver. The proteins usually circulate as non-functional precursor molecules until activated.

## CELLULAR RESPONSES

Cellular responses of the innate immune system involve a variety of different types of leukocytes. Many of these leukocytes circulate in the blood and act like independent, single-celled organisms, searching out and destroying pathogens in the human host. These and other immune cells of the innate system identify pathogens or debris and then help to eliminate them in some way. One way is phagocytosis.

### PHAGOCYTOSIS

Phagocytosis is an important feature of innate immunity that is performed by cells classified as phagocytes. In the process of phagocytosis, phagocytes engulf and digest pathogens or other harmful particles. Phagocytes generally patrol the body searching for pathogens, but they can also be called to specific locations by the release of cytokines when inflammation occurs. Some phagocytes reside permanently in certain tissues.

As shown in Figure **10.4.4**, when a pathogen such as a bacterium is encountered by a phagocyte, the phagocyte extends a portion of its plasma membrane, wrapping the membrane around the pathogen until it is enveloped. Once inside the phagocyte, the pathogen becomes enclosed within an intracellular vesicle called a phagosome. The phagosome then fuses with another vesicle called a lysosome, forming a phagolysosome. Digestive enzymes and acids from the lysosome kill and digest the pathogen in the phagolysosome. The final step of phagocytosis is the excretion of soluble debris from the destroyed pathogen through exocytosis.

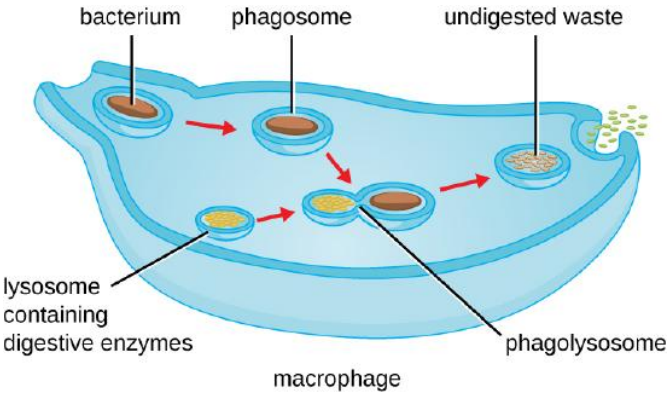



Figure **10.4.4**: Phagocytosis is a multi-step process in which a pathogen is engulfed and digested by immune cells called phagocytes.

## LEUKOCYTES

Types of leukocytes that kill pathogens by phagocytosis include neutrophils, macrophages, and dendritic cells. Macrophages and dendritic cells are the derivatives of monocytes. Figure **10.4.5** shows five major types of leukocytes, lymphocytes, basophils, eosinophils, neutrophils, and monocytes. Because lymphocytes are mainly involved in the adaptive immune system, they are not discussed in this concept.

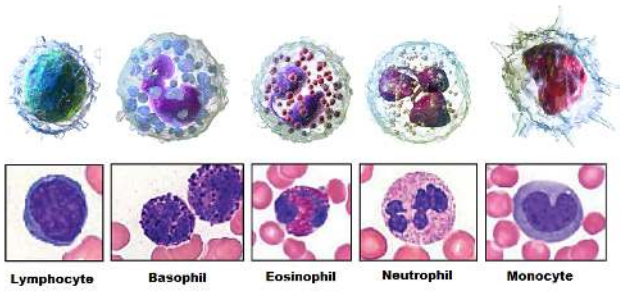



Figure **10.4.5**: Five types of leukocytes: from left to right, lymphocyte, basophil, eosinophil, neutrophil, and monocytes.

### NEUTROPHILS

Neutrophils are leukocytes that travel throughout the body in the blood and are usually the first immune cells to arrive at the site of an infection. As shown in Figure **10.4.5**, these cells contain granules and carry a multilobed nucleus. They are the most numerous types of phagocytes and normally make up at least half of the total circulating leukocytes. The bone marrow of a normal healthy adult produces more than 100 billion neutrophils per day. During acute inflammation, more than 10 times that many neutrophils may be produced each day. Many neutrophils are needed to fight infections because after a neutrophil phagocytizes just a few pathogens, it generally dies.

### MACROPHAGES

Macrophages are large phagocytic leukocytes that develop from monocytes. Macrophages spend much of their time within the interstitial fluid in tissues of the body. As shown in Figure **10.4.5**, monocytes do not contain granules and carry a big kidney-shaped nucleus. They are the most efficient phagocytes and can phagocytize a substantial number of pathogens or other cells. Macrophages are also versatile cells that produce a wide array of chemicals — including enzymes, complement proteins, and cytokines — in addition to their phagocytic action. As phagocytes, macrophages act as scavengers that rid tissues of worn-out cells and other debris as well as pathogens. In addition, macrophages act as antigen-presenting cells that activate the adaptive immune system. (To learn more about antigen-presenting cells, see the concept Adaptive Immune System.)

### EOSINOPHILS

Eosinophils are non-phagocytic leukocytes that are related to neutrophils. They specialize in defending against parasites. As shown in Figure **10.4.5**, these cells contain granules and carry a bilobed earmuff-shaped nucleus. These leukocytes are very effective in killing large parasites such as worms by secreting a range of highly toxic substances when activated. Eosinophils may become overactive and cause allergies or asthma.

### BASOPHILS

Basophils are non-phagocytic leukocytes that are also related to neutrophils. They are the least numerous of all white blood cells. As shown in Figure **10.4.5**, these cells contain granules and carry a bilobed nucleus. Basophils secrete two types of chemicals that aid in body defenses: histamines and heparin. Histamines are responsible for dilating blood vessels and increasing their permeability in inflammation. Heparin inhibits blood clotting and also promotes the movement of leukocytes into an area of infection.

### DENDRITIC CELLS

Like macrophages, dendritic cells develop from monocytes (see Figure **10.4.6**. They reside in tissues that have contact with the external environment, so they are located mainly in the skin, nose, lungs, stomach, and intestines. Their plasma membrane has extensions. Besides engulfing and digesting pathogens, dendritic cells also act as antigen-presenting cells that trigger adaptive immune responses.

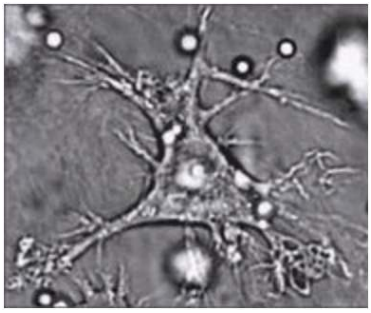


Figure **10.4.6**: dendritic cell

### MAST CELLS

Mast cells are non-phagocytic leukocytes that help to initiate inflammation by secreting histamines. In some people, histamines trigger allergic reactions as well as inflammation. Mast cells may also secrete chemicals that help defend against parasites.

### NATURAL KILLER CELLS

Natural killer cells are in the subset of leukocytes called lymphocytes, which are produced by the lymphatic system. Natural killer cells destroy cancerous or virus-infected host cells, although they do not directly attack invading pathogens. Natural killer cells recognize these host cells by a condition they exhibit called “missing self.” Cells with missing self have abnormally low levels of cell-surface proteins of the major histocompatibility complex (MHC), which normally identify body cells as self.

## REVIEW

1. What is the innate immune system?
2. Identify the body’s first line of defense.
3. Define and give examples of mechanical and chemical barriers of the innate immune system.
4. What are biological barriers, and how do they protect the body?
5. State the purposes of inflammation.
6. What triggers inflammation, and what signs and symptoms does it cause?
7. Define the complement system. How does it help destroy pathogens?
8. List six different types of leukocytes and state their roles in innate immune responses.
9. Describe two ways that pathogens may evade the innate immune system.
10. Explain how mucus can contribute to the immune system as both a mechanical barrier and a chemical barrier.
11. Which type of immune system cell can both phagocytize pathogens and produce chemicals that promote inflammation?

    A. Macrophages

    B. Natural killer cells

    C. Basophils

    D. Mast cells
12. What are the ways in which phagocytes can encounter pathogens in the body?
13. Describe different two ways in which enzymes play a role in the innate immune response.
14. *True or False.* Complement proteins can be produced by macrophages.
15. *True or False.* The main function of inflammation is to secrete repair proteins at the site of damage.

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# 10.5: ADAPTIVE IMMUNE SYSTEM

## THE KISS OF DEATH

The photomicrograph in Figure **10.5.1** shows a group of killer T cells (green and red) surrounding a cancer cell (blue, center). When a killer T cell makes contact with the cancer cell, it attaches to and spreads over the dangerous target. The killer T cell then uses special chemicals stored in vesicles (red) to deliver the killing blow. This event has thus been nicknamed "the kiss of death." After the target cell is killed, the killer T cells move on to find the next victim. Killer T cells like these are important players in the adaptive immune system.

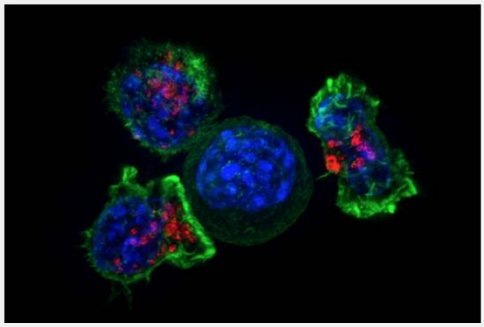


Figure **10.5.1**: Three Killer T cells surrounding Cancer Cells

The **adaptive immune system** (also called **specific immunity**) is a subsystem of the overall immune system. It is composed of highly specialized cells and processes that eliminate specific pathogens and tumor cells. An adaptive immune response is set in motion by antigens that the immune system recognizes as foreign. Unlike an innate immune response, an adaptive immune response is highly specific to a particular pathogen (or its antigen). An important function of the adaptive immune system that is not shared by the innate immune system is the creation of immunological memory or immunity. This occurs after the initial response to a specific pathogen. It allows a faster, stronger response on subsequent encounters with the same pathogen, usually before the pathogen can cause symptoms of illness.

Lymphocytes are the main cells of the adaptive immune system. They are leukocytes that arise and mature in organs of the lymphatic system, including the bone marrow and thymus. The human body normally has about 2 trillion lymphocytes, which constitute about a third of all leukocytes. Most of the lymphocytes are normally sequestered within tissue fluid or organs of the lymphatic system, including the tonsils, spleen, and lymph nodes. Only about 2 percent of the lymphocytes are normally circulating in the blood. There are two main types of lymphocytes involved in adaptive immune responses, called T cells and B cells. T cells destroy infected cells or release chemicals that regulate immune responses. B cells secrete antibodies that bind with antigens of pathogens so they can be removed by other immune cells or processes.

## T CELLS

There are multiple types of **T cells** or T lymphocytes. Major types are killer (or cytotoxic) T cells and helper T cells. Both types develop from immature T cells that become activated by exposure to an antigen.

### T CELL ACTIVATION

T cells must be activated. After the pathogen is phagocytized and digested by macrophages, a part of the pathogen is displayed on the surface of the macrophage. The proteins that display the antigen (part of the pathogen) are called Major Histocompatibility Complex (MHC). There are two types of MHC, MHCI and MHCII. Therefore macrophages are called antigen-presenting cells as shown in Figure **10.5.2** and Figure **10.5.3**. B lymphocytes can also act as antigen-presenting cells. Helper T cells are more easily activated than killer T cells. Activation of killer T cells is strongly regulated and may require additional stimulation from helper T cells.

### HELPER T CELLS

Activated helper T cells do not kill infected or cancerous cells. Instead, their role is to "manage" both innate and adaptive immune responses by directing other cells to perform these tasks. They control other cells by releasing cytokines. These are proteins that can influence the activity of many cell types, including cytotoxic killer T cells (sometimes referred to as only killer T cells), B cells, and macrophages. For example, some cytokines released by helper T cells help activate killer T cells.

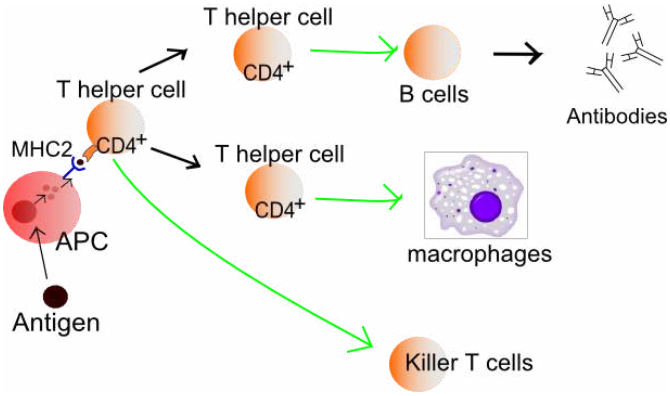



Figure **10.5.2**: After getting activated by an antigen-presenting cell, helper T cells trigger various other cells of the immune system, such as activation of B cells to produce antibodies, recruitment and activation of macrophages, and activation of cytotoxic killer T cells. In this image, APC stands for antigen-presenting cells and $CD4^+$ stands for Cluster Differentiation glycoprotein which is present on the surface of helper T cells.

### KILLER T CELLS (CYTOTOXIC T CELLS)

When infected body cells present pathogen antigen to a killer T cell, it gets activated (see lower panel of Figure **10.5.3**). Activated killer T cells induce the death of cells that bear a specific non-self antigen because they are infected with pathogens or are cancerous. The antigen targets the cell for destruction by killer T cells, which travel

through the bloodstream searching for target cells to kill. Killer T cells may use various mechanisms to kill target cells. One way is by releasing toxins in granules that enter and kill infected or cancerous cells (Figure 10.5.3).

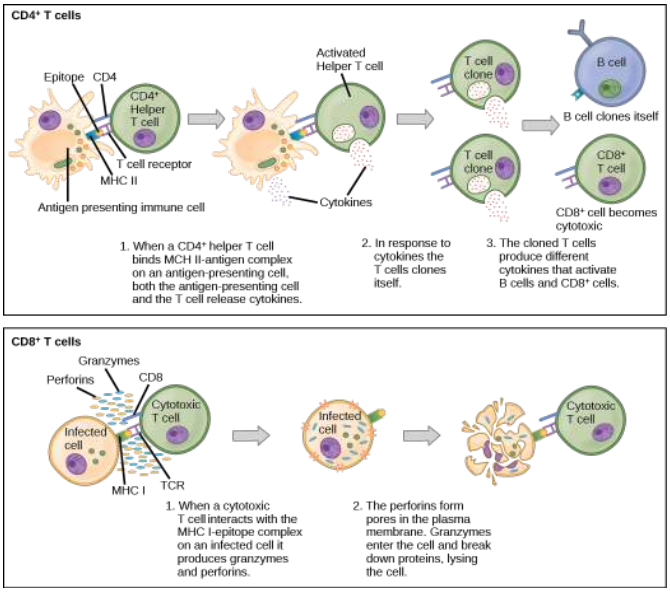



Figure 10.5.3: Naïve CD4+ (Helper) T cells engage MHC II molecules on antigen-presenting cells (APCs) and become activated. Clones of the activated helper T cell, in turn, activate B cells and CD8+ T (killer) cells, which become cytotoxic T cells. Cytotoxic T cells kill infected cells.

## B CELLS AND B CELL ACTIVATION

**B cells**, or B lymphocytes, are the major cells involved in the creation of antibodies that circulate in blood plasma and lymph. Antibodies are large, Y-shaped proteins used by the immune system to identify and neutralize foreign invaders. Besides producing antibodies, B cells may also function as antigen-presenting cells or secrete cytokines that help control other immune cells and responses.

Before B cells can actively function to defend the host, they must be activated. As shown in Figure 10.5.4, B cell activation begins when a B cell engulfs and digests an antigen. The antigen may be either free-floating or on top of the pathogen. B cell internalize antigen and present it on its MHC to a helper T cell. The T cell activates and secretes cytokines that help the B cell to multiply and the daughter cells to mature into plasma cells and memory B cells. Plasma B cells produce antibodies.

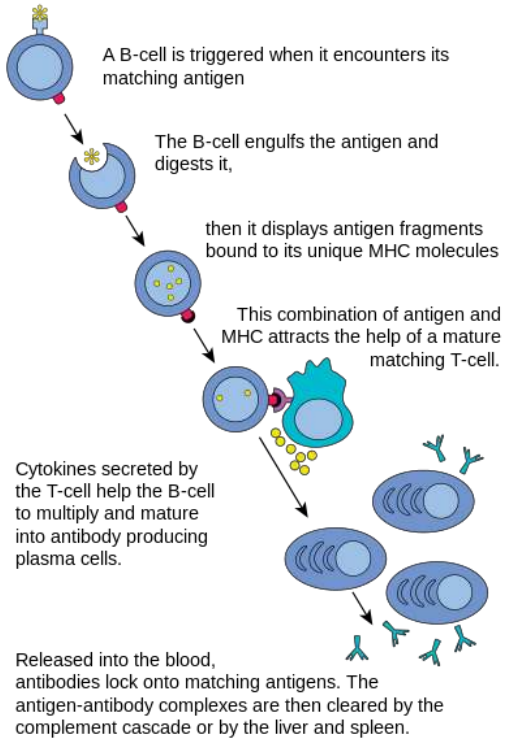



Figure 10.5.4: B cells are activated and become antibody-producing plasma cells with the help of helper T cells.

## PLASMA CELLS

Plasma cells are antibody-secreting cells that form from activated B cells. Each plasma cell is like a tiny antibody factory. It may secrete millions of copies of an antibody, each of which can bind to the specific antigen that activated the original B cell. The specificity of an antibody to a specific antigen is illustrated in Figure 10.5.5. When antibodies bind with antigens, it makes the cells bearing them easier targets for phagocytes to find and destroy. Antibody-antigen complexes may also trigger the complement system of the innate immune system, which destroys the cells in a cascade of protein enzymes. In addition, the complexes are likely to clump together (agglutinate). If this occurs, they are filtered out of the blood in the spleen or liver.

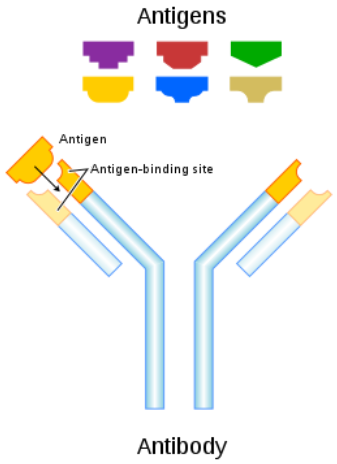



Figure **10.5.5**: Each antibody fits its antigen like a lock fits a key.

## IMMUNITY

Most activated T cells and B cells die within a few days once a pathogen has been cleared from the body. However, a few of the cells survive and remain in the body as memory T cells or memory B cells. These memory cells are ready to activate an immediate response if they are exposed to the same antigen again in the future. This is the basis of **immunity.**

The earliest known reference to the concept of immunity relates to the bubonic plague (see Figure **10.5.6**). In 430 B.C., a Greek historian and general named Thucydides noted that people who had recovered from a previous bout of the plague could nurse people sick with the plague without contracting the illness a second time. We now know that this is true of many diseases and it occurs because of active immunity.



Figure **10.5.6**: Dead, blackened tissues at the fingertips and other extremities are a sign of the bubonic plague, giving rise to its other name, the black death.

## ACTIVE IMMUNITY

**Active immunity** is the ability of the adaptive immune system to resist a specific pathogen because it has formed an immunological memory of the pathogen. Active immunity is adaptive because it occurs during the lifetime of an individual as an adaptation to infection with a specific pathogen and prepares the immune system for future challenges from that pathogen. Active immunity can come about naturally or artificially.

### *NATURALLY ACQUIRED ACTIVE IMMUNITY*

Active immunity is acquired naturally when a pathogen invades the body and activates the adaptive immune system. When the initial infection is over, memory B cells and memory T cells remain that provide immunological memory of the pathogen. As long as the memory cells are alive, the immune system is ready to mount an immediate response if the same pathogen tries to infect the body again.

### *ARTIFICIALLY ACQUIRED ACTIVE IMMUNITY*

Active immunity can also be acquired artificially through immunization. **Immunization** is the deliberate exposure of a person to a pathogen in order to provoke an adaptive immune response and the formation of memory cells specific to that pathogen. The pathogen is introduced in a vaccine — usually by injection, sometimes by nose or mouth (Figure **10.5.7**) — so immunization is also called vaccination.



Figure **10.5.7**: This young child is receiving an oral polio vaccine.

In a **vaccine,** only part of a pathogen, a weakened form of the pathogen, or a dead pathogen is typically used. This causes an adaptive immune response without making the immunized person sick. This is how you most likely became immune to diseases such as measles, mumps, and chickenpox. Immunizations may last for a lifetime or require periodic booster shots to maintain immunity. While immunization generally has long-lasting effects, it usually takes several weeks to develop full immunity.

Immunization is the most effective method ever discovered in preventing infectious diseases. As many as 3 million deaths are prevented each year because of vaccinations. Widespread immunity due to vaccinations is largely responsible for the worldwide eradication of smallpox and the near elimination of several other infectious diseases from many populations, including such diseases as polio and measles. Immunization is so successful because it exploits the natural specificity and inducibility of the adaptive immune system.

## PASSIVE IMMUNITY

**Passive immunity** results when pathogen-specific antibodies or activated T cells are transferred to a person who has never been exposed to the pathogen. Passive immunity provides immediate protection from a pathogen, but the adaptive immune system does not develop immunological memory to protect the host from the same pathogen in the future. Unlike active immunity, passive immunity lasts only as long as the transferred antibodies or T cells survive in the blood. This is usually between a few days and a few

months. However, like active immunity, passive immunity can be acquired both naturally and artificially.

#### NATURALLY ACQUIRED PASSIVE IMMUNITY

Passive immunity is acquired naturally by a fetus through its mother's blood. Antibodies are transported from mother to fetus across the placenta, so babies have high levels of antibodies at birth. Their antibodies have the same range of antigen specificity as their mother's. Passive immunity may also be acquired by an infant through the mother's breast milk. This gives young infants protection from common pathogens in their environment while their own immune system matures.

#### ARTIFICIALLY ACQUIRED PASSIVE IMMUNITY

Older children and adults can acquire passive immunity artificially through the injection of antibodies or activated T cells. This may be done when there is a high risk of infection and insufficient time for the body to develop active immunity through vaccination. It may also be done to reduce symptoms of ongoing disease or to compensate for immunodeficiency diseases (for the latter, see the concept Disorders of the Immune System).

## ADAPTIVE IMMUNE EVASION

Many pathogens have been around for a long time, living with human populations for generations. To persist, some have evolved mechanisms to evade the adaptive immune system of human hosts. One way they have done this is by rapidly changing their non-essential antigens. This is called antigenic variation. An example of a pathogen that takes this approach is the human immunodeficiency virus (HIV). It mutates rapidly so the proteins on its viral envelope are constantly changing. By the time the adaptive immune system responds, the virus's antigens have changed. Antigenic variation is the main reason that efforts to develop a vaccine against HIV have not yet been successful.

Another evasion approach some pathogens may take is to mask pathogen antigens with host molecules so the host's immune system cannot detect the antigens. HIV takes this approach as well. The envelope that covers the virus is formed from the outermost membrane of the host cell.

### FEATURE: MY HUMAN BODY

If you think that immunizations are just for kids, think again. There are several vaccines recommended by the CDC for people over the age of 18. This link shows the vaccine schedule recommended for all adults aged 19 years and older. Additional vaccines may be recommended for certain adults based on specific medical conditions or other indications. Are you up to date with your vaccines? You can check with your doctor to be sure.

## REVIEW

1. What is the adaptive immune system?
2. Describe the main cells of the adaptive immune system.
3. How are lymphocytes activated?
4. Identify two common types of T cells and their functions.
5. How do activated B cells help defend against pathogens?
6. Define immunity.
7. What are two ways active immunity may come about?
8. How does passive immunity differ from active immunity?
9. How may passive immunity occur?
10. What ways of evading the human adaptive immune system evolved in the human immunodeficiency virus (HIV)?
11. Describe two ways in which B cells and T cells work together to generate adaptive immune responses.
12. Which cells directly kill pathogen-infected or cancerous cells?
    A. A. Plasma cells
    B. B. Killer T cells
    C. C. Helper T cells
    D. D. All of the above
13. Why do vaccinations involve the exposure of a person to a version of a pathogen?
14. *True or False.* Immunization is a form of passive immunity.
15. *True or False.* Antibodies transmitted from mother to child via breast milk cause the formation of memory B cells and long-term immunity.

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# 10.6: DISORDERS OF THE IMMUNE SYSTEM

## ALLERGY EYES

Eyes that are red, watery, and itchy are typical of an allergic reaction known as allergic rhinitis. Commonly called hay fever, allergic rhinitis is an immune system reaction typically to the pollen of certain plants. Your immune system usually protects you from pathogens and keeps you well. However, like any other body system, the immune system itself can develop problems. Sometimes it responds to harmless foreign substances as though they were pathogens. That's the basis of allergies such as hay fever.



Figure **10.6.1**: Oedema of the conjunctiva due to hay fever allergy

## ALLERGIES

An **allergy** is a disorder in which the immune system makes an inflammatory response to a harmless antigen. It occurs when the immune system is hypersensitive to an antigen in the environment that causes little or no response in most people. Allergies are strongly familial: allergic parents are more likely to have allergic children and those children's allergies are likely to be more severe. This is evidence that there is a heritable tendency to develop allergies. Allergies are more common in children than adults because many children outgrow their allergies by adulthood.

### ALLERGENS



Figure **10.6.2**: Common causes of allergies include pollen and poison ivy

Any antigen that causes an allergy is called an **allergen.** Common allergens are plant pollens, dust mites, mold, specific foods (such as peanuts or shellfish), insect stings, and certain common medications (such as aspirin and penicillin). Allergens may be inhaled or ingested, or they may come into contact with the skin or eyes. Symptoms vary depending on the type of exposure and the severity of the immune system response. Two common causes of allergies are ragweed and poison ivy. Inhaling ragweed pollen may cause symptoms of allergic rhinitis, such as sneezing and red itchy eyes. Skin contact with oils in poison ivy may cause an itchy rash. This type of allergy is called contact dermatitis.

### PREVALENCE OF ALLERGIES

There has been a significant increase in the prevalence of allergies over the past several decades, especially in the rich nations of the world, where allergies are now very common disorders. In the developed countries, about 20 percent of people have or have had hay fever, another 20 percent have had contact dermatitis, and about 6 percent have food allergies. In the poorer nations of the world, on the other hand, allergies of all types are much less common.

One explanation for the rise in allergies in the developed world is called the hygiene hypothesis. According to this hypothesis, people in developed countries live in relatively sterile environments because of hygienic practices and sanitation systems. As a result, people in these countries are exposed to fewer pathogens than their immune system evolved to cope with. To compensate, their immune system "keeps busy" by attacking harmless antigens in allergic responses.

### HOW ALLERGIES OCCUR

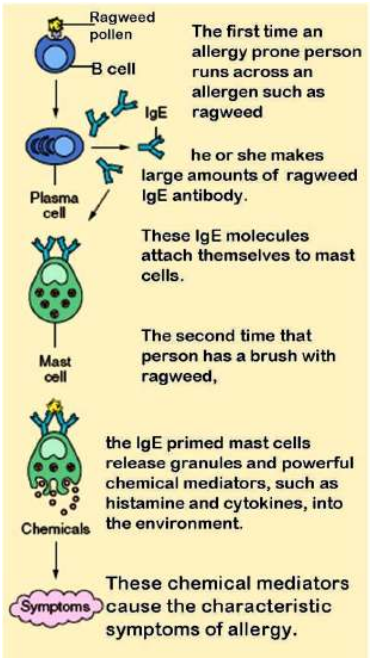



Figure **10.6.3**: This diagram shows how the adaptive immune system is activated by an otherwise harmless antigen on ragweed pollen, responding to the allergen as though it was a pathogen.

The diagram in Figure **10.6.3** shows how an allergic reaction occurs. At the first exposure to an allergen, B cells are activated to form plasma cells that produce large amounts of antibodies to the allergen. These antibodies attach to leukocytes called mast cells. Subsequently, every time the person encounters the allergen again,

the mast cells are already primed and ready to deal with it. The primed mast cells immediately release cytokines and histamines, which in turn cause inflammation and recruitment of leukocytes, among other responses. These responses are responsible for the signs and symptoms of allergies.

## TREATING ALLERGIES

The symptoms of allergies can range from mild to life-threatening. Mild allergy symptoms are often treated with antihistamines. These are drugs that reduce or eliminate the effects of the histamines that produce allergy symptoms.

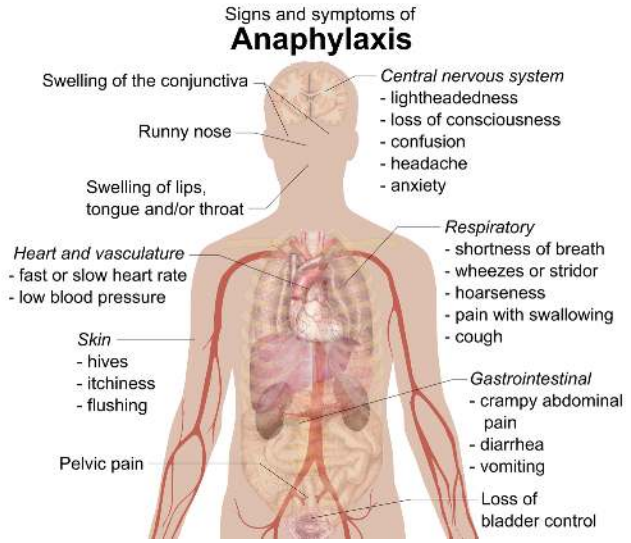



Figure **10.6.4**: Anaphylaxis is a rapid, systemic reaction to allergens that may lead to life-threatening symptoms.

### *TREATING ANAPHYLAXIS*

The most severe allergic reaction is a systemic reaction called **anaphylaxis.** This is a life-threatening response caused by a massive release of histamines. Many of the signs and symptoms of anaphylaxis are shown in Figure **10.6.4**. Some of them include a drop in blood pressure, changes in heart rate, shortness of breath, and swelling of the tongue and throat, which may threaten the patient with suffocation unless emergency treatment is given. People who have had anaphylactic reactions may carry an epinephrine autoinjector (widely known by its brand name EpiPen®) so they can inject themselves with epinephrine if they start to experience an anaphylactic response. The epinephrine helps to control the immune reaction until medical care can be provided. Epinephrine constricts blood vessels to increase blood pressure, relaxes smooth muscles in the lungs to reduce wheezing and improve breathing, modulates heart rate, and works to reduce swelling that may otherwise block the airways.

### *IMMUNOTHERAPY FOR ALLERGIES*

Another way to treat allergies is called **immunotherapy,** commonly called "allergy shots." This approach may actually cure specific allergies, at least for several years if not lifelong. It may be particularly beneficial for allergens such as pollen that are difficult or impossible to avoid. First, however, patients must be tested to identify the specific allergens that are causing their allergies. As shown in Figure **10.6.5**, this may involve scratching tiny amounts of common allergens into the skin and then observing whether there is a localized reaction to any of them. Each allergen is applied in a different numbered location on the skin so if there is a reaction, such as redness or swelling, the responsible allergens can be identified. Then, through periodic injections (usually weekly or monthly), patients are gradually exposed to larger and larger amounts of the allergens. Over time, generally from months to years, the immune system becomes desensitized to the allergens. This method of treating allergies is often effective for allergies to pollen or insect stings, but its usefulness for allergies to food is unclear.



Figure **10.6.5**: Skin testing for common allergens is one way to identify the cause(s) of a patient's allergic symptoms.

## AUTOIMMUNE DISEASES

**Autoimmune diseases** occur when the immune system fails to recognize the body's own molecules as self. As a result, instead of ignoring the body's healthy cells, it attacks them, causing damage to tissues and altered organ growth and function. Most often, it is B cells that are at fault in autoimmune responses. They are generally the cells that lose tolerance for self. Why does this occur? Some autoimmune diseases are thought to be caused by exposure to pathogens that have antigens similar to the body's own molecules. After this exposure, the immune system responds to body cells as though they were pathogens as well.

Certain individuals are genetically susceptible to developing autoimmune diseases. These individuals are also more likely to develop more than one such disease. Gender is also a risk factor for autoimmunity. Females are much more likely than males to develop autoimmune diseases, probably in part because of gender differences in sex hormones.

At a population level, autoimmune diseases are less common where infectious diseases are more common. The hygiene hypothesis has been proposed to explain the inverse relationship between infectious and autoimmune diseases as well as the prevalence of allergies. According to the hypothesis, without infectious diseases to "keep it busy," the immune system may attack the body's own cells instead.

### COMMON AUTOIMMUNE DISEASES

An estimated 15 million or more people worldwide have one or more autoimmune diseases. Two of the most common autoimmune diseases are type I diabetes and multiple sclerosis. Both are localized diseases in terms of the specific body cells that are attacked by the immune system. In the case of type I diabetes, the immune system

attacks and destroys insulin-secreting islet cells in the pancreas. In the case of multiple sclerosis, the immune system attacks and destroys the myelin sheaths that normally insulate the axons of neurons and allow rapid transmission of nerve impulses.

Some relatively common autoimmune diseases are systemic, or body-wide, diseases. They include rheumatoid arthritis and systemic lupus erythematosus (SLE). In these diseases, many tissues and organs may be attacked and injured by the immune system. For example, as you can see in Figure **10.6.6**, symptoms of SLE may involve the muscular, skeletal, integumentary, respiratory, and cardiovascular systems.

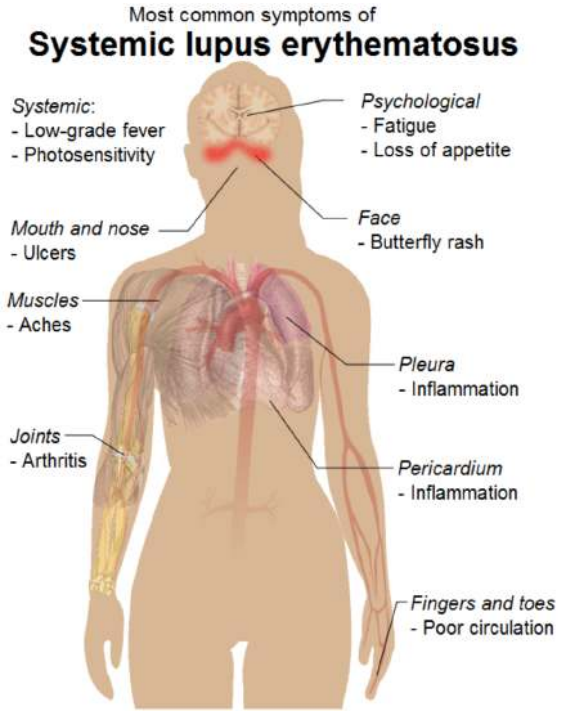



Figure **10.6.6**: Systemic lupus erythematosus is an autoimmune disease that may cause symptoms of body-wide tissue damage. The symptoms listed here are psychological fatigue and loss of appetite, butterfly rash on the face, inflammation of pleura and pericardium, poor circulation to finger and toes, fever, photosensitivity, mouth and nose ulcers, muscle aches, and joint arthritis.

### TREATMENT FOR AUTOIMMUNE DISEASES

None of these common autoimmune diseases can be cured, although all of them have treatments that may help relieve symptoms and prevent some of the long-term damage they may cause. Traditional treatments for autoimmune diseases include immunosuppressive drugs to block the immune response and anti-inflammatory drugs to quell inflammation. Hormone replacement may be another option. For example, type I diabetes is treated with injections of the hormone insulin because islet cells in the pancreas can no longer secrete it.

## IMMUNODEFICIENCY

**Immunodeficiency** occurs when the immune system is not working properly, generally because one or more components of the immune system are inactive. As a result, the immune system may be unable to fight off pathogens or cancers that a normal immune system would be able to resist. Immunodeficiency may occur for a variety of reasons.

### CAUSES OF IMMUNODEFICIENCY

Dozens of rare genetic diseases can result in a defective immune system. This type of immunodeficiency is called primary immunodeficiency. One is born with one of these diseases rather than acquiring it after birth. Probably the best known of these primary immunodeficiency diseases is severe combined immunodeficiency (SCID). It is also known as “bubble boy disease” because people with this disorder are extremely vulnerable to infectious diseases and some of them have become well known for living inside a bubble that provides a sterile environment. SCID is most often caused by an X-linked recessive mutation that interferes with normal B cell and T cell production.

Other types of immunodeficiency are not present at birth but acquired due to experiences or exposures that occur after birth. Acquired immunodeficiency is called secondary immunodeficiency because it is secondary to some other event or exposure. Secondary immunodeficiency may occur for a number of different reasons:

- The immune system naturally becomes less effective as people get older. This age-related decline, called immunosenescence, generally begins at about age 50 and worsens with increasing age. Immunosenescence is why older people are generally more susceptible to disease than younger people.
- The immune system may be damaged by another disorder, such as obesity, alcoholism, or the abuse of other drugs.
- In developing countries, malnutrition is the most common cause of immune system damage and immunodeficiency. Inadequate protein intake is especially damaging to the immune system. It can lead to impaired complement system activity, phagocyte malfunction, and lower-than-normal production of antibodies and cytokines.
- Surgical removal or disease of the thymus, where T lymphocytes normally mature, results in severe immunodeficiency. People without a functioning thymus are extremely susceptible to infections.
- Certain medications can suppress the immune system. This is the intended effect of immunosuppressant drugs given to people with transplanted organs so they do not reject them. In many cases, however, immunosuppression is an unwanted side effect of drugs used to treat other disorders.
- Some pathogens attack and destroy cells of the immune system. An example is a virus known as HIV, which attacks and destroys T cells.

### FOCUS ON HIV

**The human immunodeficiency virus (HIV)** is the most common cause of immunodeficiency in the world today, so it is the focus of the rest of this concept. It is also covered in the concept HIV and AIDS. HIV infections of human hosts are a relatively recent phenomenon. Scientists think that the virus originally infected

monkeys but then jumped to human populations, probably sometime during the early to mid-1900s. This most likely occurred in West Africa, but the virus soon spread around the world. HIV was first identified by medical researchers in 1981. Since then, HIV has killed almost 40 million people worldwide, and its economic toll has also been enormous. The hardest hit countries are in Africa, where the virus has infected human populations the longest, and medications to control the virus are least available.

### HIV TRANSMISSION

HIV is transmitted through direct contact of mucous membranes or body fluids such as blood, semen, or breast milk. As shown in Figure **10.6.7**, the transmission of the virus can occur through sexual contact or the use of contaminated hypodermic needles. It can also be transmitted from an infected mother's blood during late pregnancy or childbirth or through breast milk after birth. In the past, HIV was also transmitted occasionally through blood transfusions. Because donated blood is now screened for HIV, the virus is no longer transmitted this way.

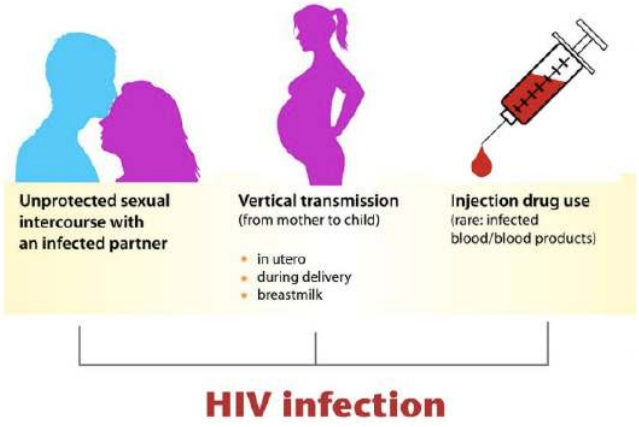



Figure **10.6.7**: HIV may be transmitted in all of the ways shown here.

### HIV AND THE IMMUNE SYSTEM

HIV infects and destroys helper T cells, the type of lymphocytes that regulate the immune response. How this occurs is shown in Figure **10.6.8**. The virus injects its own nucleic acid into a helper T cell and uses the T cell's "machinery" to make copies of itself. In the process, the helper T cell is destroyed, and the virus copies go on to infect other helper T cells. HIV is able to evade the immune system and keep destroying helper T cells by mutating frequently so its surface antigens keep changing and by using the host cell's membrane to hide its own antigens.

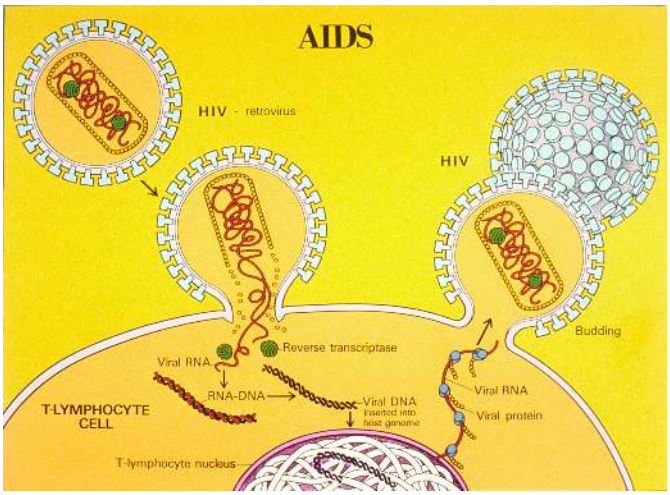



Figure **10.6.8**: The human immunodeficiency virus (HIV-I) enters the T-lymphocyte where the virus loses its outer envelope, releasing its RNA and its reverse transcriptase. The reverse transcriptase builds a complementary DNA strand from the viral RNA template. The DNA helix is inserted into the host genome. When this is transcribed by the infected cell, the new viral RNA and proteins are produced to form new viruses that then bud from the cell membrane, thus completing the life cycle of the virus.

**Acquired immunodeficiency syndrome (AIDS)** may result from years of damage to the immune system by HIV. It occurs when helper T cells fall to a very low level and opportunistic diseases occur. Opportunistic diseases are infections and tumors that are rare except in people with a damaged immune system. The diseases take advantage of the "opportunity" presented by people whose immune systems cannot fight back. Opportunistic diseases are usually the direct cause of death of people with AIDS.

### TREATING HIV/AIDS

For patients who have access to HIV medications, infection with the virus has ceased to be the death sentence that it once was. By 1995, combinations of drugs called "highly active antiretroviral therapy" were developed. For some patients, these drugs can reduce the amount of virus they are carrying to undetectable levels. However, some amount of virus always hides in the body's immune cells and will multiply again if a patient stops taking the medications. Researchers are trying to develop drugs to kill these hidden viruses as well. If their efforts are successful, it could bring an end to AIDS.

### FEATURE: HUMAN BIOLOGY IN THE NEWS

EpiPens® and their sole manufacturer, pharmaceutical company Mylan, were featured in the news headlines in 2016 but not for a good reason. A drastic price hike in EpiPens® and Mylan's apparent greed triggered the media outburst.

EpiPens® are auto-injectable syringes preloaded with a measured dose of epinephrine, a drug that can rapidly stop a life-threatening anaphylactic response to an allergen. Using the device is easy and does not require any special training. The injector just needs to be jammed against the thigh, which can be done through clothing or on bare skin. Each year, doctors write millions of prescriptions for EpiPens®. Many people with

severe allergies always carry two of the devices with them just in case they experience anaphylaxis, although most of them never need to use them. Other people with severe allergies have literally had their lives saved multiple times by EpiPens® when they had anaphylactic reactions. Even when the devices haven't been used, they must be replaced each year due to the expiration of the epinephrine.

You might think that EpiPens® would be relatively inexpensive, given their life-saving potential. As recently as 2009, a two-pack of EpiPens® cost about $100. However, in just 7 years, the cost of the same two-pack of EpiPens® skyrocketed by an incredible 400 percent! By 2016, the cost was $600 or more. Mylan apparently raised the price for the sole purpose of increasing profits. The company also raised prices significantly on many other drugs. The price hike in EpiPens® alone was certainly profitable. In 2015, the sale of EpiPens® earned Mylan $1 billion. Mylan's CEO took home almost $19 million the same year, which was an increase of more than 600 percent over her prior salary.

News coverage of the price hike in EpiPens® began in the summer of 2016 after a price increase in May of that year. Both private citizens and elected officials expressed outrage over the price increase, especially when coupled with the gluttonous profits of the company and its CEO. By late August, Mylan responded to the backlash by offering discount coupons for EpiPens®. A few days later, the company promised to introduce a cheaper, generic version of the device. Analysts quickly determined that selling a generic version would allow Mylan to make more money on the product than reducing the price of the name-brand device, which they still declined to do. By September of 2016, Mylan was being investigated for antitrust violations relating to sales of EpiPens® to public schools in New York City.

The Mylan/EpiPen® story may still be making the news. But whatever its outcome, the story has already added fuel to public and private debates about important ethical issues — issues such as the excessive costs of life-saving drugs and the huge profits of big pharma. What is the most recent news on EpiPens® and Mylan? If you are interested, you can check the headlines online to find out. What are your views on the ethical issues they raise?

## REVIEW

1. What are allergies? What causes them?
2. Compare the prevalence of allergies in developed and developing countries. How does the hygiene hypothesis explain the differences in prevalence?
3. How do allergies occur?
4. How are mild allergy symptoms treated?
5. What is anaphylaxis, and how is it treated?
6. How does immunotherapy for allergies work?
7. What are autoimmune diseases?
8. Identify two risk factors for autoimmune diseases.
9. Autoimmune diseases may be specific to particular tissues, or they may be systemic. Give an example of each type of autoimmune disease.
10. What is immunodeficiency?
11. Compare and contrast primary and secondary immunodeficiency, and give an example of each.
12. What is the most common cause of immunodeficiency in the world today? How does this cause affect the immune system?
13. Distinguish between HIV and AIDS.
14. *True or False.* Allergies and autoimmune diseases both result from an over-reactive immune system.
15. *True or False.* An anaphylactic reaction can be stopped by administering a shot of histamine.

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# 10.7: HUMAN MICROBIOME

## BENEFICIAL MICROBES: THE PHARMACY IN THE GUT

While some bacteria can cause disease, others play beneficial roles in human health. We have co-evolved with microbes in and on our body, with everyone having a unique set of microorganisms. The most abundant and well-studied microbiome is found in the gut. It has been estimated that the number of bacteria in the human gut may outnumber the cells in the body by an order of magnitude. Thus, one may consider the gut microbiome as a multicellular organ similar in size to the liver. Indeed, it is sometimes referred to as our "forgotten organ".

Generally, the microbiome within a given body habitat can be defined as the diversity and abundance distribution of distinct types of microorganisms. This microbial composition is highly influenced by individual factors such as diet, age, lifestyle, ethnicity, and host health, among others. Although no taxa are observed to be universally present among all individuals, some microbial patterns demonstrate broad prevalence. Most bacteria belong to the genera *Bacteroides*, *Clostridium*, *Fusobacterium*, *Eubacterium*, *Ruminococcus*, *Peptococcus*, *Peptostreptococcus*, and *Bifidobacterium.*

## THE EVOLUTION OF MICROBIOME DURING LIFE

Recent research suggests early in-utero microbial exposure during pregnancy. Following birth, the newborn's digestive tract is quickly colonized by microorganisms from the mother (vaginal, fecal, skin, breast milk, etc.) and the environment in which the delivery takes place. Following birth, the microbiome that enters and evolves in the infant's gut is dependent upon a number of factors, with delivery mode and feeding regime (breastfeeding vs infant formula feeding) of prime importance in the early days and weeks of life. By the age of 2 to 3 years, the microbiome becomes essentially established, having reached a steady state, and remains relatively stable throughout life. However, the gut microbiome continuously changes in response to daily variations in diet, lifestyle, age, and host physiological and immunological health.

## HEALTH BENEFITS OF THE MICROBIOME

On the basis of the currently available literature, the gut microbiome is known to contribute to a number of important functions in the host, from protective, immunomodulatory, metabolic to trophic roles. These are promoted via a number of mechanisms. For example, members of the gut microbiome can produce anti-inflammatory factors, pain relieving compounds, antioxidants, and vitamins to protect and nurture the body. Additionally, they may prevent attachment and action of harmful bacteria that can produce toxins causing chronic disease. This close and specific contact with human cells, exchanging nutrients and metabolic wastes, makes symbiotic bacteria essentially a human organ.

### GASTROINTESTINAL INFECTION PREVENTION

The indigenous intestinal microbiome serves as a line of resistance to colonization by exogenous microbes such as *Clostridium difficile* and *Helicobacter pylori*, and thus assists in competitive exclusion of pathogens preventing the potential invasion, termed colonization resistance. Indeed, antibiotic-associated diarrhea occurs when antibiotic treatment disturbs the natural balance of the gut microbiome causing harmful bacteria (i.e., *Clostridium difficile*) to proliferate and multiply. Oral probiotics may reduce antibiotic-associated diarrhea significantly.

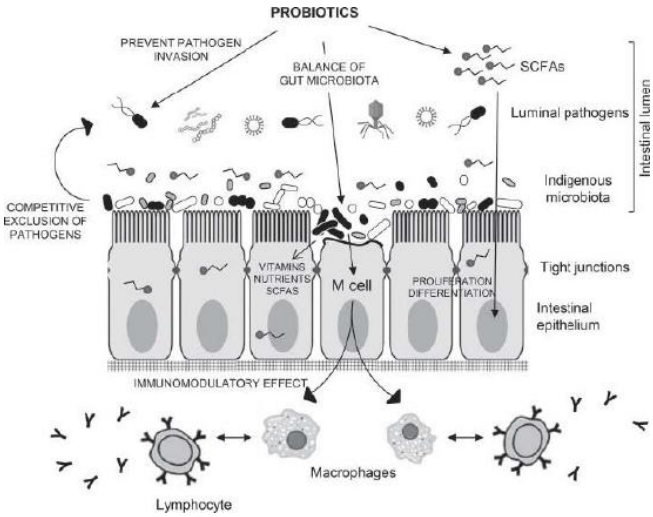



Figure **10.7.1**: Schematic representation of the cross-talk interaction of indigenous microbiome and oral probiotics with the intestinal epithelium. The intestinal microbiome protects the mucosa from invasion by pathogens. These probiotic bacteria may also allow beneficial effects through the release of nutrients (vitamins, SCFAs sugars) which are absorbed in the small intestine. Human microbes and probiotics would also interact with MALT macrophages and naive lymphocyte cells, allowing a mucosal anti-inflammatory response.

### IMMUNOMODULATORY EFFECTS

Commensal bacteria can interact with the host immune system in ways that control the host's immune response and counteracts the development of the disease. The complex interactions that may occur between ingested probiotic bacteria, commensals, and the mucosal surface are possible because of the mucosa-associated immune system, typically organized into MALT (Mucosal Associated Lymphoid Tissue, such as Peyer's patches). This cross-talk interaction enhances cellular immune response characterized by activation of macrophages, antigen-specific cytotoxic T-lymphocytes, and the release of various cytokines. Furthermore, some probiotics may be effective in the prevention and/or alleviation of allergies and auto-immune diseases like irritable bowel syndrome and inflammatory bowel diseases (Crohn's disease and ulcerative colitis).

## NUTRITIONAL BENEFITS

The metabolic activity of the gut microbiome makes an important contribution to the host's nutritional status via its ability to synthesize certain vitamins and various bioactive metabolites, such as short-chain fatty acids (SCFA), that then become bioavailable to the host. It has been reported that consumption of yogurt containing *Lactobacillus bulgaricus* or *acidophilus* could alleviate lactose intolerance during gastric passage through their enzyme lactase. However, the major metabolic function of the colonic microflora is the fermentation of nondigestible carbohydrates, which are key sources of energy in the colon. These carbohydrates also include large polysaccharides (i.e., resistant starches, pectins, and cellulose) and some oligosaccharides that escape digestion, as well as unabsorbed sugars and alcohols. Other benefits of the gut microbiome on human health, such as a role in supporting the health of the reproductive tract, oral cavity, lungs, skin, and gut-brain axis is currently under investigation.

## PROBIOTIC IMBALANCE

When the normal composition of the microbiome is thrown off balance, there is a potential risk of disease. A decrease in microbiome diversity has been linked to cancer, asthma, Parkinson's, obesity, Alzheimer's, type-2 diabetes, cardiovascular disease, and possibly even autism in comparison to healthy subjects. Over-the-counter probiotics can help. In order to arrive alive at their workplace (i.e. the gastrointestinal tract), orally administered probiotics must be able to resist stomach acid, bile, and the effects of digestive enzymes. Certain mechanisms of action (such as the delivery of certain enzymes to the intestine) may not require live cells to play a physiologic benefit. Hence, a probiotic must contain as many live bacteria as claimed on the label. In addition, to survive the stomach and arrive at the intestine in optimal numbers, probiotic strains must be able to adhere to the intestinal epithelium and/or mucus, persist and multiply in the gut to maintain its metabolic activity and confer their probiotic properties in the human body.

## RESOURCES

- BIOENGINEERED, 2016, VOL. 7, NO. 1, 11–20: http://dx.doi.org/10.1080/21655979.2015.1126015
- REVIEW: Beneficial Microbes: The pharmacy in the gut, Daniel M. Linares, Paul Ross, and Catherine Stanton, Food Biosciences Department, Teagasc Food Research Center, Moorepark, Fermoy, Cork, Ireland; APC, Microbiome Institute, University College Cork, Cork, Ireland; Biosciences Institute, University College Cork, Cork, Ireland

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# 10.8: CASE STUDY CONCLUSION- LYMPHOMA AND CHAPTER SUMMARY

## CASE STUDY CONCLUSION: DEFENDING YOUR DEFENSES

The person in Figure **10.8.1** is participating in a bike ride to raise funds for leukemia and lymphoma research. Leukemia and lymphoma are blood cancers. About every three minutes, one person in the U.S. is diagnosed with blood cancer. Lymphoma is the most common type of blood cancer. As a lymphoma patient, Wei, whom you learned about in the beginning of this chapter, may eventually benefit from research funded by a bike ride like this one.




Figure **10.8.1**: Fundraising for research

What type of blood cell is affected in lymphoma? As the name implies, lymphoma is cancer that affects lymphocytes, which are a type of white blood cell. As you have learned in this chapter, there are different types of lymphocytes, including the B and T cells of the adaptive immune system. Different types of lymphoma affect different types of lymphocytes in different ways. It is important to correctly identify the type of lymphoma so that patients can be treated appropriately.

You may recall that one of Wei's symptoms was a swollen lymph node, and he was diagnosed with lymphoma after a biopsy of that lymph node. Swollen lymph nodes are a common symptom of lymphoma. As you have learned, lymph nodes are distributed throughout the body along lymphatic vessels as part of the lymphatic system. The lymph nodes filter lymph and store lymphocytes and therefore play an important role in fighting infections. Because of this, they will often swell in response to an infection. In Wei's case, the swelling and other symptoms did not improve after several weeks and a course of antibiotics, which caused Dr. Bouazizi to suspect lymphoma instead. The biopsy showed that Wei did indeed have cancerous lymphocytes in his lymph nodes.

But which type of lymphocytes were affected? Lymphoma most commonly affects B or T lymphocytes. The two major types of lymphoma are called Hodgkin (HL) or non-Hodgkin lymphoma (NHL). NHL is more common than HL. There are more than 70,000 cases of NHL diagnosed in the U.S. each year, compared to about 8,000 for HL. While HL is one distinct type of lymphoma, NHL has about 60 different subtypes, depending on which specific cells are affected and how.

Wei was diagnosed with a type of NHL called diffuse large B-cell lymphoma (DLBCL)—the most common type of NHL. This type of lymphoma affects B cells and causes them to appear large under the microscope. In addition to Wei's symptoms of fatigue, swollen lymph nodes, loss of appetite, and weight loss, common symptoms of this type of lymphoma include fever and night sweats. It is an aggressive and fast-growing type of lymphoma that is fatal if not treated. But the good news is that with early detection and proper treatment, about 70% of patients with DLBCL can be cured.

How do physicians determine the specific type of lymphoma? Tissue obtained from a biopsy can be examined under a microscope to observe physical changes such as abnormal cell size or shape that are characteristic of a particular subtype of lymphoma. Additionally, tests can be performed on the tissue to determine which cell-surface antigens are present. Recall that antigens are molecules that bind to specific antibodies. Antibodies can be produced in the laboratory and labeled with compounds that can be identified by their color under a microscope. When these antibodies are applied to a tissue sample, this color will appear wherever the antigen is present, because it binds to the antibody. For example, this technique was used in the photomicrograph in Figure **10.8.2** to identify the presence of a cell-surface antigen (shown as reddish-brown) in a sample of skin cells. This technique, called **immunohistochemistry**, is also commonly used to identify antigens in tissue samples from lymphoma patients.

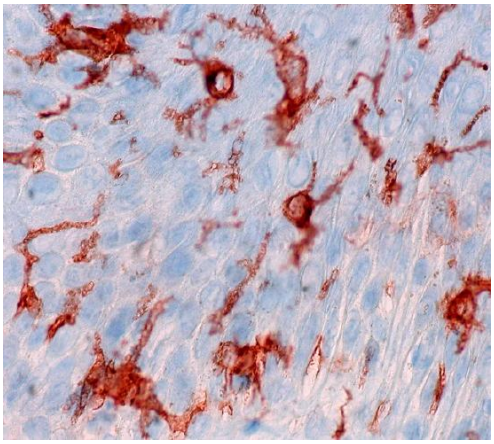


Figure **10.8.2**: Test for lymphoma

Why would identifying cell-surface antigens be important in diagnosing and treating lymphoma? As you have learned, the immune system uses antigens present on the surface of cells or pathogens to distinguish between self and non-self and to launch adaptive immune responses. Cells that become cancerous often change their cell-surface antigens, and this is one way that the immune system can identify and destroy them. Also, different cell types in the body can sometimes be identified by the presence of specific cell-surface antigens. Knowing the types of cell-surface

antigens present in a tissue sample can help physicians identify which cells are cancerous, and possibly the specific subtype of cancer. Knowing this information can be helpful in choosing more tailored and effective treatments.

In fact, one treatment for NHL is the use of medications made from antibodies that bind to cell-surface antigens present on cells affected by the specific subtype of NHL. This is called **immunotherapy**. These drugs can directly bind to and kill the cancerous cells. For patients with DLBCL such as Wei, immunotherapy is often used in conjunction with chemotherapy and radiation as a course of treatment. Although Wei has a difficult road ahead, he and his medical team are optimistic that he may be able to be cured, given the high success rate when DLBCL is caught and treated early. More research into how the immune system functions may lead to even better treatments for lymphoma, and other types of cancers, in the future.

## CHAPTER SUMMARY

In this chapter, you learned about the immune system. Specifically, you learned that:

- Any agent that can cause disease is called a pathogen. Most human pathogens are microorganisms such as bacteria and viruses. The immune system is the body system that defends the human host from pathogens and cancerous cells.
- The innate immune system is a subset of the immune system that provides very quick but non-specific responses to pathogens. It includes multiple types of barriers to pathogens, leukocytes that phagocytize pathogens, and several other general responses.
- The adaptive immune system is a subset of the immune system that provides specific responses tailored to particular pathogens. It takes longer to put into effect, but it may lead to immunity to the pathogens.
- Both innate and adaptive immune responses depend on the ability of the immune system to distinguish between self and non-self molecules. Most body cells have major histocompatibility complex (MHC) proteins that identify them as self. Pathogens, infected cells, and tumor cells have non-self proteins called antigens that the immune system recognizes as foreign.
- Antigens are proteins that bind to specific receptors on immune system cells and elicit an adaptive immune response. Some immune cells (B cells) respond to foreign antigens by producing antibodies that bind with antigens and target pathogens for destruction.
- An important role of the immune system is tumor surveillance. Killer T cells of the adaptive immune system find and destroy tumor cells, which they can identify from their abnormal antigens.
- The neuroimmune system that protects the central nervous system is thought to be distinct from the peripheral immune system that protects the rest of the human body. The blood-brain and blood-spinal cord barriers are one type of protection of the neuroimmune system. Glial cells also play role in this system—for example, by carrying out phagocytosis.
- The lymphatic system is a human organ system that is a vital part of the adaptive immune system. It consists of several organs and a system of vessels that transport or filter the fluid called lymph. The main immune function of the lymphatic system is to produce, mature, harbor, and circulate white blood cells called lymphocytes, which are the main cells in the adaptive immune system and are circulated in the lymph.
- The return of lymph to the bloodstream is one of the functions of the lymphatic system. Lymph flows from tissue spaces, where it leaks out of blood vessels, to major veins in the upper chest, where it is returned to the cardiovascular system. Lymph is similar in composition to blood plasma. Its main cellular components are lymphocytes.
- Lymphatic vessels called lacteals are found in villi that line the small intestine. Lacteals absorb fatty acids from the digestion of lipids in the digestive system. The fatty acids are then transported through the network of lymphatic vessels to the bloodstream. Although it plays a role in digestion, the primary function of the lymphatic system is host defense.
- Lymphocytes, which include B cells and T cells, are the subset of white blood cells that are involved in adaptive immune responses. They may create a lasting memory of and immunity to specific pathogens.
- All lymphocytes are produced in the bone marrow and then go through a process of maturation in which they “learn” to distinguish self from non-self. B cells mature in the bone marrow, and T cells mature in the thymus. Both the bone marrow and thymus are considered primary lymphatic organs.
- Secondary lymphatic organs include the tonsils, spleen, and lymph nodes. There are four pairs of tonsils that encircle the throat. The spleen filters blood as well as lymph. There are hundreds of lymph nodes located in clusters along the lymphatic vessels. All of these secondary organs filter lymph and store lymphocytes, so they are sites where pathogens encounter and activate lymphocytes and initiate adaptive immune responses.
- Unlike the adaptive immune system, the innate immune system does not confer immunity. The innate immune system includes surface barriers, inflammation, the complement system, and a variety of cellular responses.
- The body’s first line of defense consists of three different types of barriers that keep most pathogens out of body tissues. The types of barriers are mechanical, chemical, and biological barriers.
- Mechanical barriers—which include the skin, mucous membranes, and fluids such as tears and urine—physically block pathogens from entering the body.
- Chemical barriers—such as enzymes in sweat, saliva, and semen—kill pathogens on body surfaces.
- Biological barriers are harmless bacteria that use up food and space so pathogenic bacteria cannot colonize the body.

- If pathogens breach the protective barriers, inflammation occurs. This creates a physical barrier against the spread of infection and repairs tissue damage. Inflammation is triggered by chemicals such as cytokines and histamines, and it causes swelling, redness, and warmth.
- The complement system is a complex biochemical mechanism that helps antibodies kill pathogens. Once activated, the complement system consists of more than two dozen proteins that lead to disruption of the cell membrane of pathogens and bursting of the cells.
- Cellular responses of the innate immune system involve various types of leukocytes (white blood cells). For example, neutrophils, macrophages, and dendritic cells phagocytize pathogens. Basophils and mast cells release chemicals that trigger inflammation. Natural killer cells destroy cancerous or virus-infected cells, and eosinophils kill parasites.
- Many pathogens have evolved mechanisms that help them evade the innate immune system. For example, some pathogens form a protective capsule around themselves, and some mimic host cells so the immune system does not recognize them as foreign.
- The main cells of the adaptive immune system are lymphocytes. There are two major types of lymphocytes: T cells and B cells. Both types must be activated by foreign antigens to become functioning immune cells.
- Most activated T cells become either killer T cells or helper T cells. Killer T cells destroy cells that are infected with pathogens or are cancerous. Helper T cells manage immune responses by releasing cytokines that control other types of leukocytes.
- Activated B cells form plasma cells that secrete antibodies, which bind to specific antigens on pathogens or infected cells. The antibody-antigen complexes generally lead to the destruction of the cells, for example, by attracting phagocytes or triggering the complement system.
- After an adaptive immune response occurs, long-lasting memory B cells and memory T cells may remain to confer immunity to the specific pathogen that caused the adaptive immune response. These memory cells are ready to activate an immediate response if they are exposed to the same antigen again in the future.
- Immunity may be active or passive. Active immunity occurs when the immune system has been presented with antigens that elicit an adaptive immune response. This may occur naturally as the result of an infection or artificially as the result of immunization. Active immunity may last for years or even for life.
- Passive immunity occurs without an adaptive immune response by the transfer of antibodies or activated T cells. This may occur naturally between a mother and her fetus or her nursing infant, or it may occur artificially by injection. Passive immunity lasts only as long as the antibodies or activated T cells remain alive in the body, generally just weeks or months.
- Many pathogens have evolved mechanisms to evade the adaptive immune system. For example, human immunodeficiency virus (HIV) evades the adaptive immune system by frequently changing its antigens and by forming its outer envelope from the host's cell membrane.
- An allergy is a disorder in which the immune system makes an inflammatory response to a harmless antigen. Any antigen that causes allergies is called an allergen. Common allergens include pollen, dust mites, mold, specific foods such as peanuts, insect stings, and certain medications such as aspirin.
- The prevalence of allergies has been increasing for decades, especially in developed countries where they are much more common than in developing countries. The hygiene hypothesis posits that this has occurred because humans evolved to cope with more pathogens than we now typically face in our relatively sterile environments in developed countries. As a result, the immune system "keeps busy" by attacking harmless antigens.
- Allergies occur when B cells are first activated to produce large amounts of antibodies to an otherwise harmless allergen and the antibodies attach to mast cells. On subsequent exposures to the allergen, the mast cells immediately release cytokines and histamines that cause inflammation.
- Mild allergy symptoms are frequently treated with antihistamines that counter histamines and reduce allergy symptoms. A severe systemic allergic reaction, called anaphylaxis, is a medical emergency that is usually treated with injections of epinephrine. Immunotherapy for allergies involves injecting increasing amounts of allergens to desensitize the immune system to them.
- Autoimmune diseases occur when the immune system fails to recognize the body's own molecules as self and attacks them, causing damage to tissues and organs. A family history of autoimmunity and female sex are risk factors for autoimmune diseases.
- In some autoimmune diseases, such as type I diabetes, the immune system attacks, and damages, specific body cells. In other autoimmune diseases, such as systemic lupus erythematosus, many different tissues and organs may be attacked and injured. Autoimmune diseases generally cannot be cured, but their symptoms can often be managed with drugs or other treatments.
- Immunodeficiency occurs when the immune system is not working properly, generally because one or more of its components are inactive. As a result, the immune system is unable to fight off pathogens or cancers that a normal immune system would be able to resist.
- Primarily immunodeficiency is present at birth and caused by rare genetic diseases. An example is severe combined immunodeficiency. Secondary immunodeficiency occurs because of some event or exposure experienced after birth. Possible causes include substance abuse, obesity, and malnutrition, among others.
- The most common cause of immunodeficiency in the world today is the human immunodeficiency virus (HIV), which infects and destroys helper T cells. HIV is transmitted through mucous membranes or body fluids. The virus may eventually lead to such low levels of helper T cells that opportunistic infections occur.

When this happens, the patient is diagnosed with acquired immunodeficiency syndrome (AIDS). Medications can control the multiplication of HIV in the human body but not eliminate the virus completely.

Up to this point, this book has covered body systems that carry out processes within individuals, such as the digestive, muscular, and immune systems. Read the next chapter to learn about the body system that allows humans to produce new individuals—the reproductive system.

## CHAPTER SUMMARY REVIEW

1. The skin plays a role in establishing mechanical, chemical, and biological barriers that protect the body against pathogens. Give one example of how the skin contributes to each type of barrier.
2. Compare and contrast a pathogen and an allergen.
3. Describe three ways in which pathogens can enter the body.
4. For each of the following immune responses, state whether it is an innate or adaptive immune response.
   A. Inflammation
   B. Lymphocyte activation
   C. Phagocytosis by leukocytes
   D. Plasma cell maturation
5. The complement system involves the activation of several proteins to kill pathogens. Why do you think this is considered part of the innate immune system instead of the adaptive immune system?
6. Why are innate immune responses generally faster than adaptive immune responses?
7. *Rrue or False.* There is more than one type of immune system cell that can carry out phagocytosis.
8. *True or False.* Semen can act as a chemical barrier against pathogens.
9. *True or False.* Leukocytes in the innate immune system are all phagocytic.
10. Which type of immunity is triggered by vaccination?
    A. Artificially acquired active immunity
    B. Artificially acquired natural immunity
    C. Artificially acquired passive immunity
    D. Innate immunity
11. Explain how an autoimmune disease could be triggered by a pathogen.
12. What is an opportunistic infection? Name two diseases or conditions that could result in opportunistic infections. Explain your answer.
13. Match each description below with the cell type that best fits it from the list provided. Each cell type is used only once. Cell types: mast cells; B cells; killer T cells
    A. Directly destroys body cells that are cancerous or infected with a pathogen
    B. Secretes histamines and are involved in allergies
    C. Once activated, these cells multiply and their daughter cells mature into plasma cells
14. Which cell type in the immune system can be considered an “antibody factory”?
15. Besides foreign pathogens, what is one other thing that the immune system protects the body against?
16. What cell type in the immune system is infected and killed by HIV?
17. What is the difference between primary lymphoid organs and secondary lymphoid organs? Give one example of each in your answer.
18. Name two types of cells that produce cytokines in the immune system. What are two functions of cytokines in the immune system?
19. Many pathogens evade the immune system by altering their outer surface in some way. Based on what you know about the functioning of the immune system, why is this often a successful approach?
20. Major histocompatibility complex proteins:
    A. are involved in antigen-presentation by B cells
    B. help distinguish cells as self
    C. produce histamines
    D. A and B
21. What is “missing self” and how does this condition arise?
22. *True or False.* Sometimes only part of a pathogen is used to create a vaccine.
23. *True or False.* An antigen is the same thing as an allergen.

## ATTRIBUTIONS


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# CHAPTER OVERVIEW

## 11: THE RESPIRATORY SYSTEM

This chapter describes the structure and function of the respiratory system, including how breathing occurs and what controls it, as well as how the process of gas exchange takes place in the lungs. The chapter also describes several disorders of the respiratory system and details the adverse health effects of smoking.


11.1: Case Study- Respiratory System and Gas Exchange

11.2: Structure and Function of the Respiratory System

11.3: Breathing

11.4: Disorders of the Respiratory System

11.5: Smoking and Health

11.6: Case Study Conclusion- Bronchitis and Chapter Summary


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# 11.1: CASE STUDY- RESPIRATORY SYSTEM AND GAS EXCHANGE

## CASE STUDY: COUGH THAT WON'T QUIT

Three weeks ago, 20-year-old Sacheen came down with symptoms typical of the common cold. She had a runny nose, fatigue, and a mild cough. Her symptoms had been starting to improve, but recently her cough has been getting worse. She coughs up a lot of thick mucus, her throat is sore from frequent coughing, and her chest feels very congested. According to her wife, Sacheen has a "chest cold." Sacheen is a smoker and wonders if her habit is making her cough worse. She decides that it is time to see a doctor.



Figure **11.1.1**: Coughing

Dr. Tsosie examines Sacheen and asks about her symptoms and health history. She checks the level of oxygen in Sacheen's blood by attaching a device called a pulse oximeter to Sacheen's finger (Figure **11.1.2**). Dr. Tsosie concludes that Sacheen has bronchitis, an infection that commonly occurs after a person has a cold or flu. Bronchitis is sometimes referred to as a "chest cold," so Sacheen's wife was right! Bronchitis causes inflammation and a build-up of mucus in the bronchial tubes in the chest.



Figure **11.1.2**: A pulse oximeter, used to measure blood oxygen levels.

Because viruses, and not bacteria, usually cause bronchitis, Dr. Tsosie tells Sacheen that antibiotics are not likely to help. Instead, she recommends that Sacheen try to thin and remove the mucus by drinking plenty of fluids and using a humidifier, or spending time in a steamy shower. She also recommends that Sacheen get plenty of rest.

Dr. Tsosie also tells Sacheen some things *not* to do—most importantly, not to smoke while she is sick and to try to quit smoking in the long term. She explains that smoking can make people more susceptible to bronchitis and can hinder recovery. She also advises Sacheen not to take over-the-counter cough suppressant medication.

As you read this chapter on the respiratory system, you will better understand what bronchitis is and why Dr. Tsosie made the treatment recommendations that she did. At the end of the chapter, you will learn more about acute bronchitis, which is the type that Sacheen has. This information may come in handy to you personally because the chances are high that you will get this common infection at some point in your life—there are millions of bronchitis cases every year!

## CHAPTER OVERVIEW: RESPIRATORY SYSTEM

In this chapter, you will learn about the respiratory system, the system that exchanges gases such as oxygen and carbon dioxide between the body and the outside air. Specifically, you will learn about:

- The process of respiration, in which oxygen moves from the outside air into the body and carbon dioxide and other waste gases move from inside the body into the outside air.
- The organs of the respiratory system, including the lungs, bronchial tubes, and the rest of the respiratory tract.
- How the respiratory tract protects itself from pathogens and other potentially harmful substances in the air.
- How the rate of breathing is regulated to maintain homeostasis of blood gases and pH.
- How ventilation, or breathing, allows us to inhale air into the body and exhale air out of the body.
- The conscious and unconscious control of breathing.
- Nasal breathing compared to mouth breathing.
- What happens when a person is drowning.
- How gas exchange occurs between the air and blood in the alveoli of the lungs, and between the blood and cells throughout the body.
- Disorders of the respiratory system, including asthma, pneumonia, chronic obstructive pulmonary disease (COPD), and lung cancer.
- The negative health effects of smoking.

As you read the chapter, think about the following questions:

1. Where are the bronchial tubes, and what is their function?
2. What is the function of mucus, and why can too much mucus be a bad thing?
3. Why did Dr. Tsosie check Sacheen's blood oxygen level?
4. Why do you think Dr. Tsosie warned Sacheen not to take cough suppressant medications?
5. How does acute bronchitis compare to chronic bronchitis, and how do they both relate to smoking?

## ATTRIBUTIONS

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# 11.2: STRUCTURE AND FUNCTION OF THE RESPIRATORY SYSTEM

## SEEING YOUR BREATH

Why can you "see your breath" on a cold day? The air you exhale through your nose and mouth is warm, like the inside of your body. Exhaled air also contains a lot of water vapor because it passes over moist surfaces from the lungs to the nose or mouth. The water vapor in your breath cools suddenly when it reaches the much colder outside air. This causes the water vapor to condense into a fog of tiny droplets of liquid water. You release water vapor and other gases from your body through the process of respiration.



Figure **11.2.1**: Breath on a cold day

## WHAT IS RESPIRATION?

**Respiration** is the life-sustaining process in which gases are exchanged between the body and the outside atmosphere. Specifically, oxygen moves from the outside air into the body; and water vapor, carbon dioxide, and other waste gases move from inside the body into the outside air. Respiration is carried out mainly by the **respiratory system.** It is important to note that respiration by the respiratory system is not the same process as cellular respiration that occurs inside cells, although the two processes are closely connected. Cellular respiration is the metabolic process in which cells obtain energy, usually by "burning" glucose in the presence of oxygen. When cellular respiration is aerobic, it uses oxygen and releases carbon dioxide as a waste product. Respiration by the respiratory system supplies the oxygen needed by cells for aerobic cellular respiration and removes the carbon dioxide produced by cells during cellular respiration.

Respiration by the respiratory system actually involves two subsidiary processes. One process is ventilation or breathing. This is the physical process of conducting air to and from the lungs. The other process is gas exchange. This is the biochemical process in which oxygen diffuses out of the air and into the blood while carbon dioxide and other waste gases diffuse out of the blood and into the air. All of the organs of the respiratory system are involved in breathing, but only the lungs are involved in gas exchange.

## RESPIRATORY ORGANS

The organs of the respiratory system form a continuous system of passages called the **respiratory tract,** through which air flows into and out of the body. The respiratory tract has two major divisions: the upper respiratory tract and the lower respiratory tract. The organs in each division are shown in Figure **11.2.2**. In addition to these organs, certain muscles of the thorax (the body cavity that fills the chest) are also involved in respiration by enabling breathing. Most important is a large muscle called the diaphragm, which lies below the lungs and separates the thorax from the abdomen. Smaller muscles between the ribs also play a role in breathing. You can learn more about breathing muscles in the concept of *Breathing*.

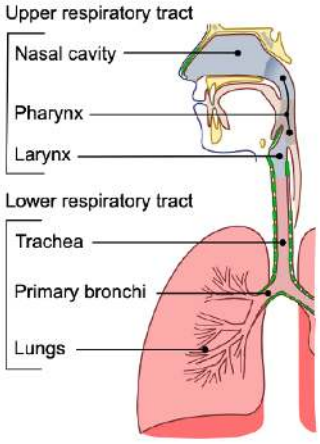



Figure **11.2.2**: During breathing, inhaled air enters the body through the nose and passes through the pharynx, larynx, trachea, bronchi, and then enters the lungs. Exhaled air travels from the lungs in the opposite direction.

### UPPER RESPIRATORY TRACT

All of the organs and other structures of the upper respiratory tract are involved in the conduction or the movement of air into and out of the body. Upper respiratory tract organs provide a route for air to move between the outside atmosphere and the lungs. They also clean, humidity, and warm the incoming air. However, no gas exchange occurs in these organs.

#### *NASAL CAVITY*

The **nasal cavity** is a large, air-filled space in the skull above and behind the nose in the middle of the face. It is a continuation of the two nostrils. As inhaled air flows through the nasal cavity, it is warmed and humidified. Hairs in the nose help trap larger foreign particles in the air before they go deeper into the respiratory tract. In addition to its respiratory functions, the nasal cavity also contains chemoreceptors that are needed for the sense of smell and that contribute importantly to the sense of taste.

#### *PHARYNX*

The **pharynx** is a tube-like structure that connects the nasal cavity and the back of the mouth to other structures lower in the throat, including the larynx. The pharynx has dual functions: both air and

food (or other swallowed substances) pass through it, so it is part of both the respiratory and digestive systems. Air passes from the nasal cavity through the pharynx to the larynx (as well as in the opposite direction). Food passes from the mouth through the pharynx to the esophagus.

### LARYNX

The **larynx** connects the pharynx and trachea and helps to conduct air through the respiratory tract. The larynx is also called the voice box because it contains the vocal cords, which vibrate when air flows over them, thereby producing sound. You can see the vocal cords in the larynx in Figure **11.2.3**. Certain muscles in the larynx move the vocal cords apart to allow breathing. Other muscles in the larynx move the vocal cords together to allow the production of vocal sounds. The latter muscles also control the pitch of sounds and help control their volume.

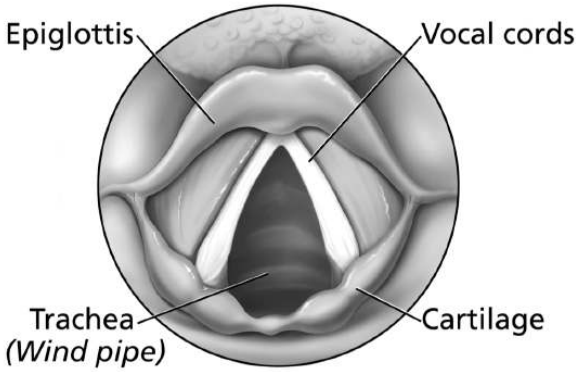



Figure **11.2.3**: The larynx is viewed from the top. opening to the trachea is closed by epiglottis during swallowing. Cartilage and vocal cords are also visible.

A very important function of the larynx is protecting the trachea from aspirated food. When swallowing occurs, the backward motion of the tongue forces a flap called the epiglottis to close over the entrance to the larynx. You can see the epiglottis in Figure **11.2.3**. This prevents swallowed material from entering the larynx and moving deeper into the respiratory tract. If swallowed material does start to enter the larynx, it irritates the larynx and stimulates a strong cough reflex. This generally expels the material out of the larynx and into the throat.

## LOWER RESPIRATORY TRACT

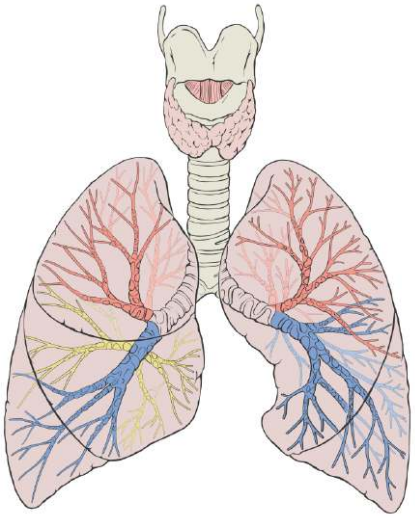


Figure **11.2.4**: This diagram illustrates the tree-like branching of the passages of the lower respiratory tract within the lungs.

The trachea and other passages of the lower respiratory tract conduct air between the upper respiratory tract and the lungs. These passages form an inverted tree-like shape (Figure **11.2.4**), with repeated branching as they move deeper into the lungs. All told, there are an astonishing 1,500 miles of airways conducting air through the human respiratory tract! It is only in the lungs, however, that gas exchange occurs between the air and the bloodstream.

### TRACHEA

The **trachea,** or windpipe, is the widest passageway in the respiratory tract. It is about 2.5 cm (1 in.) wide and 10-15 cm (4-6 in.) long. It is formed by rings of cartilage, which make it relatively strong and resilient. The trachea connects the larynx to the lungs for the passage of air through the respiratory tract. The trachea branches at the bottom to form two bronchial tubes.

### BRONCHI AND BRONCHIOLES

There are two main bronchial tubes, or **bronchi (singular, bronchus)**, called the right and left bronchi. The bronchi carry air between the trachea and lungs. Each bronchus branches into smaller, secondary bronchi; and secondary bronchi branch into still smaller tertiary bronchi. The smallest bronchi branch into very small tubules called bronchioles. The tiniest bronchioles end in alveolar ducts, which terminate in clusters of minuscule air sacs, called alveoli (singular, alveolus), in the lungs.

### LUNGS

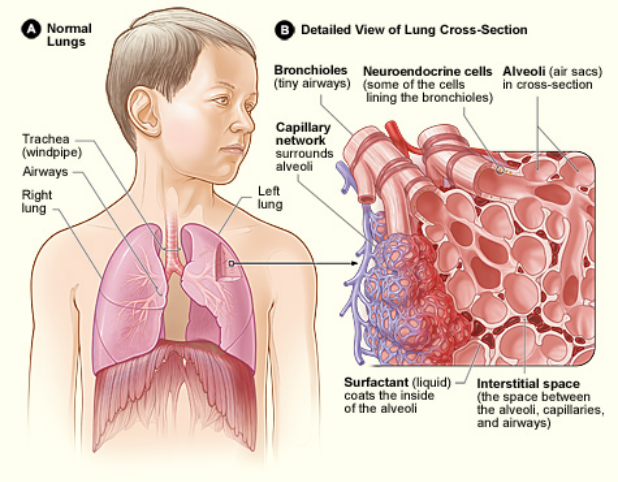



Figure **11.2.5**: The cross-section of lung tissue on the right shows the alveoli in which gas exchange takes place with the capillary network that surrounds them. Neuroendocrine cells lining the bronchioles control their diameter and the flow of air through them. A surfactant is a liquid that covers the inside of the alveoli and prevents them from collapsing and sticking together when air empties out of them during exhalation.

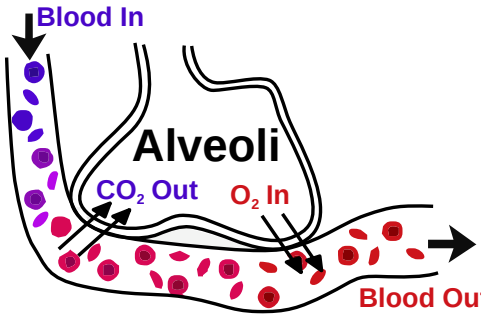



Figure **11.2.6**: The gaseous exchange between blood and outside air inside the lung alveoli.

The **lungs** are the largest organs of the respiratory tract. They are suspended within the pleural cavity of the thorax. In Figure **11.2.5**, you can see that each of the two lungs is divided into sections. These are called lobes, and they are separated from each other by connective tissues. The right lung is larger and contains three lobes. The left lung is smaller and contains only two lobes. The smaller left lung allows room for the heart, which is just left of the center of the chest.

Lung tissue consists mainly of alveoli (Figure **11.2.6**). These tiny air sacs are the functional units of the lungs where gas exchange takes place. The two lungs may contain as many as 700 million alveoli, providing a huge total surface area for gas exchange to take place. In fact, alveoli in the two lungs provide as much surface area as half a tennis court! Each time you breathe in, the alveoli fill with air, making the lungs expand. Oxygen in the air inside the alveoli is absorbed by the blood in the mesh-like network of tiny capillaries that surrounds each alveolus. The blood in these capillaries also releases carbon dioxide into the air inside the alveoli. Each time you breathe out, air leaves the alveoli and rushes into the outside atmosphere, carrying waste gases with it.

The lungs receive blood from two major sources. They receive deoxygenated blood from the heart. This blood absorbs oxygen in the lungs and carries it back to the heart to be pumped to cells throughout the body. The lungs also receive oxygenated blood from the heart that provides oxygen to the cells of the lungs for cellular respiration.

## PROTECTING THE RESPIRATORY SYSTEM

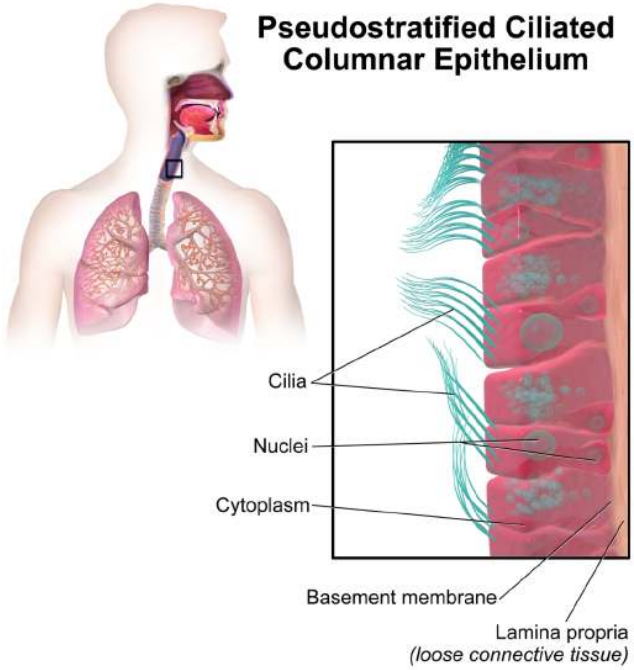



Figure **11.2.7**: The upward sweeping motion of cilia lining the respiratory tract helps keep it free from dust, pathogens, and other harmful substances.

You may be able to survive for weeks without food and for days without water, but you can survive without oxygen for only a matter of minutes except under exceptional circumstances. Therefore, protecting the respiratory system is vital. That's why making sure a patient has an open airway is the first step in treating many medical emergencies. Fortunately, the respiratory system is well protected by the ribcage of the skeletal system. However, the extensive surface area of the respiratory system is directly exposed to the outside world and all its potential dangers in inhaled air. Therefore, it should come as no surprise that the respiratory system has a variety of ways to protect itself from harmful substances such as dust and pathogens in the air.

The main way the respiratory system protects itself is called the mucociliary escalator. From the nose through the bronchi, the respiratory tract is covered in the epithelium that contains mucus-secreting goblet cells. The mucus traps particles and pathogens in the incoming air. The epithelium of the respiratory tract is also covered with tiny cell projections called cilia (singular, cilium), as shown in Figure **11.2.7**. The cilia constantly move in a sweeping motion upward toward the throat, moving the mucus and trapped particles and pathogens away from the lungs and toward the outside of the body.

What happens to the material that moves up the mucociliary escalator to the throat? It is generally removed from the respiratory tract by clearing the throat or coughing. Coughing is a largely involuntary response of the respiratory system that occurs when nerves lining the airways are irritated. The response causes air to be expelled forcefully from the trachea, helping to remove mucus and any debris it contains (called phlegm) from the upper respiratory tract to the mouth. The phlegm may spit out (expectorated), or it may be swallowed and destroyed by stomach acids.

Sneezing is a similar involuntary response that occurs when nerves lining the nasal passage are irritated. It results in forceful expulsion of air from the mouth, which sprays millions of tiny droplets of mucus and other debris out of the mouth and into the air, as shown in Figure **11.2.8**. This explains why it is so important to sneeze into a sleeve rather than the air to help prevent the transmission of respiratory pathogens.



Figure **11.2.8**: Sneezing results in tiny particles from the mouth being forcefully ejected into the air.

## HOW THE RESPIRATORY SYSTEM WORKS WITH OTHER ORGAN SYSTEMS

The amount of oxygen and carbon dioxide in the blood must be maintained within a limited range for the survival of the organism. Cells cannot survive for long without oxygen, and if there is too much carbon dioxide in the blood, the blood becomes dangerously acidic (pH is too low). Conversely, if there is too little carbon dioxide in the blood, the blood becomes too basic (pH is too high). The respiratory system works hand-in-hand with the nervous and cardiovascular systems to maintain homeostasis in blood gases and pH.

It is the level of carbon dioxide rather than the level of oxygen that is most closely monitored to maintain blood gas and pH homeostasis. The level of carbon dioxide in the blood is detected by cells in the brain, which speed up or slow down the rate of breathing through the autonomic nervous system as needed to bring the carbon dioxide level within the normal range. Faster breathing lowers the carbon dioxide level (and raises the oxygen level and pH); slower breathing has the opposite effects. In this way, the levels of carbon dioxide and oxygen, as well as pH, are maintained within normal limits.

The respiratory system also works closely with the cardiovascular system to maintain homeostasis. The respiratory system exchanges gases between the blood and the outside air, but it needs the cardiovascular system to carry them to and from body cells. Oxygen is absorbed by the blood in the lungs and then transported through a vast network of blood vessels to cells throughout the body where it is needed for aerobic cellular respiration. The same system absorbs carbon dioxide from cells and carries it to the respiratory system for removal from the body.

### FEATURE: MY HUMAN BODY

Choking is the mechanical obstruction of the flow of air from the atmosphere into the lungs. It prevents breathing and may be partial or complete. Partial choking allows some though inadequate airflow into the lung—prolonged or complete choking results in asphyxia, or suffocation, which is potentially fatal.

Obstruction of the airway typically occurs in the pharynx or trachea. Young children are more prone to choking than are older people, in part because they often put small objects in their mouths and do not appreciate the risk of choking that they pose. Young children may choke on small toys or parts of toys or on household objects in addition to food. Foods that can adapt their shape to that of the pharynx, such as bananas and marshmallows, are especially dangerous and may cause choking in adults as well as children.

How can you tell if a loved one is choking? The person cannot speak or cry out or has great difficulty doing so. Breathing, if possible, is labored, producing gasping or wheezing. The person may desperately clutch at his or her throat or mouth. If breathing is not soon restored, the person's face will start to turn blue from lack of oxygen. This will be followed by unconsciousness if oxygen deprivation continues beyond a few minutes.

If an infant is choking, turning the baby upside down and slapping on the back may dislodge the obstructing object. To help an older person who is choking, first, encourage the person to cough. Give them a few hardback slaps to help force the lodged object out of the airway. If these steps fail, perform the Heimlich maneuver on the person. You can easily find instructional videos online to learn how to do it. If the Heimlich maneuver also fails, call for emergency medical care immediately.



Figure **11.2.9**: The Heimlich maneuver may be needed to help force an aspirated object out of the respiratory tract.

## REVIEW

1. What is respiration, as carried out by the respiratory system? Name the two subsidiary processes it involves.
2. Describe the respiratory tract.
3. Identify the organs of the upper respiratory tract, and state their functions.
4. List the organs of the lower respiratory tract. Which organs are involved only in conduction?
5. Where does gas exchange take place?
6. How does the respiratory system protect itself from potentially harmful substances in the air?
7. Explain how the rate of breathing is controlled.
8. Why does the respiratory system need the cardiovascular system to help it perform its main function of gas exchange?
9. Place the following organs or structures of the respiratory system in order of when they are encountered by air entering the body — from earliest to latest.

   trachea; nasal cavity; alveoli; bronchioles; larynx; bronchi; pharynx
10. Which organ is part of both the digestive and respiratory systems?

    A. Larynx

    B. Trachea

    C. Pharynx

    D. Bronchus
11. Describe two ways in which the body prevents food from entering the lungs.
12. *True or False.* The lungs receive some oxygenated blood.
13. *True or False.* Gas exchange occurs in both the upper and lower respiratory tracts.
14. Coughing can expel _____ from the body.

    A. mucus

    B. food particles

    C. phlegm

    D. All of the above
15. What is the relationship between respiration and cellular respiration?

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# 11.3: BREATHING

## DOING THE 'FLY

The swimmer in this photo is doing the butterfly stroke. This swimming style requires the swimmer to carefully control his breathing so it is coordinated with his swimming movements. Breathing is the process of moving air into and out of the lungs, which are the organs in which gas exchange takes place between the atmosphere and the body. Breathing is also called **ventilation,** and it is one of two parts of the life-sustaining process of respiration, the other part being gas exchange. Before you can understand how breathing is controlled, you need to know how breathing occurs.



Figure **11.3.1**: Butterfly stroke

## HOW BREATHING OCCURS

Breathing is a two-step process that includes drawing air into the lungs, or inhaling, and letting the air out of the lungs, or exhaling. Both processes are illustrated in Figure **11.3.2**.

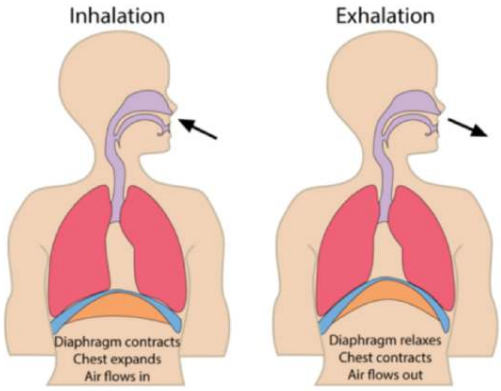



Figure **11.3.2**: Inhalation and exhalation during breathing depend mainly on repeated contractions of the diaphragm.

### INHALING

Inhaling is an active process that results mainly from the contraction of a muscle called the diaphragm, shown in Figure **11.3.2**. The **diaphragm** is a large, dome-shaped muscle below the lungs that separates the thoracic (chest) and abdominal cavities. When the diaphragm contracts, the thoracic cavity expands and the contents of the abdomen are pushed downward. Other muscles, such as external intercostal muscles between the ribs, also contribute to the process of inhalation, especially when inhalation is forced, as when taking a deep breath. These muscles help increase thoracic volume by expanding the ribs outward. With the chest expanded, there is lower air pressure inside the lungs than outside the body, so outside air flows into the lungs via the respiratory tract.

### EXHALING

Exhaling involves the opposite series of events. The diaphragm relaxes, so it moves upward and decreases the volume of the thorax ( Figure **11.3.2**. Air pressure inside the lungs increases so it is higher than the air pressure outside the lungs. Exhaling, unlike inhaling, is typically a passive process that occurs mainly due to the elasticity of the lungs. With the change in air pressure, the lungs contract to their pre-inflated size, forcing out the air they contain in the process. Air flows out of the lungs, similar to the way air rushes out of a balloon when it is released. If exhalation is forced, internal intercostal and abdominal muscles may help move the air out of the lungs.

## CONTROL OF BREATHING

Breathing is one of the few vital bodily functions that can be controlled consciously as well as unconsciously. Think about using your breath to blow up a balloon. You take a long, deep breath, and then you exhale the air as forcibly as you can into the balloon. Both the inhalation and exhalation are consciously controlled.

### CONSCIOUS CONTROL OF BREATHING

You can control your breathing by holding your breath, slowing your breathing, or **hyperventilating,** which is breathing more quickly and shallowly than necessary. You can also exhale or inhale more forcefully or deeply than usual. Conscious control of breathing is common in many activities besides blowing up balloons, including swimming, speech training, singing, playing many different musical instruments ( Figure **11.3.3**), and doing yoga, to name just a few.



Figure **11.3.3**: Playing the oboe is hard work. Exhaled air must be forced through a tiny opening between two very small wooden reeds.

There are limits on the conscious control of breathing. For example, it is not possible for a healthy person to voluntarily stop breathing indefinitely. Before long, there is an irrepressible urge to breathe. If you were able to stop breathing for a long enough time, you would lose consciousness. The same thing would happen if you were to

hyperventilate for too long. Once you lose consciousness so you can no longer exert conscious control over your breathing, involuntary control of breathing takes over.

## UNCONSCIOUS CONTROL OF BREATHING

Unconscious breathing is controlled by **respiratory centers** in the medulla and pons of the brainstem ( Figure **11.3.4**). The respiratory centers automatically and continuously regulate the rate of breathing depending on the body's needs. These are determined mainly by blood acidity or pH. When you exercise, for example, carbon dioxide levels increase in the blood because of increased cellular respiration by muscle cells. The carbon dioxide reacts with water in the blood to produce carbonic acid, making the blood more acidic, so pH falls. The drop in pH is detected by chemoreceptors in the medulla. Blood levels of oxygen and carbon dioxide, in addition to pH, are also detected by chemoreceptors in major arteries, which send the "data" to the respiratory centers. The respiratory center responds by sending nerve impulses to the diaphragm, "telling" it to contract more quickly so the rate of breathing speeds up. With faster breathing, more carbon dioxide is released into the air from the blood, and blood pH returns to the normal range.

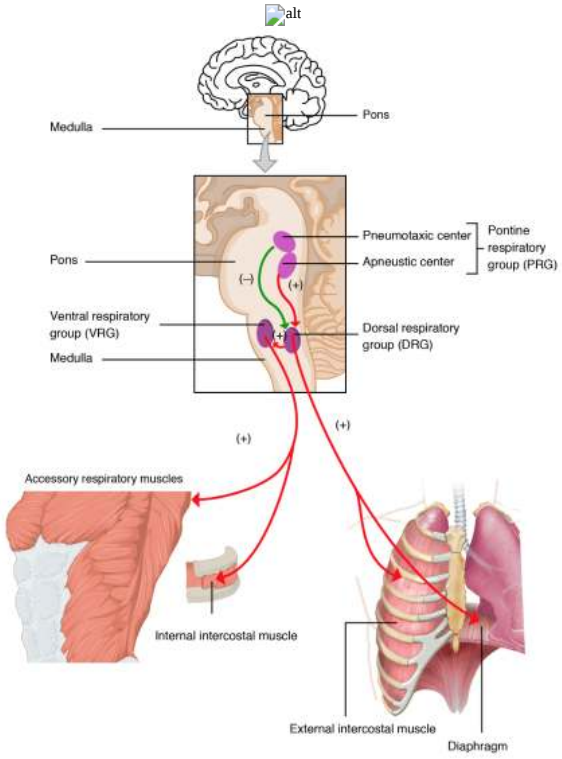



Figure **11.3.4**: Clusters of cells in the pons and medulla of the brain stem are the respiratory centers of the brain that have involuntary control over breathing muscles, such as the diaphragm and external and internal intercostal.

The opposite events occur when the level of carbon dioxide in the blood becomes too low and blood pH rises. This may occur with involuntary hyperventilation, which can happen in panic attacks, episodes of severe pain, asthma attacks, and many other situations. When you hyperventilate, you blow off a lot of carbon dioxide, leading to a drop in blood levels of carbon dioxide. The blood becomes more basic (alkaline), causing its pH to rise.

## NASAL VS. MOUTH BREATHING

Nasal breathing is breathing through the nose rather than the mouth, and it is generally considered to be superior to mouth breathing. The hair-lined nasal passages do a better job of filtering particles out of the air before it moves deeper into the respiratory tract. The nasal passages are also better at warning and moistening the air, so nasal breathing is especially advantageous in the winter when the air is cold and dry. In addition, the smaller diameter of the nasal passages creates greater pressure in the lungs during exhalation. This slows the emptying of the lungs, giving them more time to extract oxygen from the air.

### FEATURE: MYTH VS. REALITY

**Drowning** is defined as respiratory impairment from being in or under a liquid. It is further classified according to its outcome into death, ongoing health problems, or no ongoing health problems (full recovery). In the United States, accidental drowning is the second leading cause of death (after motor vehicle crashes) in children aged 12 years and younger. There are some potentially dangerous myths about drowning. Knowing what they are might save your life or the life of a loved one, especially a child.

**Myth:** People drown when they aspirate water into their lungs.

**Reality:** Generally, in the early stages of drowning, very little water enters the lungs. A small amount of water entering the trachea causes a muscular spasm in the larynx that seals the airway and prevents the passage of water into the lungs. This spasm is likely to last until unconsciousness occurs.

**Myth:** You can tell when someone is drowning because they will shout for help and wave their arms to attract attention.

**Reality:** The muscular spasm that seals the airway prevents the passage of air as well as water, so a person who is drowning is unable to shout or call for help. In addition, instinctive reactions that occur in the final minute or so before a drowning person sinks under the water may look similar to calm, safe behavior. The head is likely to be low in the water, tilted back with the mouth open. The person may have uncontrolled movements of the arms and legs, but they are unlikely to be visible above the water.

**Myth:** It is too late to save a person who is unconscious in the water.

**Reality:** An unconscious person rescued with an airway still sealed from the muscular spasm of the larynx stands a good chance of full recovery if they start receiving CPR within minutes. Without water in the lungs, CPR is much more effective. Even if the cardiac arrest has occurred so the heart is no longer beating, there is still a chance of recovery. However, the longer the brain goes without oxygen, the more likely brain

cells will die. Brain death is likely after about six minutes without oxygen, except in exceptional circumstances, such as young people drowning in very cold water. There are examples of children surviving, apparently without lasting ill effects, for as long as an hour in cold water (see Explore More below for an example). Therefore, rescuers retrieving a child from cold water should attempt resuscitation even after a protracted period of immersion.

**Myth:** If someone is drowning, you should start administering CPR immediately, even before you try to get the person out of the water.

**Reality:** Removing a drowning person from the water is the first priority because CPR is ineffective in the water. The goal should be to bring the person to stable ground as quickly as possible and then to start CPR.

**Myth:** You are unlikely to drown unless you are in water over your head.

**Reality:** Depending on circumstances, people have drowned in as little as 30 mm (about 1 ½ in.) of water. For example, inebriated people or those under the influence of drugs have been known to have drowned in puddles. Hundreds of children have drowned in the water in toilets, bathtubs, basins, showers, pails, and buckets (see figure below).




Figure **11.3.5**: Young children should never be left unattended around sources of water that pose a risk of drowning, including water in toilets, bathtubs, and buckets.

## REVIEW

1. Define breathing.
2. What is another term for the process of breathing?
3. What is the main difference between the processes of inhaling and exhaling?
4. Give examples of activities in which breathing is consciously controlled.
5. Young children sometimes threaten to hold their breath until they get something they want. Why is this an idle threat?
6. Explain how unconscious breathing is controlled.
7. Why is nasal breathing generally considered to be superior to mouth breathing?
8. For each of the following, indicate whether it occurs during the process of inhalation (I) or exhalation (E).
   A. The diaphragm moves downward.
   B. The diaphragm relaxes.
   C. The thoracic cavity becomes smaller.
   D. The air pressure in the lungs is lower than outside the body.
9. Give one example of a situation that would cause blood pH to rise excessively and explain why this occurs.
10. Blood levels of oxygen and carbon dioxide and pH are detected by which of these:
    A. Mechanoreceptors
    B. Chemoreceptors
    C. Lung receptors
    D. Carbon receptors
11. True or False. The diaphragm can contract due to conscious control.
12. True or False. Hypoventilating is breathing that is fast and shallow.

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# 11.4: DISORDERS OF THE RESPIRATORY SYSTEM

## A "MITEY" MONSTER

The scary beast in Figure **11.4.1** is likely to be lurking in your own home, where it feeds on organic debris, including human skin. What is it? It's the common dust mite, a close relative of spiders. The dust mite is so small that it is barely visible with the unaided eye, so it's obviously shown above greatly enlarged. If you think you can get rid of dust mites in your home by frequent and thorough cleaning, think again. There may be thousands of dust mites in just one gram of dust! Regardless of how clean you keep your house, you can't eliminate dust mites entirely. So why even bother trying? The feces of dust mites contain proteins that are a common trigger of asthma attacks.



Figure **11.4.1**: Dust mite

## ASTHMA

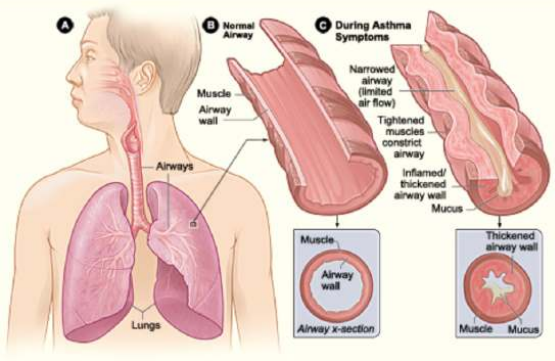



Figure **11.4.2**: During an asthma attack, airways narrow and may become clogged with mucus, making breathing difficult.

**Asthma** is a chronic inflammatory disease of the airways in the lungs, in which the airways periodically become inflamed. As you can see in Figure **11.4.2**, this causes swelling and narrowing of the airways, often accompanied by excessive mucus production. Symptoms of asthma include difficulty breathing, coughing, wheezing, shortness of breath, and chest tightness. Some people with asthma rarely experience symptoms, and then usually only in response to certain triggers in the environment. Other people may have symptoms almost all of the time.

Asthma is thought to be caused by a combination of genetic and environmental factors. A person with a family history of asthma is more likely to develop the disease. Dozens of genes have been found to be associated with asthma, many of which are related to the immune system. Additional risk factors include obesity and sleep apnea (see the feature My Human Body below). Environmental factors trigger asthma attacks in people who have a genetic predisposition to the disease. Besides dust mite feces, triggers may include other allergens (such as pet dander, cockroaches, and mold), certain medications including aspirin, air pollution, and stress, among other possible factors. Symptoms tend to be worse at night and early in the morning. They may also worsen during upper respiratory tract infections, strenuous exercise, or when the airways are exposed to cold air.

There is no cure for asthma at present, but the symptoms of asthma attacks usually can be reversed with the use of inhaled medications called bronchodilators. These medications soothe the constricted air passages and help to re-expand them, making breathing easier. The medications usually start to take effect almost immediately. Other medications can be taken for long-term control of the disease. These medications help prevent asthma attacks from occurring. Corticosteroids are generally considered the most effective treatment for long-term control. Another way to prevent asthma attacks is by avoiding triggers whenever possible.

## PNEUMONIA

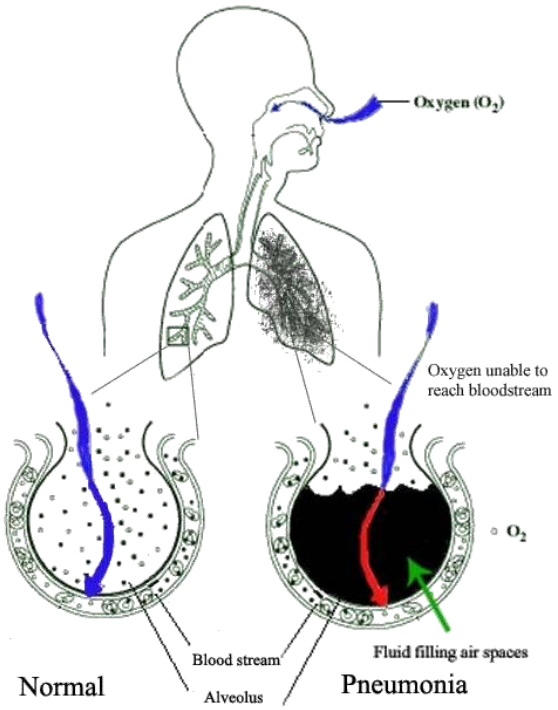



Figure **11.4.3**: Fluid-filled alveoli characteristic of pneumonia inhibit normal gas exchange with the blood.

Another common inflammatory disease of the respiratory tract is **pneumonia.** In pneumonia, the inflammation affects primarily the alveoli, which are the tiny air sacs of the lungs. Inflammation causes some of the alveoli to become filled with fluid so that gas exchange cannot occur. This is illustrated in Figure **11.4.3**. Symptoms of pneumonia typically include coughing, chest pain, difficulty breathing, and fever.

Pneumonia often develops as a consequence of an upper respiratory tract infection such as the common cold or flu, especially in the very young and the elderly. It is usually caused by bacteria or viruses, although some cases may be caused by other microorganisms such as fungi. The majority of cases are caused by just a few pathogens, the most common being the bacterium *Streptococcus pneumoniae.* Pneumonia is more likely to develop in people who have other lung diseases such as asthma, a history of smoking, heart failure, or a weakened immune system.

Vaccines are available to prevent certain types of bacterial and viral pneumonia, including pneumonia caused by *Streptococcus pneumoniae.* Treatment of pneumonia depends on the cause. For example, if it is caused by bacteria, antibiotics are generally prescribed. In cases of severe pneumonia, hospitalization and supplemental oxygen may be required.

## CHRONIC OBSTRUCTIVE PULMONARY DISEASE

**Chronic obstructive pulmonary disease (COPD)** is a lung disease characterized by chronic poor airflow. The main symptoms include shortness of breath and a cough that produces phlegm. These symptoms are usually present for a long period of time and typically become worse over time. Eventually, walking upstairs and similar activities become difficult because of shortness of breath.

COPD formerly was referred to as chronic bronchitis or emphysema. Now, the term *chronic bronchitis* is used to refer to the symptoms of COPD, and the term *emphysema* is used to refer to the lung changes that occur with COPD. Some of these lung changes are shown in Figure **11.4.4**. They include a breakdown of connective tissues that reduces the number and elasticity of alveoli. As a result, the patient can no longer fully exhale air from the lungs, so the air becomes trapped in the lungs. Gas exchange is hampered and may lead to low oxygen levels and too much carbon dioxide in the blood.

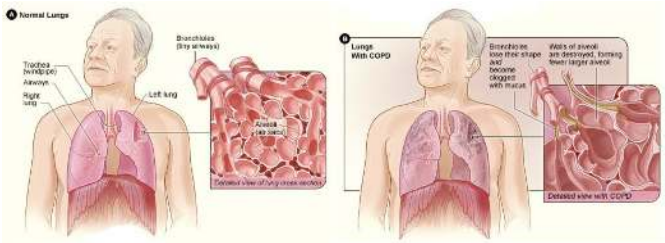



Figure **11.4.4**: The physiological changes that occur with COPD include a breakdown of alveolar walls, reducing the surface area for gas exchange.

Tobacco smoking is the major cause of COPD, with a number of other factors such as air pollution and genetics playing smaller roles. Of people who are life-long smokers, about half will eventually develop COPD. Exposure to secondhand smoke in nonsmokers also increases the risk of COPD and accounts for about 20 percent of cases. Most cases of COPD could have been prevented by never smoking. In people who have already been diagnosed with COPD, cessation of smoking can slow down the rate at which COPD worsens. People with COPD may be treated with supplemental oxygen and inhaled bronchodilators. These treatments may reduce the symptoms but there is no cure for COPD except, in very severe cases, lung transplantation (see the Explore More video below).

## LUNG CANCER

**Lung cancer** is a malignant tumor characterized by uncontrolled cell growth in tissues of the lung. The tumor may arise directly from lung tissue (primary lung cancer) or as a result of metastasis from cancer in another part of the body (secondary lung cancer). Primary lung cancer may also metastasize and spread to other parts of the body. Lung cancer develops following genetic damage to DNA that affects the normal functions of the cell. As more damage accumulates, the risk of cancer increases. The most common symptoms of lung cancer include coughing (especially coughing up blood), wheezing, shortness of breath, chest pain, and weight loss.

The major cause of primary lung cancer is tobacco smoking, which accounts for about 85 percent of cases. Cigarette smoke contains numerous cancer-causing chemicals. Besides smoking, other potential causes of lung cancer include exposure to radon gas, asbestos, secondhand smoke, or other air pollutants. When tobacco smoking is combined with other risk factors such as exposure to radon or asbestos, the risk of lung cancer is heightened. People who have close biological relatives with lung cancer are also at increased risk of developing the disease.

Most cases of lung cancer cannot be cured. In many people, cancer has already spread beyond the original site by the time they have symptoms and seek medical attention. About 10 percent of people with lung cancer do not have symptoms when they are diagnosed, and the cancers are found when they have a chest X-ray for another problem. In part because of its typically late diagnosis, lung cancer is the most common cause of cancer-related death in men and the second most common cause in women (after breast cancer). Common treatments for lung cancer include surgical removal of the tumor, radiation therapy, chemotherapy, or some combination of these three types of treatment.

### FEATURE: MY HUMAN BODY

Do you — or someone you love — snore? Snoring may be more than just an annoyance. It may also be a sign of a potentially dangerous and common disorder known as sleep apnea. **Sleep apnea** is characterized by pauses in breathing that occur most often because of physical blockage to airflow during sleep. When breathing is paused, carbon dioxide builds up in the bloodstream. The higher-than-normal level of carbon dioxide in the blood causes the respiratory centers in the brain to wake the person enough to start breathing normally. This reduces the carbon dioxide level, and the person falls back asleep. This occurs repeatedly throughout the night, causing serious disruption in sleep. Most people with sleep apnea are unaware that they have the disorder because they don't awake fully enough to remember the repeated awakenings throughout the night. Instead, sleep apnea is more commonly recognized by other people who witness the episodes.

Figure 11.4.5shows how sleep apnea typically occurs. The muscle tone of the body normally relaxes during sleep, allowing the soft tissues in the throat to collapse and block the airway. The relaxation of muscles may be exacerbated by the use of alcohol, tranquilizers, or muscle relaxants. The risk of sleep apnea is greater in people who are overweight, smoke tobacco, or have diabetes. The disorder is also more likely to occur in older people and males. Common symptoms of sleep apnea include loud snoring, restless sleep, and daytime sleepiness and fatigue. Daytime sleepiness, in turn, increases the risk of driving and work-related accidents. Continued sleep deprivation may cause moodiness and belligerence. Lack of adequate oxygen to the body because of sleep apnea may also lead to other health problems including fatty liver diseases and high blood pressure. Symptoms of sleep apnea may be present for years or even decades until (and if) a diagnosis is finally made.

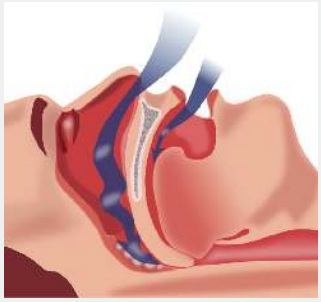


Figure 11.4.5: Sleeping on one's back may increase the risk of the airway becoming temporarily blocked during sleep, resulting in sleep apnea.

Treatment of sleep apnea may include avoiding alcohol, quitting smoking, or losing weight. Elevating the upper body during sleep or sleeping on one's side may help prevent airway collapse in many people with sleep apnea. Another type of treatment is the use of an oral device during sleep that shifts the lower jaw forward to help keep the airway open. The most common treatment for moderate to severe sleep apnea is the use during sleep of CPAP (continuous positive airway pressure), which keeps the airway open by means of pressurized air. In this treatment, the person typically wears a plastic facial mask that is connected by a flexible tube to a small bedside CPAP machine. Although CPAP is effective, long-term compliance is often poor because patients find the mask uncomfortable or they experience unpleasant side effects such as dry mouth and nose. A more extreme form of treatment is surgery to remove some of the tissues — such as the tonsils or part of the soft palate — that tend to collapse and block the airway in people with sleep apnea.

## REVIEW

1. What is asthma, and what are its symptoms and causes?
2. Identify common risk factors and triggers of asthma attacks.
3. How can asthma attacks be prevented or controlled?
4. What are the causes and symptoms of pneumonia?
5. How can pneumonia be prevented? How is it treated?
6. Define COPD. How is it related to chronic bronchitis and emphysema?
7. Relate COPD to tobacco smoking.
8. What is the difference between primary and secondary lung cancer?
9. What is the major cause of primary lung cancer?
10. Discuss lung cancer as a cause of death.
11. How is lung cancer treated?
12. Define sleep apnea.
13. What is the difference between how COPD and pneumonia affect the alveoli?

## EXPLORE MORE

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# 11.5: SMOKING AND HEALTH

## SURE DEATH

The anti-smoking cartoon in Figure **11.5.1** clearly makes the point that smoking causes death. The cartoon is not using hyperbole, because smoking actually is deadly. It causes about six million deaths each year and is the single greatest cause of preventable death worldwide. As many as half of all people who smoke tobacco die from it. As a result of smoking's deadly effects, the life expectancy of long-term smokers is significantly less than that of non-smokers. In fact, long-term smokers can expect their lifespan to be reduced by as much as 18 years, and they are three times as likely to die before the age of 70 as non-smokers.




Figure **11.5.1**: Have another! Sure death

## WHY IS SMOKING DEADLY?

As shown in Figure **11.5.2**, tobacco smoking has adverse effects on just about every bodily system and organ. The detrimental health effects of smoking depend on the number of years that a person smokes and how much the person smokes. Contrary to popular belief, all forms of tobacco smoke — including smoke from cigars and tobacco pipes — have similar health risks as those of cigarette smoke. Smokeless tobacco may be less of a danger to the lungs and heart, but it too has serious health effects. It significantly increases the risk of cancers of the mouth and throat, among other health problems.

Even non-smokers may not be spared the deadly risks of tobacco smoke. If you spend time around smokers either at home or on the job, then you are at risk of the dangers of secondhand smoke. **Secondhand smoke** enters the air directly from burning cigarettes (and cigars and pipes) and indirectly from the lungs of smokers. This smoke may linger in indoor air for hours and increase the risk of a wide range of adverse health effects. For example, non-smokers who are exposed to secondhand smoke may have as much as a 30 percent increase in their risk of lung cancer and heart disease. The 2014 U.S. Surgeon General's Report concluded that there is no established risk-free level of exposure to secondhand smoke.

Tobacco contains **nicotine,** which is a psychoactive drug. Although nicotine in tobacco smoke does not directly cause cancer or most of the other health risks of smoking, it is a highly addictive drug. In fact, nicotine is even more addictive than cocaine or heroin. The addictive nature of nicotine explains why it is so difficult for smokers to quit the habit even when they know the health risks and really want to stop smoking. The good news is that if someone does stop smoking, his or her risks of smoking-related diseases and death soon start to fall. For example, by one year after quitting, the risk of heart disease drops to only half of that of a continuing smoker.

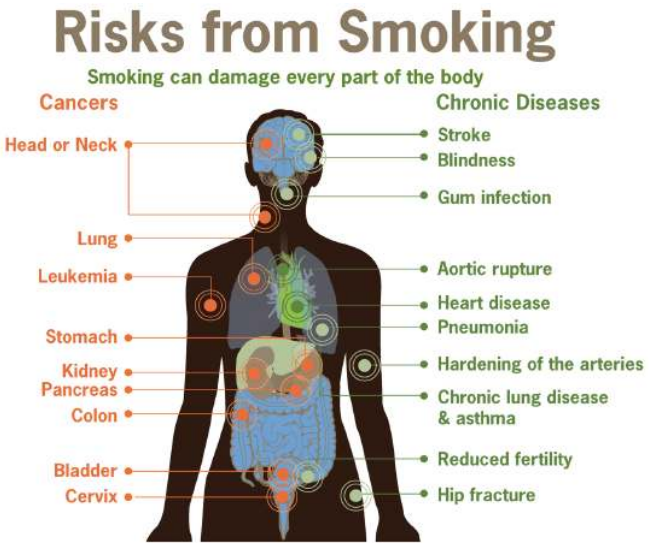



Figure **11.5.2**: Smoking is known to cause many different cancers and chronic diseases such as stroke, blindness, gum infection, aortic rupture, heart disease, pneumonia, hardening of the arteries, chronic lung diseases, reduced fertility, and hip fracture.

## SMOKING AND CANCER

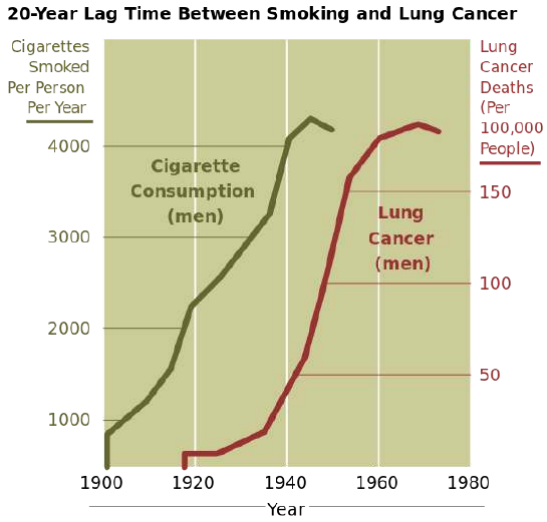



Figure **11.5.3**: Cigarette smoking by men in the U.S. began to decline in the 1950s, but it wasn't until the 1970s — roughly 20 years later — that this was reflected by a concomitant decline in lung cancer deaths in men.

One of the main health risks of smoking is cancer, particularly cancer of the lung. Because of the increased risk of lung cancer with

smoking, the risk of dying from lung cancer before age 85 is more than 20 times higher for a male smoker than for a male non-smoker. As the rate of smoking increases, so does the rate of lung cancer deaths, although the effects of smoking on lung cancer deaths can take up to 20 years to manifest themselves, as shown in Figure **11.5.3**.

Besides lung cancer, several other forms of cancer are also significantly more likely in smokers than non-smokers, including cancers of the kidney, larynx, mouth, lip, tongue, throat, bladder, esophagus, pancreas, and stomach. Unfortunately, many of these cancers have extremely low cure rates.

When you consider the composition of tobacco smoke, it's not surprising that it increases the risk of cancer. Tobacco smoke contains dozens of chemicals that have been proven to be carcinogens or causes of cancer. Many of these chemicals bind to DNA in a smoker's cells and may either kill the cells or cause mutations. If the mutations inhibit programmed cell death, the cells can survive to become cancer cells. Some of the most potent carcinogens in tobacco smoke include benzopyrene, acrolein, and nitrosamines. Other carcinogens in tobacco smoke are radioactive isotopes, including lead-210 and polonium-210.

## RESPIRATORY EFFECTS OF SMOKING

Long-term exposure to the compounds found in cigarette smoke, such as carbon monoxide and cyanide, is thought to be responsible for much of the lung damage caused by smoking. These chemicals reduce the elasticity of alveoli, leading to chronic obstructive pulmonary disease (COPD). COPD is a permanent, incurable, and often fatal reduction in the capacity of the lungs, reducing the ability of the lungs to fully exhale air. The chronic inflammation that is also present in COPD is exacerbated by the tobacco smoke carcinogen acrolein and its derivatives. COPD is almost completely preventable simply by not smoking and by also avoiding secondhand smoke.

## CARDIOVASCULAR EFFECTS OF SMOKING

Inhalation of tobacco smoke causes several immediate responses in the heart and blood vessels. Within one minute of inhalation of smoke, the heart rate begins to rise, increasing by as much as 30 percent during the first 10 minutes of smoking. Carbon monoxide in tobacco smoke binds with hemoglobin in red blood cells, thereby reducing the blood's ability to carry oxygen. Hemoglobin bound to carbon monoxide forms such a stable complex that it may result in a permanent loss of red blood cell function. Several other chemicals in tobacco smoke lead to the narrowing and weakening of blood vessels and an increase in substances that contribute to blood clotting. These changes increase blood pressure and the chances of a blood clot forming and blocking a vessel, thereby elevating the risk of heart attack and stroke. A recent study found that smokers are five times more likely than non-smokers to have a heart attack before the age of 40.

Smoking has also been shown to have a negative impact on the levels of blood lipids. Total cholesterol levels tend to be higher in smokers than non-smokers. Ratios of "good" cholesterol to "bad" cholesterol tend to be lower in smokers than in non-smokers.

## ADDITIONAL ADVERSE HEALTH EFFECTS OF SMOKING

A wide diversity of additional adverse health effects are attributable to smoking. Here are just a few of them:

- Smokers are at a significantly increased risk of developing chronic kidney disease (in addition to kidney cancer). For example, smoking hastens the progression of kidney damage in people with diabetes.
- People who smoke, especially the elderly, have a greater risk of influenza and other infectious diseases than non-smokers. Smoking more than 20 cigarettes a day has been found to increase the risk of infectious diseases by as much as four times the risk in non-smokers. These effects occur because of damage to both the respiratory system and the immune system.
- In addition to oral cancer, smoking causes other oral problems including periodontitis (gum disease). Roughly half of the cases of gum inflammation are attributable to current or former smoking. Such inflammation increases the risk of tooth loss, which is also higher in smokers than non-smokers. In addition, smoking stains the teeth and causes halitosis (bad breath).
- Smoking is a key cause of erectile dysfunction (ED), probably because it leads to narrowing of arteries in the penis as it does elsewhere in the body. The incidence of ED is about 85 percent higher in males who smoke than it is in non-smokers.
- Smoking also has adverse effects on the female reproductive system, potentially causing infertility, in part because it interferes with the body's ability to produce estrogen. Female smokers are about 60 percent more likely to be infertile than non-smokers. Pregnant women who smoke or are exposed to secondhand smoke have a higher risk of miscarriages and low-birth-weight infants.
- Certain therapeutic drugs, including some antidepressants and anticonvulsants, are less effective in smokers than in non-smokers. This occurs because smoking increases levels of liver enzymes that break down the drugs.
- Smoking causes an estimated 10 percent of all deaths due to fires worldwide. Smokers are also at greater risk of dying in motor vehicle crashes and other accidents.
- Smoking leads to an increased risk of bone fractures, especially of the hip. It also leads to slower wound healing after surgery and an increased rate of postoperative complications.

### FEATURE: HUMAN BIOLOGY IN THE NEWS

The item in Figure **11.5.4** looks like a regular cigarette, but it's actually an electronic cigarette or e-cigarette. E-cigarettes are battery-powered devices that change flavored liquids and nicotine into a vapor that is inhaled by the user. E-cigarettes are often promoted as being safer than traditional tobacco products and their use is touted as a good way to quit smoking. They are

often not banned in smoke-free areas where it is illegal to smoke tobacco cigarettes.



Figure **11.5.4**: e-cigarette

A study completed in 2015 by researchers at the Harvard School of Public Health and widely reported in the mass media found that e-cigarettes may in fact be very harmful to the user's health. E-cigarettes contain nicotine and cancer-causing chemicals such as formaldehyde. According to the study, about three-quarters of flavored e-cigarettes also contain a chemical named diacetyl that causes an incurable and potentially fatal disorder of the lungs, commonly called "popcorn lung" (bronchiolitis obliterans). In this disorder, the bronchioles compress and narrow due to the formation of scar tissue. This greatly diminishes the breathing capacity of people with the disorder. Popcorn lung gained its common name in 2004 when it was diagnosed in workers at popcorn factories. The buttery flavoring used in the factories contained diacetyl.

Some manufacturers of e-cigarettes and flavorings advertise that their products are now free of diacetyl. However, because e-cigarettes are not currently regulated by the FDA, there is no way of knowing for sure whether the products are actually safe. Equally disturbing is the appeal of flavored e-cigarettes to teens and the attempts of producers to specifically market their products to this age group. Flavors such as "cotton candy," "Katy Perry's cherry," and "alien blood" are obviously marketed to youth. Not surprisingly, the use of e-cigarettes is on the rise in middle and high school students, who are more likely to use them than regular cigarettes. Public health officials fear that e-cigarettes will be a gateway for teens to move on to smoking tobacco cigarettes. Some states have recently passed laws prohibiting minors from buying e-cigarettes. As more questions are raised about their potential negative health effects, it is likely that more laws will be passed to regulate them. Watch the news for updates on this issue.

## REVIEW

1. What percentage of people who smoke are likely to die from it?
2. Contrast the life expectancy of long-term smokers and non-smokers.
3. What factors related to smoking determine how smoking affects a smoker's health?
4. What are the two sources of secondhand cigarette smoke? How does exposure to secondhand smoke affect non-smokers?
5. Why is it so difficult for smokers to quit the habit? How is their health likely to be affected by quitting?
6. List five types of cancer that are significantly more likely in smokers than non-smokers.
7. Why does smoking cause cancer?
8. Explain how smoking causes COPD.
9. Identify some of the adverse effects of smoking on the cardiovascular system.
10. Give three examples of additional adverse health effects that are more likely with smoking.
11. Do you think e-cigarettes can be addictive? Explain your reasoning.
12. People who smoke are more likely to get which of these than people who do not smoke.

    A. lung cancer
    B. influenza
    C. kidney disease
    D. All of the above

13. Name three toxic chemicals present in tobacco smoke.
14. *True or False.* Nicotine is more addictive than heroin.
15. *True or False.* Smoking has many negative effects on the respiratory and cardiovascular systems, but not on other systems of the body.

## EXPLORE MORE

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# 11.6: CASE STUDY CONCLUSION- BRONCHITIS AND CHAPTER SUMMARY

## CASE STUDY CONCLUSION: COUGH THAT WON'T QUIT

The little child shown in Figure **11.6.1** seems to be enjoying the air coming out of a humidifier. Inhaling the moist air from a humidifier or steamy shower can feel particularly good if you have a respiratory system infection, such as bronchitis. The moist air helps to loosen and thin mucus in the respiratory system, allowing you to breathe easier.



Figure **11.6.1**: Enjoying the Humidifier

At the beginning of this chapter, you learned about Sacheen, who developed acute bronchitis after getting a cold. She had a worsening cough, sore throat due to coughing, and chest congestion. She was also coughing up thick mucus.

Acute bronchitis usually occurs after a cold or flu, usually due to the same viruses that cause cold or flu. Because bronchitis is not usually caused by bacteria (although it can be), antibiotics are not an effective treatment in most cases.

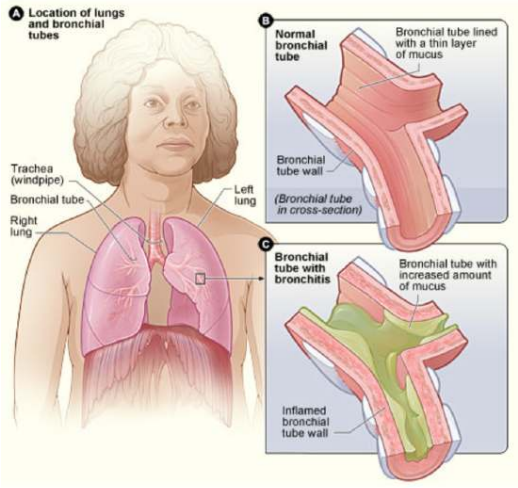



Figure **11.6.2**: Acute Bronchitis

Bronchitis affects the bronchial tubes, which, as you have learned, are air passages in the lower respiratory tract. The main bronchi branch off of the trachea and then branch into smaller bronchi and then bronchioles. In bronchitis, the walls of the bronchi become inflamed, which makes them narrower. Also, there is excessive production of mucus in the bronchi, which further narrows the pathway through which can flow. Figure **11.6.2** shows how bronchitis affects the bronchial tubes.

The function of mucus is to trap pathogens and other potentially dangerous particles that enter the respiratory system from the air. However, when too much mucus is produced in response to an infection (as in the case of bronchitis), it can interfere with normal airflow. The body responds by coughing as it tries to rid itself of the pathogen-laden mucus.

The treatment for most cases of bronchitis involves thinning and loosening the mucus so that it can be effectively coughed out of the airways. This can be done by drinking plenty of fluids, using humidifiers or steam, and in some cases, using over-the-counter medications such as expectorants that are found in some cough medicines. This is why Dr. Tsosie recommended some of these treatments to Sacheen and also warned against using cough suppressants. Cough suppressants work on the nervous system to suppress the cough reflex. When a patient has a “productive” cough —i.e. they are coughing up mucus—doctors generally advise them to not take cough suppressants so that they can cough the mucus out of their bodies.

When Dr. Tsosie was examining Sacheen, she used a pulse oximeter to measure the oxygen level in her blood. Why did she do this? As you have learned, the bronchial tubes branch into bronchioles, which ultimately branch into the alveoli of the lungs. The alveoli are where gas exchange occurs between the air and the blood to take in oxygen and remove carbon dioxide and other wastes. By checking Sacheen’s blood oxygen level, Dr. Tsosie was making sure that her clogged airways were not impacting her level of much-needed oxygen.

Sacheen has acute bronchitis, but you may recall that *chronic* bronchitis was discussed earlier in this chapter as a term that describes the symptoms of chronic obstructive pulmonary disease (COPD). COPD is often due to tobacco smoking and causes damage to the walls of the alveoli, whereas acute bronchitis typically occurs after a cold or flu and involves inflammation and mucus build-up in the bronchial tubes. As implied by the difference in their names, chronic bronchitis is an ongoing, long-term condition, while acute bronchitis is likely to resolve relatively quickly with proper rest and treatment.

However, Sacheen smokes cigarettes, so she is more likely to develop chronic respiratory conditions such as COPD. As you have learned, smoking damages the respiratory system as well as many other systems of the body. Smoking increases the risk of respiratory infections, including bronchitis and flu, due to its damaging effects on the respiratory and immune systems. Dr. Tsosie strongly encouraged Sacheen to quit smoking, not only so that her acute bronchitis resolves, but so that she can avoid future infections and other negative health outcomes associated with smoking, including COPD and lung cancer.

As you have learned in this chapter, the respiratory system is critical to carry out the gas exchange necessary for life’s functions and to

protect the body from pathogens and other potentially harmful substances in the air. But this ability to interface with the outside air has a cost. The respiratory system is prone to infections, as well as damage and other negative effects from allergens, mold, air pollution, and cigarette smoke. Although exposure to most of these things cannot be avoided, not smoking is an important step you can take to protect this organ system—as well as many other systems of your body.

## CHAPTER SUMMARY

In this chapter, you learned about the respiratory system. Specifically, you learned that:

- Respiration is the process in which oxygen moves from the outside air into the body and carbon dioxide and other waste gases move from inside the body into the outside air. It involves two subsidiary processes: ventilation and gas exchange.
- The organs of the respiratory system form a continuous system of passages called the respiratory tract. It has two major divisions: the upper respiratory tract and the lower respiratory tract.
    - The upper respiratory tract includes the nasal cavity, pharynx, and larynx. All of these organs are involved in conduction or the movement of air into and out of the body. Incoming air is also cleaned, humidified, and warmed as it passes through the upper respiratory tract. The larynx is also called the voice box because it contains the vocal cords, which are needed to produce vocal sounds.
    - The lower respiratory tract includes the trachea, bronchi and bronchioles, and the lungs. The trachea, bronchi, and bronchioles are involved in conduction. Gas exchange takes place only in the lungs, which are the largest organs of the respiratory tract. Lung tissue consists mainly of tiny air sacs called alveoli, which is where gas exchange takes place between the air in the alveoli and the blood in capillaries surrounding them.
- The respiratory system protects itself from potentially harmful substances in the air by the mucociliary escalator. This includes mucus-producing cells, which trap particles and pathogens in the incoming air. It also includes tiny hair-like cilia that continually move to sweep the mucus and trapped debris away from the lungs and toward the outside of the body.
- The level of carbon dioxide in the blood is monitored by cells in the brain. If the level becomes too high, it triggers a faster rate of breathing, which lowers the level to the normal range. The opposite occurs if the level becomes too low. The respiratory system exchanges gases with the outside air, but it needs the cardiovascular system to carry the gases to and from cells throughout the body.
- Breathing, or ventilation, is the two-step process of drawing air into the lungs (inhaling) and letting the air out of the lungs (exhaling). Inhaling is an active process that results mainly from the contraction of a muscle called the diaphragm. Exhaling is typically a passive process that occurs mainly due to the elasticity of the lungs when the diaphragm relaxes.
    - Breathing is one of the few vital bodily functions that can be controlled consciously as well as unconsciously. Conscious control of breathing is common in many activities, including swimming and singing. However, there are limits on the conscious control of breathing. If you try to hold your breath, for example, you will soon have an irrepressible urge to breathe.
    - Unconscious breathing is controlled by respiratory centers in the medulla and pons of the brainstem. They respond to variations in blood pH by either increasing or decreasing the rate of breathing as needed to return the pH level to the normal range.
    - Nasal breathing is generally considered to be superior to mouth breathing because it does a better job of filtering, warming, and moistening incoming air. It also results in slower emptying of the lungs, which allows more oxygen to be extracted from the air.
- Gas exchange is the biological process through which gases are transferred across cell membranes to either enter or leave the blood. Gas exchange takes place continuously between the blood and cells throughout the body and also between the blood and the air inside the lungs.
    - Gas exchange in the lungs takes place in alveoli. The pulmonary artery carries deoxygenated blood from the heart to the lungs, where it travels through pulmonary capillaries, picking up oxygen, and releasing carbon dioxide. The oxygenated blood then leaves the lungs through pulmonary veins.
    - Gas exchange occurs by diffusion across cell membranes. Gas molecules naturally move down a concentration gradient from an area of higher concentration to an area of lower concentration. This is a passive process that requires no energy.
    - Gas exchange by diffusion depends on the large surface area provided by the hundreds of millions of alveoli in the lungs. It also depends on a steep concentration gradient for oxygen and carbon dioxide. This gradient is maintained by continuous blood flow and constant breathing.
- Asthma is a chronic inflammatory disease of the airways in the lungs, in which the airways periodically become inflamed. This causes swelling and narrowing of the airways, often with excessive mucus production, leading to difficulty breathing and other symptoms. Asthma is thought to be caused by a combination of genetic and environmental factors. Asthma attacks are triggered by allergens, air pollution, or other factors.
- Pneumonia is a common inflammatory disease of the respiratory tract in which inflammation affects primarily the alveoli, which become filled with fluid that inhibits gas exchange. Most cases of pneumonia are caused by viral or bacterial infections.

Vaccines are available to prevent pneumonia; treatment often includes prescription antibiotics.

- Chronic obstructive pulmonary disease (COPD) is a lung disease characterized by chronic poor airflow, which causes shortness of breath and a productive cough. It is caused most often by tobacco smoking, which leads to the breakdown of connective tissues in the lungs. Alveoli are reduced in number and elasticity, making it impossible to fully exhale air from the lungs. There is no cure for COPD, but stopping smoking may reduce the rate at which COPD worsens.
- Lung cancer is a malignant tumor characterized by uncontrolled cell growth in tissues of the lung. It results from accumulated DNA damage, most often caused by tobacco smoking. Lung cancer is typically diagnosed late, so most cases cannot be cured. It may be treated with surgery, chemotherapy, and/or radiation therapy.
- Smoking is the single greatest cause of preventable death worldwide. It has adverse effects on just about every body system and organ. Tobacco smoke affects not only smokers but also non-smokers who are exposed to secondhand smoke. The nicotine in tobacco is highly addictive, making it very difficult to quit smoking.
  - The major health risk of smoking is cancer of the lungs. Smoking also increases the risk of many other types of cancer. Tobacco smoke contains dozens of chemicals that are known carcinogens.
  - Smoking is the primary cause of COPD. Chemicals such as carbon monoxide and cyanide in tobacco smoke reduce the elasticity of alveoli so the lungs can no longer fully exhale air.
  - Smoking damages the cardiovascular system and increases the risk of high blood pressure, blood clots, heart attack, and stroke. Smoking also has a negative impact on levels of blood lipids.
  - A wide diversity of additional adverse health effects are attributable to smoking, such as erectile dysfunction, female infertility, and slow wound healing.

## CHAPTER SUMMARY REVIEW

1. Describe the relationship between the bronchi, secondary bronchi, tertiary bronchi, and bronchioles.
2. What is the uppermost structure in the lower respiratory tract?
   A. Bronchus
   B. Lung
   C. Alveolus
   D. Trachea
3. Deoxygenated and oxygenated blood both travel to the lungs. Describe what happens to each there.
4. *True or False.* There are radioactive isotopes in cigarette smoke.
5. *True or False.* The right and left lungs are identical in structure.
6. Explain the difference between ventilation and gas exchange.
7. Which way do oxygen and carbon dioxide flow during a gas exchange in the lungs?
   A. Why does this happen?
   B. Which way do oxygen and carbon dioxide flow during the gas exchange between the blood and the body's cells?
   C. Why does this happen?
8. Why does the body require oxygen and give off carbon dioxide as a waste product?
9. *True or False.* Conduction refers to the movement of gases across cell membranes.
10. *True or False.* Gas exchange does not require energy.
11. What do coughing and sneezing have in common?
12. What is the name of the escalator that protects the respiratory system?
    A. phlegmociliary
    B. mucociliary
    C. mucoflagellar
    D. surfactociliary
13. COPD can lead to too much carbon dioxide in the blood. Answer the following questions about this.
    A. Why can COPD cause there to be too much carbon dioxide in the blood?
    B. What does this do to the blood pH?
    C. How does the body respond to this change in blood pH?
14. From the following list of diseases, choose which one best fits each description. Each disease is used only once. Diseases: asthma, pneumonia, COPD, lung cancer
    A. Alveoli become inflamed and fill with fluid
    B. Can be caused by exposure to inhaled carcinogens
    C. There is a reduction in the number of alveoli
    D. Airways periodically narrow and fill with mucus
15. *True or False.* Pneumonia can be caused by fungi.
16. *True or False.* The diaphragm contracts during exhalation.
17. What are three different types of things that can enter the respiratory system and cause illness or injury? Describe the negative health effects of each in your answer.
18. Where are the respiratory centers of the brain located? What is the main function of the respiratory centers of the brain?
19. Smoking increases the risk of getting influenza, commonly known as the flu. Explain why this could lead to a greater risk of getting pneumonia.
20. If people had a gene that caused them to get asthma, could changes to their environment (such as more frequent cleaning) help their asthma? Why or why not?
21. What does the term *bronchodilator* refer to?
    A. The largest bronchial tube
    B. An area of the brain that increases breathing rate
    C. A medication that opens constricted airways
    D. A medication that clears the nasal cavity
22. Explain why nasal breathing generally stops particles from entering the body at an earlier stage than mouth breathing.

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# CHAPTER OVERVIEW

## 12: THE DIGESTIVE SYSTEM

This chapter outlines the structure and function of the gastrointestinal tract and accessory organs of digestion. It explains the processes of peristalsis, mechanical and chemical digestion of food, and absorption of nutrients. The chapter also describes several disorders of the gastrointestinal tract.


12.1: Case Study- Food Processing

12.2: Introduction to the Digestive System

12.3: Digestion and Absorption

12.4: Upper Gastrointestinal Tract

12.5: Lower Gastrointestinal Tract

12.6: Accessory Organs of Digestion

12.7: Disorders of the Gastrointestinal Tract

12.8: Case Study Conclusion- Celiac and Chapter Summary


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# 12.1: CASE STUDY- FOOD PROCESSING

## CASE STUDY: PLEASE DON'T PASS THE BREAD

Rania and Tui are college students who met in physics class. They decide to study together for their upcoming midterm, but first, they want to grab some lunch. Rania says there is a particular restaurant she would like to go to because they are able to accommodate her dietary restrictions. Tui agrees and they head to the restaurant.

At lunch, Tui asks Rania what is special about her diet. Rania tells her that she can't eat gluten. Tui says, "Oh yeah, my cousin did that for a while because she heard that gluten is bad for you. But it was too hard for her to not eat bread and pasta, so she gave it up." Rania tells Tui that avoiding gluten isn't optional for her—she has celiac disease. Eating even very small amounts of gluten could damage her digestive system.




Figure **12.1.1**: Gluten Free (Pizzaberg sign)

You have probably heard of gluten—but what is it and why is it harmful to people with celiac disease? Gluten is a protein found in wheat and some other grains such as barley, rye, and oats. Therefore, it is commonly found in foods such as bread, pasta, baked goods, and many packaged foods. In people with celiac disease, eating gluten causes an autoimmune reaction that results in damage to the small, finger-like villi lining the small intestine, causing them to become inflamed and flattened. This damage interferes with the digestive process, which can result in a wide variety of symptoms including diarrhea, anemia, skin rash, bone pain, depression, and anxiety, among others. The degree of damage to the villi can vary from mild to severe, with more severe damage generally resulting in more significant symptoms and complications. Celiac disease can have serious long-term consequences, such as osteoporosis, problems in the nervous and reproductive systems, and the development of certain types of cancers.

How can celiac disease cause so many different types of symptoms and have such significant negative health consequences? As you read this chapter and learn about how the digestive system works, you will see just how important the villi of the small intestine are to the body as a whole. At the end of the chapter, you will learn more about celiac disease, why it can be so serious, and whether it is worth avoiding gluten for people who do not have a diagnosed medical issue with it.

## CHAPTER OVERVIEW: DIGESTIVE SYSTEM

In this chapter, you will learn about the digestive system, which processes food so that our bodies can obtain nutrients. Specifically, you will learn about:

- The structures and organs of the gastrointestinal (GI) tract through which food directly passes. This includes the mouth, pharynx, esophagus, stomach, small intestine, and large intestine.
- The functions of the GI tract, including mechanical and chemical digestion, absorption of nutrients, and the elimination of solid waste.
- The accessory organs of digestion—the liver, gallbladder, and pancreas—secrete substances needed for digestion into the GI tract, in addition to other important functions.
- Specializations of the tissues of the digestive system that allow it to carry out its functions.
- How different types of nutrients such as carbohydrates, proteins, and fats are digested and absorbed by the body.
- Beneficial bacteria that live in the GI tract and help us digest food, produce vitamins, and protect us from harmful pathogens and toxic substances.
- Disorders of the digestive system, including inflammatory bowel diseases, ulcers, diverticulitis, and gastroenteritis (commonly known as "stomach flu").

As you read this chapter, think about the following questions related to celiac disease:

1. What are the general functions of the small intestine? What do the villi in the small intestine do?
2. Why do you think celiac disease causes so many different types of symptoms and potentially serious complications?
3. What are some other autoimmune diseases that involve the body attacking its own digestive system?

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# 12.2: INTRODUCTION TO THE DIGESTIVE SYSTEM

**YUMMY!**

If you're a dessert lover, then just the sight of this flan dish may make your mouth water. The "water" in your mouth is actually saliva, a fluid released by glands that are part of the digestive system. Saliva contains digestive enzymes among other substances important for digestion. When your mouth waters at the sight of a tasty treat, it's a sign that your digestive system is preparing to digest food.



Figure **12.2.1**: Caramel Cream Flan

## WHAT IS THE DIGESTIVE SYSTEM?

The **digestive system** consists of organs that break down food, absorb its nutrients, and expel any remaining waste. Organs of the digestive system are shown in Figure **12.2.2**. Most of these organs make up the gastrointestinal (GI) tract. Food actually passes through these organs. The rest of the organs of the digestive system are called accessory organs. These organs secrete enzymes and other substances into the GI tract, but food does not actually pass through them.

### FUNCTIONS OF THE DIGESTIVE SYSTEM

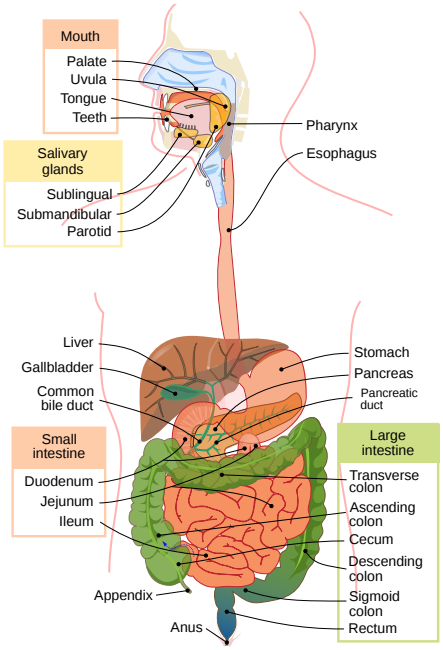



Figure **12.2.2**: The components of the digestive system include the gastrointestinal tract and accessory organs of digestion. The image has labeled parts of the mouth, salivary glands, liver, gallbladder and associated ducts, stomach, pancreas, and small and large intestine parts. Find the organs of the digestive system in this diagram as you read about them in the text.

The digestive system has three main functions relating to food: digestion of food, absorption of nutrients from food, and elimination of solid food waste. Digestion is the process of breaking down food into components the body can absorb. It consists of two types of processes: mechanical digestion and chemical digestion. Mechanical digestion is the physical breakdown of chunks of food into smaller pieces. This type of digestion takes place mainly in the mouth and stomach. Chemical digestion is the chemical breakdown (bonds are broken) of large, complex food molecules into smaller, simpler nutrient molecules that can be absorbed by body fluids (blood or lymph). This type of digestion begins in the mouth and continues in the stomach but occurs mainly in the small intestine.

After food is digested, the resulting nutrients are absorbed. Absorption is the process in which substances pass into the bloodstream or lymph system to circulate throughout the body. The absorption of nutrients occurs mainly in the small intestine. Any remaining matter from food that is not digested and absorbed passes out of the body through the anus in the process of elimination.

## GASTROINTESTINAL TRACT

The **gastrointestinal (GI) tract** is basically a long, continuous tube that connects the mouth with the anus. If it were fully extended, it would be about 9 meters (30 feet) long in adults. It includes the mouth, pharynx, esophagus, stomach, and small and large intestines. Food enters the mouth and then passes through the other organs of the GI tract where it is digested and/or absorbed. Finally, any remaining food waste leaves the body through the anus at the end of the large intestine. It takes up to 50 hours for food or food waste to make the complete trip through the GI tract.

### TISSUES OF THE GI TRACT

The walls of the organs of the GI tract consist of four different tissue layers, which are illustrated in Figure **12.2.3**: mucosa, submucosa, muscularis externa, and serosa.

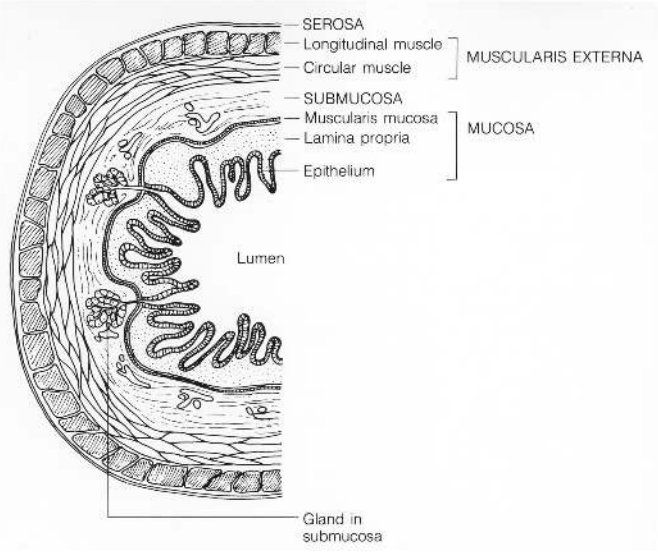



Figure **12.2.3**: This cross-sectional diagram of the wall of a typical GI tract organ shows the layers that comprise it.

1. The mucosa is the innermost layer surrounding the lumen, or open space within the organs of the GI tract. This layer consists mainly of the epithelium with the capacity to secrete and absorb substances. For example, the epithelium can secrete digestive enzymes and mucus, and it can absorb nutrients and water.
2. The submucosa layer consists of connective tissue that contains blood and lymph vessels and also nerves. The vessels are needed to absorb and carry away nutrients after food is digested, and nerves help control the muscles of the GI tract organs.
3. The muscularis externa layer contains two types of smooth muscle: longitudinal muscle and circular muscle. The longitudinal muscle runs the length of the GI tract organs and circular muscle encircles the organs. Both types of muscles contract to keep food moving through the track by the process of peristalsis (Figure **12.2.4**.
4. The serosa layer is the outermost layer of the walls of GI tract organs. This is a thin layer that consists of connective tissue and separates the organs from surrounding cavities and tissues.

## PERISTALSIS IN THE GI TRACT

The muscles in the walls of GI tract organs enable peristalsis, which is illustrated in Figure **12.2.4**. Peristalsis is a continuous sequence of involuntary muscle contraction and relaxation that moves rapidly along an organ like a wave, similar to the way a wave moves through a spring toy. Peristalsis in organs of the GI tract propels food through the tract.

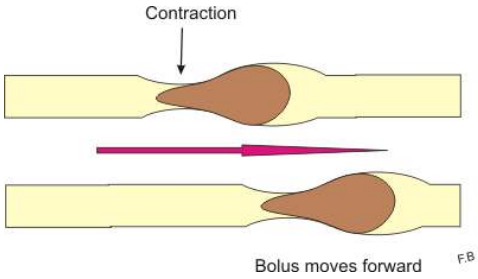



Figure **12.2.4**: Peristalsis pushes food through the GI tract.

## DIVISIONS OF THE GI TRACT

The GI tract is often divided into an upper GI tract and a lower GI tract. For medical purposes, the upper GI tract is typically considered to include all the organs from the mouth through the first part of the small intestine, called the duodenum. For instructional purposes, it makes more sense to include the mouth through the stomach in the upper GI tract and all of the small intestine as well as the large intestine in the lower GI tract. The latter approach is followed here. All organs of GI which are discussed in the text are illustrated in Figure **12.2.2**.

### *UPPER GI TRACT*

The mouth is the first digestive organ that food enters. The sight, smell, or taste of food stimulates the release of digestive enzymes and other secretions by salivary glands inside the mouth. The major salivary gland enzyme is amylase. It begins the chemical digestion of carbohydrates by breaking down starches into sugar. The mouth also begins the mechanical digestion of food. When you chew, your teeth break, crush, and grind food into increasingly smaller pieces. Your tongue helps to mix the food with saliva and also helps you swallow.

A lump of swallowed food is called a **bolus.** The bolus passes from the mouth into the pharynx and from the pharynx into the esophagus. The esophagus is a long, narrow tube that carries food from the pharynx to the stomach. It has no other digestive functions. Peristalsis starts at the top of the esophagus when food is swallowed and continues down the esophagus in a single wave, pushing the bolus of food ahead of it.

From the esophagus, food passes into the stomach, where both mechanical and chemical digestion continue. The muscular walls of the stomach churn and mix the food, thus completing mechanical digestion as well as mixing the food with digestive fluids secreted by the stomach. One of these fluids is hydrochloric acid. As well as killing pathogens in food, it gives the stomach the low pH needed by digestive enzymes that work in the stomach. One of these enzymes is pepsin, which chemically digests proteins. The stomach stores the partially digested food until the small intestine is ready to receive it. Food that enters the small intestine from the stomach is in the form of a thick slurry (semi-liquid) called **chyme.**

### *LOWER GI TRACT*

The small intestine is a narrow but very long tubular organ. It may be almost 7 meters (23 feet) long in adults. It is the site of most chemical digestion and virtually all absorption of nutrients. Many digestive enzymes are active in the small intestine, some of which are produced by the small intestine itself, and some of which are produced by the pancreas, an accessory organ of the digestive system. Much of the inner lining of the small intestine is covered by tiny finger-like projections called **villi,** each of which in turn is covered by even tinier projections called **microvilli.** These projections, shown in Figure **12.2.5**, greatly increase the surface area through which nutrients can be absorbed from the small intestine.

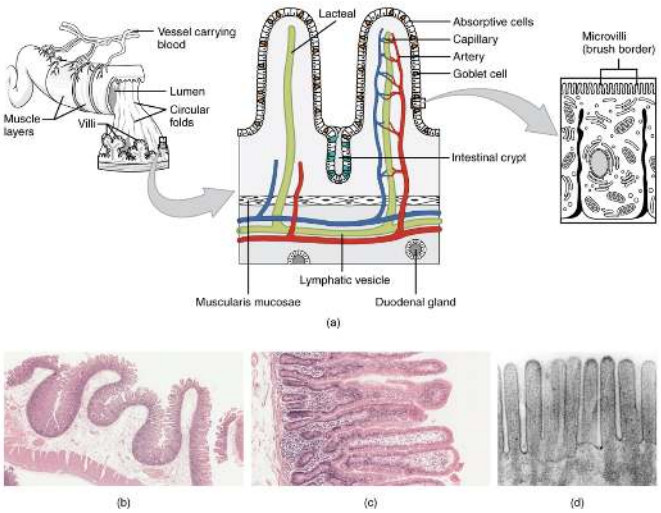



Figure **12.2.5**: The figure above shows three hierarchical small intestine wall modifications that increase the absorptive surface area. The broadest and most gross modification is the projection of mucosa and submucosa called circular folds (b); then, there are projections of mucosa called villi (c); and, finally, the projections of the plasma membrane of absorptive cells called microvilli (d). Microvilli are also referred to as brush border where enzymes reside.

The small intestine is made up of three parts:

1. The duodenum is the first part of the small intestine. It is also the shortest part. This is where most chemical digestion takes place.
2. The jejunum is the second part of the small intestine. This is where most nutrients are absorbed into the blood.
3. The ileum is the last part of the small intestine. A few remaining nutrients are absorbed in the ileum. From the ileum, any remaining food waste passes into the large intestine.

From the small intestine, any remaining nutrients and food waste pass into the large intestine. The large intestine is another tubular organ like the small intestine, but it is wider and shorter than the small intestine. It connects the small intestine and the anus. Waste that enters the large intestine is in a liquid state. As it passes through the large intestine, excess water is absorbed from it. The remaining solid waste, called feces, is eventually eliminated from the body through the anus.

## ACCESSORY ORGANS OF THE DIGESTIVE SYSTEM

Accessory organs of the digestive system are not part of the GI tract, so they are not sites where digestion or absorption take place. Instead, these organs secrete or store substances that are needed for the chemical digestion of food. The accessory organs include the liver, gallbladder, and pancreas. They are shown in Figure **12.2.6** and described in the text:

- The liver is an organ that has a multitude of functions. Its main digestive function is producing and secreting a fluid called bile, which reaches the small intestine through a duct. Bile breaks down large globules of lipids into smaller ones that are easier for enzymes to chemically digest. Bile is also needed to reduce the acidity of food entering the small intestine from the highly acidic stomach because enzymes in the small intestine require a less acidic environment in order to work.
- The gallbladder is a small sac below the liver that stores some of the bile from the liver. The gallbladder also concentrates the bile by removing some of the water from it. It then secretes the concentrated bile into the small intestine as needed for fat digestion following a meal.
- The pancreas secretes many digestive enzymes and releases them into the small intestine for the chemical digestion of carbohydrates, proteins, and lipids. The pancreas also helps to lessen the acidity of the small intestine by secreting bicarbonate, a basic substance that neutralizes the acid.

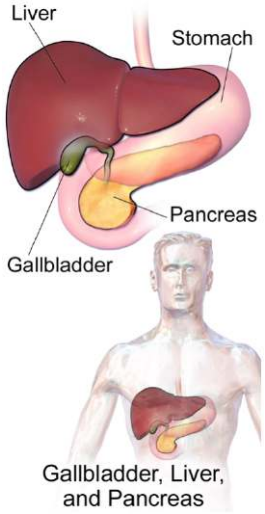



Figure **12.2.6**: This diagram shows the locations of the accessory organs of digestion: the liver, gallbladder, and pancreas.

## REVIEW

1. What is the digestive system?
2. What are the three main functions of the digestive system? Define each function.
3. Describe the GI tract.
4. Distinguish between the upper and lower GI tracts.
5. Relate the tissues in the walls of GI tract organs to the functions the organs perform.
6. Identify accessory organs of digestion and their general function in digestion.
7. Identify the points in the GI tract where food becomes a bolus, chyme, and feces, respectively.
8. Does food pass through the pancreas? Why or why not?
9. *True or False.* Absorption mainly occurs in the stomach.
10. *True or False.* Some chemical digestion occurs in the mouth.
11. Most chemical digestion occurs in the _____ .

    A. Gall bladder

    B. Stomach

    C. Small intestine

    D. Large intestine

12. a. Describe one way in which proteins are at least partially chemically digested in the digestive system.

    b. Describe one way in which carbohydrates are at least partially chemically digested in the digestive system.

13. If the villi in your small intestine were damaged and could not function normally, what effect might this have on your body? Explain your reasoning.
14. The esophagus is considered:

    A. An accessory organ of the digestive system

    B. Part of the upper GI tract

    C. Part of the lower GI tract

    D. The longitudinal muscle

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# 12.3: DIGESTION AND ABSORPTION

## INDIGESTION

The process of digestion does not always go as it should. Many people suffer from indigestion, or dyspepsia, a condition of impaired digestion. Symptoms may include upper abdominal fullness or pain, heartburn, nausea, belching, or some combination of these symptoms. The majority of cases of indigestion occur without evidence of an organic disease that is likely to explain the symptoms. Anxiety or certain foods or medications (such as aspirin) may be contributing factors in these cases. In other cases, indigestion is a symptom of an organic disease, most often gastroesophageal reflux disease (GERD) or gastritis. In a small minority of cases, indigestion is a symptom of a peptic ulcer of the stomach or duodenum, usually caused by a bacterial infection. Very rarely, indigestion is a sign of cancer.

An occasional bout of indigestion is usually nothing to worry about, especially in people less than 55 years of age. However, if you suffer frequent or chronic indigestion, it's a good idea to see a doctor. If an underlying disorder such as GERD or an ulcer is causing indigestion, this can and should be treated. If no organic disease is discovered, the doctor can recommend lifestyle changes or treatments to help prevent or soothe the symptoms of acute indigestion. Lifestyle changes might include modifications in eating habits, such as eating more slowly, eating smaller meals, or avoiding fatty foods. You also might be advised to refrain from taking certain medications, especially on an empty stomach. The use of antacids or other medications to relieve symptoms may also be recommended




Figure **12.3.1**: Add for heartburn medicine from 1882.

## DIGESTION

**Digestion** of food is a form of catabolism, in which the food is broken down into small molecules that the body can absorb and use for energy, growth, and repair. Digestion occurs when food is moved through the digestive system. It begins in the mouth and ends in the small intestine. The final products of digestion are absorbed from the digestive tract, primarily in the small intestine. There are two different types of digestion that occur in the digestive system: mechanical digestion and chemical digestion. Figure **12.3.2** summarizes the roles played by different digestive organs in mechanical and chemical digestion, both of which are described in detail in the text.

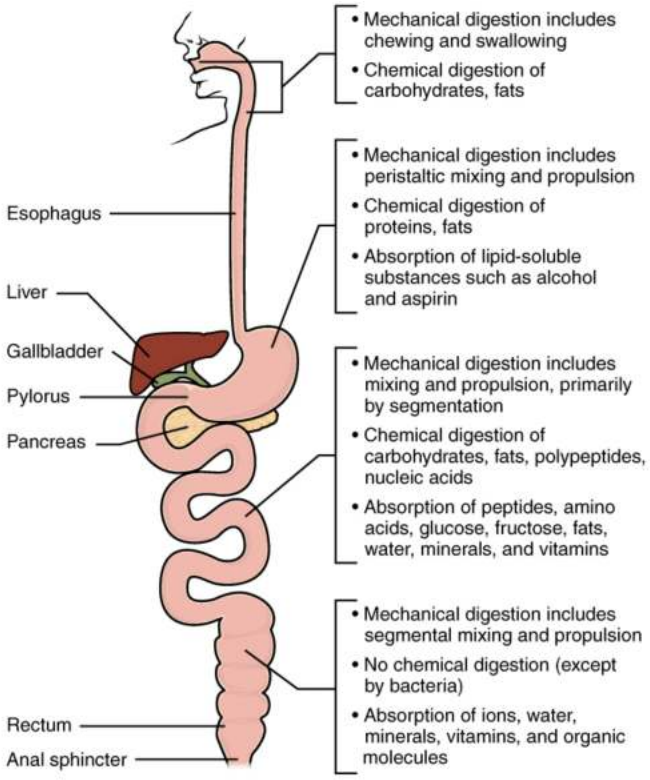



Figure **12.3.2**: Both, mechanical and chemical digestion take place throughout the gastrointestinal tract as indicated in this diagram, but absorption takes place only in the stomach and small and large intestines.

### MECHANICAL DIGESTION

**Mechanical digestion** is a physical process in which food is broken into smaller pieces without becoming changed chemically. It begins with your first bite of food and continues as you chew food with your teeth into smaller pieces. The process of mechanical digestion continues in the stomach. This muscular organ churns and mixes the food it contains, an action that breaks any solid food into still smaller pieces.

Although some mechanical digestion also occurs in the intestines, it is mostly completed by the time food leaves the stomach. At that stage, food in the GI tract has been changed to the thick semi-fluid called chyme. Mechanical digestion is necessary so that chemical digestion can be effective. Mechanical digestion tremendously increases the surface area of food particles so they can be acted upon more effectively by digestive enzymes.

### CHEMICAL DIGESTION

**Chemical digestion** is the biochemical process in which macromolecules in food are changed into smaller molecules that can be absorbed into body fluids and transported to cells throughout the body. Substances in food that must be chemically digested include carbohydrates, proteins, lipids, and nucleic acids. Carbohydrates

must be broken down into simple sugars, proteins into amino acids, lipids into fatty acids and glycerol, and nucleic acids into nitrogen bases and sugars. Some chemical digestion takes place in the mouth and stomach, but most of it occurs in the first part of the small intestine (duodenum).

### DIGESTIVE ENZYMES

Chemical digestion could not occur without the help of many different digestive enzymes. Enzymes are proteins that catalyze or speed up biochemical reactions. Digestive enzymes are secreted by exocrine glands or by the mucosal layer of the epithelium lining the gastrointestinal tract. In the mouth, digestive enzymes are secreted by salivary glands. The lining of the stomach secretes enzymes, as does the lining of the small intestine. Many more digestive enzymes are secreted by exocrine cells in the pancreas and carried by ducts to the small intestine. Table **12.3.1** lists several important digestive enzymes, the organs and/or glands that secrete them, and the compounds they digest. You can read more about them in the text.

Table **12.3.1**: Digestive Enzymes

| Digestive Enzyme | Organ, Glands That Secretes It | Compound It Digests |
|---|---|---|
| Amylase | Salivary Glands, Pancreas | Amylose (Polysaccharide) |
| Sucrase | Small Intestine | Sucrose (Disaccharide) |
| Lactase | Small Intestine | Lactose (Disaccharide) |
| Lipase | Salivary Glands, Pancreas | Lipid |
| Pepsin | Stomach | Protein |
| Trypsin | Pancreas | Protein |
| Chymotrypsin | Pancreas | Protein |
| Deoxyribonuclease | Pancreas | DNA |
| Ribonuclease | Pancreas | RNA |
| Nuclease | Small Intestine | Small Nucleic Acids |

### CHEMICAL DIGESTION OF CARBOHYDRATES

About 80 percent of digestible carbohydrates in a typical Western diet are in the form of the plant polysaccharide amylose, which consists mainly of long chains of glucose and is one of two major components of starch. Additional dietary carbohydrates include the animal polysaccharide glycogen, along with some sugars, which are mainly disaccharides.

To chemically digest amylose and glycogen, the enzyme amylase is required. The chemical digestion of these polysaccharides begins in the mouth, aided by amylase in saliva. Saliva also contains mucus, which lubricates the food, and hydrogen carbonate, which provides the ideal alkaline conditions for amylase to work. Carbohydrate digestion is completed in the small intestine, with the help of amylase secreted by the pancreas. In the digestive process, polysaccharides are reduced in length by the breaking of bonds between glucose monomers. The macromolecules are broken down to shorter polysaccharides and disaccharides, resulting in progressively shorter chains of glucose. The end result is molecules of the simple sugars glucose and maltose (which consists of two glucose molecules), both of which can be absorbed by the small intestine.

Other sugars are digested with the help of different enzymes produced by the small intestine. For example, sucrose, or table sugar, is a disaccharide that is broken down by the enzyme sucrase to form glucose and fructose, which are readily absorbed by the small intestine. Digestion of the sugar lactose, which is found in milk, requires the enzyme lactase, which breaks down lactose into glucose and galactose, which are then absorbed by the small intestine. Fewer than half of all adults produce sufficient lactase to be able to digest lactose. Those who cannot are said to be lactose intolerant.

### CHEMICAL DIGESTION OF PROTEINS

Proteins consist of polypeptides, which must be broken down into their constituent amino acids before they can be absorbed. Protein digestion occurs in the stomach and small intestine through the action of three primary enzymes: pepsin, secreted by the stomach; and trypsin and chymotrypsin secreted by the pancreas. The stomach also secretes hydrochloric acid, making the contents highly acidic, which is required for pepsin to work. Trypsin and chymotrypsin in the small intestine require an alkaline environment to work. Bile from the liver and bicarbonate from the pancreas neutralize the acidic chyme as it empties into the small intestine. After pepsin, trypsin, and chymotrypsin break down proteins into peptides, these are further broken down into amino acids by other enzymes called peptidases, also secreted by the pancreas.

### CHEMICAL DIGESTION OF LIPIDS

The chemical digestion of lipids begins in the mouth. The salivary glands secrete the digestive enzyme lipase, which breaks down short-chain lipids into molecules consisting of two fatty acids. A tiny amount of lipid digestion may take place in the stomach, but most lipid digestion occurs in the small intestine.

Digestion of lipids in the small intestine occurs with the help of another lipase enzyme from the pancreas as well as bile secreted by the liver. Bile is required for the digestion of lipids because lipids are oily and do not dissolve in the watery chyme. Bile emulsifies, or breaks up, large globules of food lipids into much smaller ones, called micelles, much as dish detergent breaks up grease. The micelles provide a great deal more surface area to be acted upon by lipase and also point the hydrophilic (“water-loving”) heads of the fatty acids outward into the watery chyme. Lipase can then access and break down the micelles into individual fatty acid molecules.

### CHEMICAL DIGESTION OF NUCLEIC ACIDS

Nucleic acids (DNA and RNA) in foods are digested in the small intestine with the help of both pancreatic enzymes and enzymes produced by the small intestine itself. Pancreatic enzymes called ribonuclease and deoxyribonuclease break down RNA and DNA, respectively, into smaller nucleic acids. These, in turn, are further broken down into nitrogen bases and sugars by small intestine enzymes called nucleases.

### CHEMICAL DIGESTION BY GUT FLORA

The human gastrointestinal tract is normally inhabited by trillions of bacteria, some of which contribute to digestion. Here are just two of

dozens of examples:

1. The most common carbohydrate in plants, which is cellulose, cannot be digested by the human digestive system. However, tiny amounts of cellulose are digested by bacteria in the large intestine.
2. Certain bacteria in the small intestine help digest lactose, which many adults cannot otherwise digest. As a byproduct of this process, the bacteria produce lactic acid, which increases the release of digestive enzymes and the absorption of minerals such as calcium and iron.

## ABSORPTION

When digestion is finished, it results in many simple nutrient molecules that must go through the process of **absorption** from the GI tract by blood or lymph so they can be used by cells throughout the body. A few substances are absorbed in the stomach and large intestine. For example, water is absorbed in both of these organs, and some minerals and vitamins are also absorbed in the large intestine. However, about 95 percent of nutrient molecules are absorbed in the small intestine. The absorption of the majority of these molecules takes place in the second part of the small intestine, called the jejunum. However, there are a few exceptions. For example, iron is absorbed in the duodenum, and vitamin B12 is absorbed in the last part of the small intestine, called the ileum. After being absorbed in the small intestine, nutrient molecules are transported to other parts of the body for storage or further chemical modification. For example, amino acids are transported to the liver to be used for protein synthesis.

The epithelial tissue lining the small intestine is specialized for absorption. It has many wrinkles and is covered with villi and microvilli, creating an enormous surface area for absorption. As shown in Figure **12.3.3**, each villus also has a network of blood capillaries and fine lymphatic vessels called lacteals close to its surface. The thin surface layer of epithelial cells of the villi transports nutrients from the lumen of the small intestine into these capillaries and lacteals. Blood in the capillaries absorbs most of the molecules, including simple sugars, amino acids, glycerol, salts, and water-soluble vitamins (vitamin C and the many B vitamins). Lymph in the lacteals absorbs fatty acids and fat-soluble vitamins (vitamins A, D, E, and K).

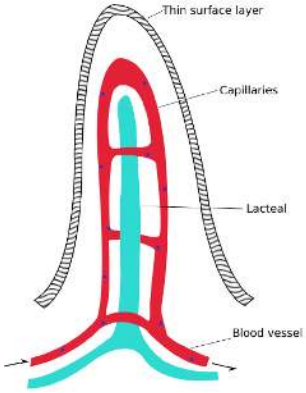



Figure **12.3.3**: This highly simplified drawing of an intestinal villus (plural villi) shows the capillaries and lacteals within it that carry away absorbed substances. Note that each cell in the thin surface layer of the villus is actually covered with microvilli that greatly increase the surface area for absorption.

### FEATURE: MY HUMAN BODY

The process of digestion does not always go as it should. Many people suffer from indigestion, or dyspepsia, a condition of impaired digestion. Symptoms may include upper abdominal fullness or pain, heartburn, nausea, belching, or some combination of these symptoms. The majority of cases of indigestion occur without evidence of an organic disease that is likely to explain the symptoms. Anxiety or certain foods or medications (such as aspirin) may be contributing factors in these cases. In other cases, indigestion is a symptom of an organic disease, most often gastroesophageal reflux disease (GERD) or gastritis. In a small minority of cases, indigestion is a symptom of a peptic ulcer of the stomach or duodenum, usually caused by a bacterial infection. Very rarely, indigestion is a sign of cancer.

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## REVIEW

1. Define digestion. Where does it occur?
2. Identify two organ systems that control the process of digestion by the digestive system.
3. What is mechanical digestion? Where does it occur?
4. Describe chemical digestion.

5. What is the role of enzymes in chemical digestion?
6. What is absorption? When does it occur?
7. a. Where does most absorption occur in the digestive system?

   b. Why does most of the absorption occur in this organ and not earlier in the GI tract?
8. Name two digestive enzymes found in saliva and identify which type of molecule they digest.
9. a. Where is bile produced?

   b. What are some functions of bile?
10. *True or False.* Pepsin digests cellulose.
11. *True or False.* Glucose can be absorbed by the body without being further broken down.
12. The pH of the stomach _____ .

    A. is neutral B. is alkaline

    C. is acidic D. depends only on what you eat
13. Lymph absorbs _____ .

    A. fatty acids B. sugars

    C. amino acids D. vitamin C

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# 12.4: UPPER GASTROINTESTINAL TRACT

## HEAD STAND

Did you ever wonder what would happen if you tried to swallow food while standing on your head? Many people think that food travels down the gullet from the mouth by the force of gravity. If that were the case, then the food you swallowed would stay in your throat while you were standing on your head. In reality, your position doesn't have much to do with your ability to swallow. Food will travel from your mouth to your stomach whether you are standing upright or upside down. That's because the tube the food travels through — the esophagus — moves the food along by the muscular contractions is known as peristalsis. The esophagus is one of several organs that make up the upper gastrointestinal tract.



Figure **12.4.1**: Headstand

## ORGANS OF THE UPPER GASTROINTESTINAL TRACT

Besides the esophagus, organs of the **upper gastrointestinal (GI) tract** include the mouth, pharynx, and stomach. These hollow organs are all connected to form a tube through which food passes during digestion. The only role in digestion played by the pharynx and esophagus is to move food through the GI tract. The mouth and stomach, in contrast, are organs where digestion, or the breakdown of food, also occurs. In both of these organs, food is broken into smaller pieces (mechanical digestion) as well as broken down chemically (chemical digestion). It should be noted that the first part of the small intestine (duodenum) is considered in some contexts to be part of the upper GI tract, but that practice is not followed here. You can read about the small intestine (and large intestine) in the concept Lower Gastrointestinal Tract.

## MOUTH

The mouth is the first organ of the GI tract. Most of the oral cavity is lined with a mucous membrane. This tissue produces mucus, which helps to moisten, soften, and lubricate food. Underlying the mucous membrane is a thin layer of smooth muscle to which the mucous membrane is only loosely connected. This gives the mucous membrane considerable ability to stretch as you eat food. The roof of the mouth, called the palate, separates the oral cavity from the nasal cavity. The front part is the hard palate, consisting of a mucous membrane covering a plate of bone. The back part of the palate is softer and more pliable, consisting of mucous membrane over muscle and connective tissue. The hard surface of the front of the palate allows for the pressure needed in chewing and mixing food. The soft, pliable surface of the back of the palate can move to accommodate the passage of food while swallowing. Muscles at either side of the soft palate contract to create the swallowing action.

Several specific structures in the mouth are specialized for digestion. These include salivary glands, tongue, and teeth.

### SALIVARY GLANDS

The mouth contains three pairs of major **salivary glands**, which are shown in Figure **12.4.2**. These three pairs are all exocrine glands that secrete **saliva** into the mouth through ducts.

1. The largest of the three major pairs of salivary glands are the parotid glands, which are located on either side of the mouth in front of the ears.
2. The next largest pair is the submandibular glands, located beneath the lower jaw.
3. The third pair is the sublingual glands, located underneath the tongue.

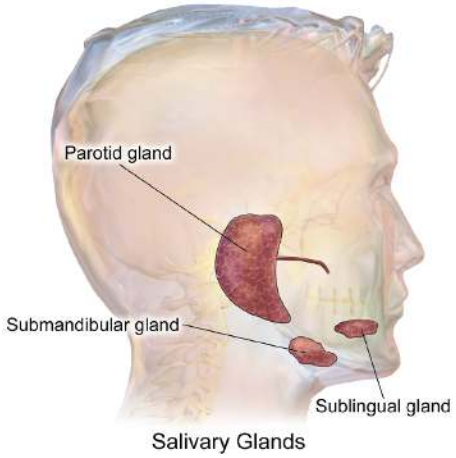



Figure **12.4.2**: Salivary glands in the mouth include the three major pairs of glands shown here. The sublingual gland is under the tongue. The submandibular gland is below the jaw. The parotid gland is the back of the mouth.

In addition to these three pairs of major salivary glands, there are also hundreds of minor salivary glands in the oral mucosa lining the mouth and on the tongue. Along with the major glands, most of the minor glands secrete the digestive enzyme amylase, which begins the chemical digestion of starch and glycogen (polysaccharides). However, the minor salivary glands on the tongue secrete the fat-digesting enzyme lipase, which in the mouth is called lingual lipase (to distinguish it from pancreatic lipase secreted by the pancreas).

The saliva secreted by the salivary glands mainly helps digestion, but it also plays other roles. It helps to maintain dental health by cleaning the teeth, and it contains antibodies that help protect against infection. By keeping the mouth lubricated, saliva also allows the mouth movements needed for speech.

## TONGUE

The tongue is a fleshy, muscular organ that is attached to the floor of the mouth by a band of ligaments that gives it great mobility. This is necessary so the tongue can manipulate food for chewing and swallowing. Movements of the tongue are also necessary for speaking. The upper surface of the tongue is covered with tiny projections called papillae, which contain taste buds. The latter are collections of chemoreceptor cells. These sensory cells sense chemicals in food and send the information to the brain via cranial nerves, thus enabling the sense of taste.

## TEETH

The teeth are complex structures made of a bone-like material called dentin and covered with enamel, which is the hardest tissue in the body. Adults normally have a total of 32 teeth, with 16 in each jaw. The right and left sides of each jaw are mirror images in terms of the numbers and types of teeth they contain. Teeth have different shapes to suit them for different aspects of mastication (chewing).

## PHARYNX

The tube-like pharynx (Figure **12.4.3**) plays a dual role as an organ of both respiration and digestion. As part of the respiratory system, it conducts air between the nasal cavity and larynx. As part of the digestive system, it allows swallowed food to pass from the oral cavity to the esophagus. Anything swallowed has priority over inhaled air when passing through the pharynx. During swallowing, the backward motion of the tongue causes a flap of elastic cartilage, called the epiglottis, to close over the opening to the larynx. This prevents food or drinks from entering the larynx.

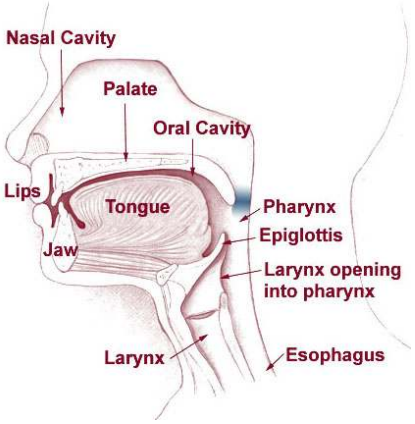



Figure **12.4.3**: The tongue moves backward during swallowing to cause the epiglottis to cover the opening to the larynx so food passes from the pharynx to the esophagus and not into the larynx.

## ESOPHAGUS

The **esophagus,** which is shown in Figure **12.4.4**, is a muscular tube through which food is pushed from the pharynx to the stomach. The esophagus passes through an opening in the diaphragm (the large breathing muscle that separates the abdomen from the thorax) before reaching the stomach. In adults, the esophagus averages about 25 cm (10 in.) in length, depending on a person's height. The inner lining of the esophagus consists of a mucous membrane, which provides a smooth, slippery surface for the passage of food. The cells of this membrane are constantly being replaced as they are worn away from the frequent passage of food over them.

When food is not being swallowed, the esophagus is closed at both ends by upper and lower esophageal sphincters. **Sphincters** are rings of muscle that can contract to close off openings between structures. The upper esophageal sphincter is triggered to relax and open by the act of swallowing, allowing a bolus of food to enter the esophagus from the pharynx. Then the esophageal sphincter closes again to prevent food from moving back into the pharynx.

Once in the esophagus, the food bolus travels down to the stomach, pushed along by the rhythmic contraction and relaxation of muscles (peristalsis). The lower esophageal sphincter is located at the junction between the esophagus and the stomach. This sphincter opens when the bolus reaches it, allowing the food to enter the stomach. The sphincter normally remains closed at other times to prevent the contents of the stomach from entering the esophagus. Failure of this sphincter to remain completely closed can lead to heartburn. If it happens chronically, it can lead to gastroesophageal reflux disease (GERD), in which the mucous membrane of the esophagus may become damaged by the highly acidic contents of the stomach.

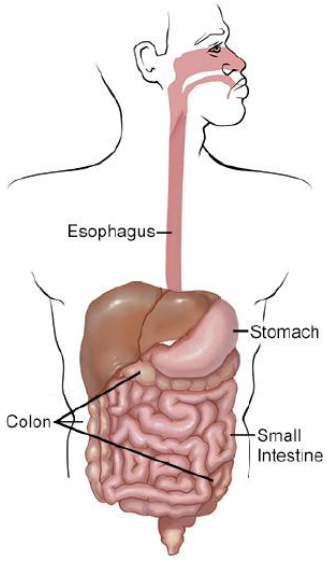



Figure **12.4.4**: The esophagus is located behind the trachea and it connects the pharynx to the stomach. The stomach is connected at the bottom to the small intestine.

## STOMACH

The **stomach** (Figure **12.4.4** is a J-shaped organ that is joined to the esophagus at its upper end and to the first part of the small intestine (duodenum) at its lower end. When the stomach is empty of food, it normally has a volume of about 75 mL. However, it can expand to hold up to about a liter of food. Waves of muscle contractions (peristalsis) passing through the muscular walls of the stomach cause the food inside to be mixed and churned. The wall of the stomach has an extra layer of muscle tissue not found in other organs of the

GI tract that helps it squeeze and mix the food. These movements of the stomach wall contribute greatly to mechanical digestion by breaking the food into much smaller pieces. The churning also helps to mix the food with stomach secretions that aid in its chemical digestion.

Secretions of the stomach include gastric acid, which consists mainly of hydrochloric acid. This makes the stomach contents highly acidic, which is necessary so that the enzyme pepsin — also secreted by the stomach — can begin the digestion of protein. Mucus is secreted by the lining of the stomach to provide a slimy protective coating against the otherwise damaging effects of gastric acid. The fat-digesting enzyme lipase is secreted in small amounts in the stomach, but very little fat digestion occurs there.

By the time food has been in the stomach for about an hour, it has become the thick, semi-liquid chyme. When the small intestine is ready to receive chyme, a sphincter between the stomach and duodenum, called the pyloric sphincter, opens to allow the chyme to enter the small intestine for further digestion and absorption.

### FEATURE: RELIABLE SOURCES

The ongoing epidemic of obesity has led to the development of several different bariatric surgeries that modify the stomach to help obese patients reduce their food intake and lose weight. Go online to learn more about bariatric surgery. Find sources you judge to be reliable that answer the following questions:

1. Who qualifies for bariatric surgery?
2. Describe the bariatric surgeries commonly called stomach stapling, lap band, and gastric sleeve. How does each type of surgery modify the stomach? How effective is each type in terms of weight loss?
3. What are the major potential risks of bariatric surgery?
4. Besides weight loss, what other benefits have been shown to result from bariatric surgery?

## REVIEW

1. List organs of the upper gastrointestinal tract.
2. Identify structures in the mouth that are specialized for digestion.
3. Describe digestion in the mouth.
4. What general role do the pharynx and esophagus play in the digestion of food?
5. How does food travel through the esophagus?
6. Describe digestion in the stomach.
7. In which of the following structures does chemical digestion occur?

   A. Mouth

   B. Esophagus

   C. Stomach

   D. A and C

   E. A, B, and C
8. In which of the following structures does mechanical digestion occur?

   A. Mouth

   B. Pharynx

   C. Stomach

   D. A and C

   E. A, B, and C
9. Describe the differences between how air and food normally move past the pharynx.
10. Name two structures in the mouth that contribute to mechanical digestion.
11. What structure normally keeps stomach contents from backing up into the esophagus?
12. *True or False.* Peristalsis occurs in the esophagus, but not in the stomach.
13. *True or False.* The sense of taste is due to the detection of chemicals by the tongue.
14. Where is most of your food located thirty minutes after you eat a meal? Explain your answer.
15. What are the two roles of mucus in the upper GI tract?

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# 12.5: LOWER GASTROINTESTINAL TRACT

## WHAT IS IT?

Figure **12.5.1** shows some of the cells of what has been called "the last human organ to be discovered." This "organ" weighs about 200 grams (0.44 lb.) and consists of a hundred trillion cells, yet scientists are only now beginning to learn everything it does and how it varies among individuals. What is it? It's the mass of bacteria that live in our lower gastrointestinal tract.



Figure **12.5.1**: Micrograph of *Bacteroides biacutis* - cultured in blood agar medium for 48 hours.

## ORGANS OF THE LOWER GASTROINTESTINAL TRACT

Most of the bacteria that normally live in the **lower gastrointestinal (GI) tract** live in the large intestine. They have important and mutually beneficial relationships with the human organism. We provide them with a great place to live, and they provide us with many benefits, some of which you can read about below. Besides the large intestine and its complement of helpful bacteria, the lower GI tract also includes the small intestine. The latter is arguably the most important organ of the digestive system. It is where most chemical digestion and virtually all absorption of nutrients take place.

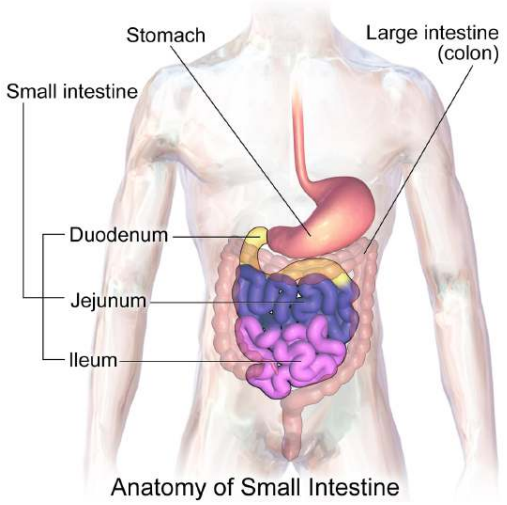



Figure **12.5.2**: The three parts of the small intestine are color-coded in this diagram, with yellow for the duodenum (the first part of the small intestines), blue for the jejunum (the middle), and pink for the ileum (the end of the small intestines).

## SMALL INTESTINE

The **small intestine** (also called the small bowel or gut) is the part of the GI tract between the stomach and large intestine. Its average length in adults is 4.6 m (15 ft) in females and 6.9 m (22 ft 8 in.) in males. It is approximately 2.5 to 3.0 cm (1.0 to 1.2 in.) in diameter (it is called "small" because it is much smaller in diameter than the large intestine). The internal surface area of the small intestine totals an average of about 30 $m^2$ (323 $ft^2$). Structurally and functionally, the small intestine can be divided into three parts, called the duodenum, jejunum, and ileum, as shown in Figure **12.5.2** and described below.

The mucosa lining the small intestine is very wrinkled and covered with finger-like projections called villi. In fact, each square inch of mucosa contains around 20,000 villi. The individual cells on the surface of the villi also have many finger-like projections, the microvilli shown in Figure **12.5.3**. There are thought to be well over 100 billion microvilli per square inch of intestinal mucosa! All of these wrinkles, villi, and microvilli greatly increase the surface area for chyme to come into contact with digestive enzymes, which coat the microvilli, as well as forming a tremendous surface area for the absorption of nutrients. Inside each of the villi is a network of tiny blood and lymph vessels that receive the absorbed nutrients and carry them away in the blood or lymph circulation. The wrinkles and projections in the intestinal mucosa also slow down the passage of chyme so there is more time for digestion and absorption to take place.

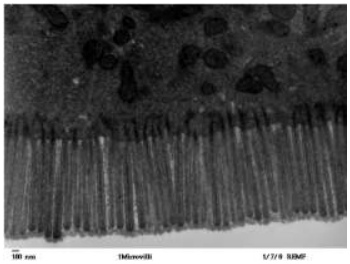


Figure **12.5.3**: The fringe-like structures in this photomicrograph are microvilli lining the inside of the small intestine.

### DUODENUM

The **duodenum** is the first part of the small intestine, directly connected to the stomach. It is also the shortest part of the small intestine, averaging only about 25 cm (10 in.) in length in adults. Its main function is chemical digestion, and it is where most of the chemical digestion in the entire GI tract takes place.

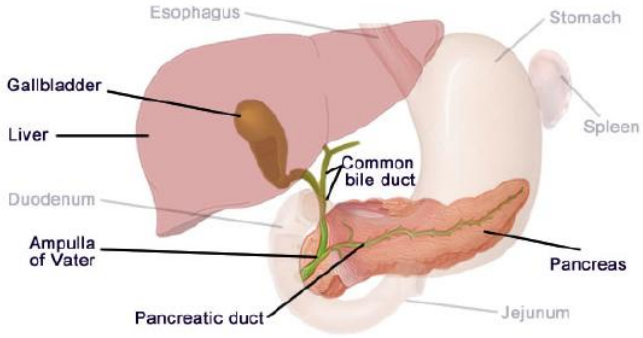



Figure **12.5.1**: This figure shows the liver, gallbladder, and pancreas, along with the ducts that carry their secretions to the duodenum

The duodenum receives partially digested, semi-liquid chyme from the stomach. It receives digestive enzymes and alkaline bicarbonate from the pancreas through the pancreatic duct, and it receives bile from the liver via the gallbladder through the common bile duct (Figure **12.5.4**). In addition, the lining of the duodenum secretes digestive enzymes and contains glands — called Brunner's glands — that secrete mucus and bicarbonate. The bicarbonate from the pancreas and Brunner's glands as well as bile from the liver neutralize the highly acidic chyme after it enters the duodenum from the stomach. This is necessary because the digestive enzymes in the duodenum require a nearly neutral environment in order to work. The three major classes of compounds that undergo chemical digestion in the duodenum are carbohydrates, proteins, and lipids.

#### *DIGESTION OF CARBOHYDRATES IN THE DUODENUM*

Complex carbohydrates such as starches are broken down by the digestive enzyme amylase from the pancreas to short-chain molecules consisting of just a few saccharides (that is, simple sugars). Disaccharides, including sucrose and lactose, are broken down into simple sugars by duodenal enzymes: sucrase breaks down sucrose, and lactase (if present) breaks down lactose. Some carbohydrates are not digested in the duodenum and ultimately pass undigested to the large intestine, where they may be digested by intestinal bacteria.

#### *DIGESTION OF PROTEINS IN THE DUODENUM*

In the duodenum, the pancreatic enzymes trypsin and chymotrypsin cleave proteins into peptides. Then, these smaller molecules are broken down into amino acids. Their digestion is catalyzed by pancreatic enzymes called peptidases.

#### *DIGESTION OF LIPIDS IN THE DUODENUM*

Pancreatic lipase breaks down triglycerides into fatty acids and glycerol. Lipase works with the help of bile secreted by the liver and stored in the gall bladder. Bile salts attach to triglycerides to help them emulsify or form smaller particles (called micelles) that can disperse through the watery contents of the duodenum. This increases the access to the molecules by pancreatic lipase.

### JEJUNUM

The **jejunum** is the middle part of the small intestine, connecting the duodenum and the ileum. The jejunum is about 2.5 m (8.2 ft) long. Its main function is the absorption of the products of digestion, including sugars, amino acids, and fatty acids. Absorption occurs by simple diffusion (water and fatty acids), facilitated diffusion (the simple sugar fructose), or active transport (amino acids, small peptides, water-soluble vitamins, and most glucose). All nutrients are absorbed into the blood except for fatty acids and fat-soluble vitamins, which are absorbed into the lymph. Although most nutrients are absorbed in the jejunum, there are a few exceptions:

- Iron is absorbed in the duodenum.
- Vitamin B12 and bile salts are absorbed in the ileum.
- Water and lipids are absorbed throughout the small intestine, including the duodenum and ileum in addition to the jejunum.

### ILEUM

The **ileum** is the third and final part of the small intestine, directly connected at its distal end to the large intestine. The ileum is about 3 m (9.8 ft) long. Some cells in the lining of the ileum secrete enzymes that catalyze the final stages of digestion of any undigested protein and carbohydrate molecules. However, the main function of the ileum is to absorb vitamin B12 and bile salts. It also absorbs any other remaining nutrients that were not absorbed in the jejunum. All substances in chyme that remain undigested or unabsorbed by the time they reach the distal end of the ileum pass into the large intestine.

## LARGE INTESTINE

The **large intestine**, also called the large bowel, is the last organ of the GI tract. In adults, it averages about 1.5 m (5 ft) in length. It is shorter than the small intestine but at least twice as wide, averaging about 6.5 cm (2.5 in.) in diameter. Water is absorbed from the chyme as it passes through the large intestine, turning the chyme into solid feces. Feces is stored in the large intestine until it leaves the body during defecation.

### PARTS OF THE LARGE INTESTINE

Like the small intestine, the large intestine can be divided into several parts, as shown in Figure **12.5.5**. The large intestine begins at the end of the small intestine, where a valve separates the small and large intestines and regulates the movement of chyme into the large intestine. The first part of the large intestine, where chyme enters from the small intestine, is called the cecum. From the cecum, the large intestine continues upward as the ascending colon, travels across the upper abdomen as the transverse colon, and then continues downward as the descending colon. It then becomes a V-shaped region called the sigmoid colon, which is attached to the rectum. The **rectum** stores feces until elimination occurs. It transitions to the final part of the large intestine, called the **anus,** which has an opening to the outside of the body for feces to pass through.

A projection from the cecum of the colon is known as the **appendix.** The function of the appendix is uncertain, but it does not seem to be involved in digestion or absorption. It may play a role in immunity, and in the fetus, it seems to have an endocrine function, releasing hormones needed for homeostasis. Some biologists speculate that the appendix may also store a sample of the colon's normal bacteria. If so, it may be able to repopulate the colon with the bacteria if illness or antibiotic medications deplete these microorganisms. Appendicitis, or infection and inflammation of the appendix, is a fairly common medical problem, typically resolved by surgical removal of the appendix (appendectomy). People who have had their appendix surgically removed do not seem to suffer any ill effects, so the organ is considered to be dispensable. As such, it is often referred to as a vestigial organ, which is a previously useful organ that has been retained over evolutionary time as part of the anatomy, even though it no longer has a function in the body.

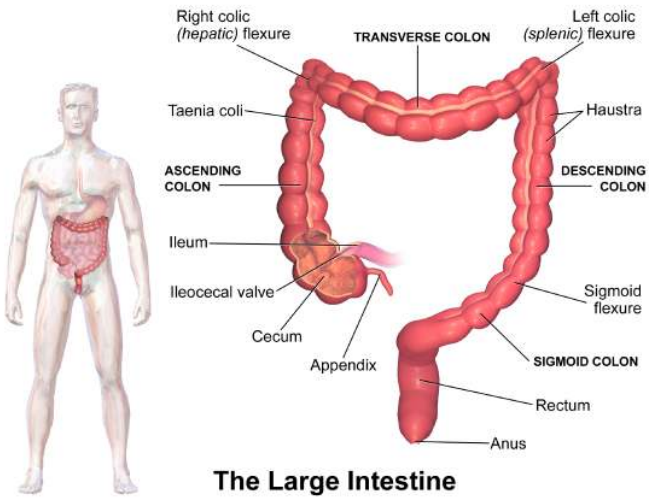



Figure **12.5.5**: The parts of the large intestine include the cecum (just after the small intestines), ascending colon (moving upward), transverse colon (moving across), descending colon (moving downward), sigmoid colon (small S-shaped segment), rectum (connecting to the anus), and anus.

## FUNCTIONS OF THE LARGE INTESTINE

The removal of water from chyme to form feces starts in the ascending colon and continues throughout much of the length of the organ. Salts such as sodium are also removed from food wastes in the large intestine before the wastes are eliminated from the body. This allows salts as well as water to be recycled in the body.

The large intestine is also the site where huge numbers of beneficial bacteria ferment many unabsorbed materials in food waste. The bacterial breakdown of undigested polysaccharides produces nitrogen, carbon dioxide, methane, and other gases that are responsible for intestinal gas, or flatulence. These bacteria are particularly prevalent in the descending colon. Some of the bacteria also produce vitamins that are absorbed from the colon. The vitamins include vitamins $B_1$ (thiamine), $B_2$ (riboflavin), $B_7$ (biotin), $B_{12}$, and K. Another role of bacteria in the colon is immune function. The bacteria may stimulate the immune system to produce antibodies that are effective against similar, but pathogenic, bacteria, thereby preventing infections. Still, other roles played by bacteria in the large intestine include breaking down toxins before they can poison the body, producing substances that help prevent colon cancer, and inhibiting the growth of harmful bacteria.

### FEATURE: MY HUMAN BODY

Colorectal cancer, or cancer of the colon or rectum, is the fourth most common cancer in the United States. It is also the second most common cause of cancer deaths in this country. Widespread screening of patients for signs of colorectal cancer has significantly lowered the death rate in recent years. Because early-stage colorectal cancer is usually asymptomatic, routine screening is important for identifying cancer early when chances of a cure are still high.

Screening for colorectal cancer has also become easier and less invasive in recent years. One way to test for colorectal cancer is to examine a sample of stool and look for occult (hidden from the unaided eye) blood in the stool. This test is based on the assumption that blood vessels in cancer are fragile and may be easily damaged by the passage of feces through the colon or rectum. The damaged vessels may bleed into the feces but rarely bleed enough for blood to be visible in the stool. Stool for the occult blood test can be collected by the patient at home with a test kit provided by a doctor. If occult blood is detected in the stool, a different type of follow-up test is generally needed to determine whether cancer is the cause of the bleeding.

A similarly simple and noninvasive but more definitive test for colorectal cancer looks for DNA from cancer cells in the stool. Again, the patient can collect the stool sample at home using a simple test kit and mail the specimen to a lab, which does the analysis. If the test comes back positive, then a direct visual examination of the colon and rectum by colonoscopy is required.

Colonoscopy is the gold standard for the diagnosis of colorectal cancer. Using a tiny camera at the end of a long tube inserted up into the colon, a doctor can directly visualize the lining of the large intestine and spot any suspicious areas that may be cancerous. While a colonoscopy is invasive and requires the patient to prepare for the test for a couple of days by changing his or her diet and drinking special fluids, it reveals more than just cancer. A colonoscopy also reveals any growths called polyps in the colon. Colon polyps are not cancer but often develop into cancerous lesions, so if they are found during a colonoscopy, a surgical instrument inserted with the scope is usually used to remove them. Therefore, a colonoscopy can not only detect cancer in its early stages, but it can even help prevent cancer by enabling the removal of potentially pre-cancerous polyps.

A test similar to colonoscopy may be done in some patients. Called a flexible sigmoidoscopy, it allows a doctor to use a small camera to inspect the rectum and lower third of the colon, where the majority of cases of colorectal cancer occur. However, the rest of the colon cannot be examined with a sigmoidoscopy. Another alternative to a full-blown colonoscopy is a virtual colonoscopy, in which a CT scan of the rectum and colon is used to make detailed cross-sectional images of the organs. The images can then be studied by a specialist to detect cancers or polyps. For both of these colonoscopy alternatives, a follow-up colonoscopy is required if polyps or potentially cancerous lesions are detected.

Unless you have a family history of colorectal cancer or certain other risk factors, you probably do not need to start routine screening for the disease until middle age. Your doctor can tell you the most appropriate starting age for your particular case, given your risk factors and current cancer guidelines. You may be able to be screened with one of the less invasive methods

rather than colonoscopy until you are somewhat older. Again, check with your doctor for specific recommendations. All of the testing methods have pros and cons that should be taken into consideration by a given patient and medical provider.

## REVIEW

1. Which organs are included in the lower GI tract?
2. Name the parts of the small intestine.
3. How is the mucosa of the small intestine specialized for digestion and absorption?
4. What digestive substances are secreted into the duodenum, and what compounds in food do they help digest?
5. What is the main function of the jejunum?
6. What roles are played by the ileum?
7. Name the parts of the large intestine.
8. Identify the main functions of the large intestine.
9. How do beneficial bacteria in the large intestine help the human organism?
10. *True or False.* The first part of the large intestine is where most chemical digestion takes place.
11. *True or False.* The small intestine is actually longer than the large intestine.
12. When diarrhea occurs, feces leaves the body in a more liquid state than normal. What part of the digestive system do you think is involved in diarrhea? Explain your answer.
13. Arrange the following parts of the lower GI tract in order of how food passes through them, from earliest to latest. Note that not all parts are listed.

    cecum; duodenum; sigmoid colon; jejunum; rectum; ileum

14. Which enzyme digests proteins?

    A. trypsin

    B. amylase

    C. lipase

    D. lactase

15. What is intestinal gas, or flatulence, due to?

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# 12.6: ACCESSORY ORGANS OF DIGESTION

## JAUNDICED EYES

Did you ever hear of a person looking at something or someone with a "jaundiced eye"? It means to take a negative view, such as envy, maliciousness, or ill will. The expression may be based on the antiquated idea that liver bile is associated with such negative emotions as these, as well as the fact that excessive liver bile causes jaundice or yellowing of the eyes and skin. Jaundice is likely to be a sign of a liver disorder or blockage of the duct that carries bile away from the liver. Bile contains waste products, making the liver an organ of excretion. Bile also has an important role in digestion, making the liver an accessory organ of digestion.



Figure **12.6.1**: Jaundice Eyes

## WHAT ARE ACCESSORY ORGANS OF DIGESTION?

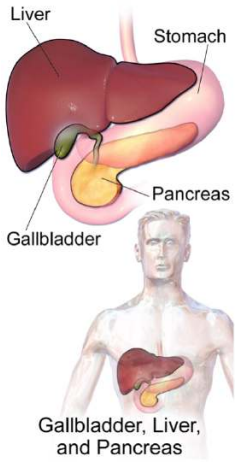



Figure **12.6.2**: The liver, gallbladder, and pancreas are the major accessory organs of digestion. In this figure, the pink tubular structure that starts at the lower stomach and wraps around the pancreas is the duodenum of the small intestine. This is where the accessory organs secrete their digestive substances. The pancreas is just behind the stomach. The liver is above on the right side and the gall bladder is just under the liver.

Accessory organs of digestion are organs that secrete substances needed for the chemical digestion of food but through which food does not actually pass as it is digested. Besides the liver, the major accessory organs of digestion are the gallbladder and pancreas. These organs secrete or store substances that are needed for digestion in the first part of the small intestine, the duodenum, where most chemical digestion takes place. You can see the three organs and their locations in Figure **12.6.2**.

## LIVER

The **liver** is a vital organ located in the upper right part of the abdomen. It lies just below the diaphragm to the right of the stomach. The liver plays an important role in digestion by secreting bile. However, the liver has a wide range of additional functions unrelated to digestion. In fact, some estimates put the number of functions of the liver at about 500! A few of them are described below.

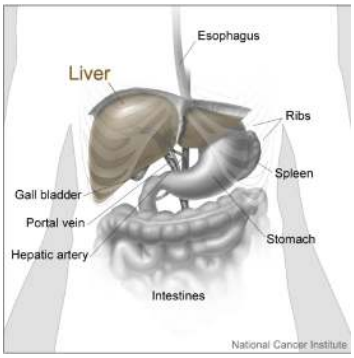



Figure **12.6.3**: The portal vein supplies the liver with wastes filtered out of the blood in the spleen as well as nutrients from the gastrointestinal tract. Oxygen-rich blood enters the liver via the hepatic artery.

### STRUCTURE OF THE LIVER

The liver is a reddish-brown, wedge-shaped structure. In adults, the liver normally weighs about 1.5 kg (3.3 lb). It is both the heaviest internal organ and the largest gland in the human body. The liver is divided into four lobes of unequal size and shape. Each lobe, in turn, is made up of lobules, which are the functional units of the liver. Each lobule consists of millions of liver cells, called hepatic cells (or hepatocytes). They are the basic metabolic cells that carry out the various functions of the liver.

As shown in Figure **12.6.3**, the liver is connected to two large blood vessels: the hepatic artery and the portal vein. The hepatic artery carries oxygen-rich blood from the aorta, whereas the portal vein carries blood that is rich in digested nutrients from the GI tract and wastes filtered from the blood by the spleen. The blood vessels subdivide into smaller arteries and capillaries, which lead to the liver lobules. The nutrients from the GI tract are used to build many vital biochemical compounds, and the wastes from the spleen are degraded and excreted.

### FUNCTIONS OF THE LIVER

The main digestive function of the liver is the production of bile. **Bile** is a yellowish alkaline liquid that consists of water, electrolytes, bile salts, and cholesterol, among other substances, many of which are waste products. Some of the components of bile are synthesized by hepatocytes; the rest are extracted from the blood.

As shown in the figure below, bile is secreted into small ducts that join together to form larger ducts, with just one large duct carrying bile out of the liver. If bile is needed to digest a meal, it goes directly

to the duodenum through the common bile duct. In the duodenum, the bile neutralizes acidic chyme from the stomach and emulsifies fat globules into smaller particles (called micelles) that are easier to digest chemically by the enzyme lipase. Bile also aids with the absorption of vitamin K. Bile that is secreted when digestion is not taking place goes to the gallbladder for storage until the next meal. In either case, the bile enters the duodenum through the common bile duct shown in Figure **12.6.4**

- The liver synthesizes glycogen from glucose and stores the glycogen as required to help regulate blood sugar levels. It also breaks down the stored glycogen to glucose and releases it back into the blood as needed.
- The liver stores many substances in addition to glycogen, including vitamins A, D, B12, and K. It also stores the minerals iron and copper.
- The liver synthesizes numerous proteins and many of the amino acids needed to make them. These proteins have a wide range of functions. They include fibrinogen, which is needed for blood clotting; insulin-like growth factor (IGF-1), which is important for childhood growth; and albumen, which is the most abundant protein in blood serum and functions to transport fatty acids and steroid hormones in the blood.
- The liver synthesizes many important lipids, including cholesterol, triglycerides, and lipoproteins.
- The liver is responsible for the breakdown of many waste products and toxic substances. The wastes are excreted in bile or travel to the kidneys, which excrete them in the urine.

The liver is clearly a vital organ that supports almost every other organ in the body. Because of its strategic location and diversity of functions, the liver is also prone to many diseases, some of which cause loss of liver function. There is currently no way to compensate for the absence of liver function in the long term, although liver dialysis techniques can be used in the short term. An artificial liver has not yet been developed, so liver transplantation may be the only option for people with liver failure.

## GALLBLADDER

The **gallbladder** is a small, hollow, pouch-like organ that lies just under the right side of the liver (Figure **12.6.2** and Figure **12.6.3**). It is about 8 cm (3.1 in.) long and shaped like a tapered sac, with the open end continuous with the cystic duct. The gallbladder stores and concentrates bile from the liver until it is needed in the duodenum to help digest lipids. After the bile leaves the liver, it reaches the gallbladder through the cystic duct. At any given time, the gallbladder may store between 30 and 60 mL (1-2 oz) of bile. A hormone stimulated by the presence of fat in the duodenum signals the gallbladder to contract and force its contents back through the cystic duct and into the common bile duct to drain into the duodenum.

## PANCREAS

The **pancreas** is a glandular organ that is part of both the digestive system and the endocrine system. As shown in Figure **12.6.4**, it is located in the abdomen behind the stomach, with the head of the pancreas surrounded by the duodenum of the small intestine. The pancreas is about 15 cm (6 in.) long, and it has two major ducts, the main pancreatic duct, and the accessory pancreatic duct. Both of these ducts drain into the duodenum.

As an endocrine gland, the pancreas secretes several hormones, including insulin and glucagon, which circulate in the blood. The endocrine hormones are secreted by clusters of cells called pancreatic islets (or islets of Langerhans). As a digestive organ, the pancreas secretes many digestive enzymes and also bicarbonate, which helps to neutralize acidic chyme after it enters the duodenum. The pancreas is stimulated to secrete its digestive substances when food in the stomach and duodenum triggers the release of endocrine hormones into the blood that reach the pancreas via the bloodstream. The pancreatic digestive enzymes are secreted by clusters of cells called acini, and they travel through the pancreatic ducts to the duodenum. In the duodenum, they help to chemically break down carbohydrates, proteins, lipids, and nucleic acids in chyme. The pancreatic digestive enzymes include:

- amylase, which helps to digest starch and other carbohydrates.
- trypsin and chymotrypsin, which help to digest proteins.
- lipase, which helps to digest lipids.
- deoxyribonucleases and ribonucleases, which help to digest nucleic acids.

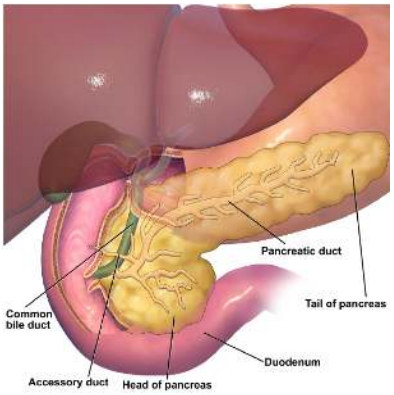



Figure **12.6.4**: Pancreatic digestive enzymes and bicarbonate travel to the duodenum through the pancreatic ducts. The main pancreatic duct joins with the common bile duct before the latter enters the duodenum

## REVIEW

1. Name three accessory organs of digestion. How do these organs differ from digestive organs that are part of the GI tract?
2. Describe the liver and its blood supply.
3. Explain the main digestive function of the liver.
4. Besides its role as a digestive organ, what other vital functions does the liver have?
5. What is the gallbladder? How does it aid in digestion in the duodenum?

6. Which two body systems include the pancreas? What type of secretions does the pancreas release as part of each body system?
7. List pancreatic enzymes that work in the duodenum and the substances they help digest.
8. What are two substances produced by accessory organs of digestion that help neutralize chyme in the small intestine, and where are they produced?
9. People who have their gallbladder removed sometimes have digestive problems after eating high-fat meals. Why do you think this happens?
10. *True or False*. The liver is a gland.
11. *True or False*. Substances secreted by the pancreas enter into the duodenum from the common bile duct.
12. *True or False*. Bile contains wastes.
13. Which accessory organ of digestion synthesizes cholesterol?

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# 12.7: DISORDERS OF THE GASTROINTESTINAL TRACT

## CROHN'S RASH

If you had a skin rash like the one in Figure **12.7.1**, you probably wouldn't assume that it was caused by a digestive system disease. However, that's exactly why the individual in the picture has a rash. He has a gastrointestinal (GI) tract disorder called Crohn's disease. This disease is one of a group of GI tract disorders that are known collectively as inflammatory bowel disease. Unlike other inflammatory bowel diseases, signs and symptoms of Crohn's disease may not be confined to the GI tract.

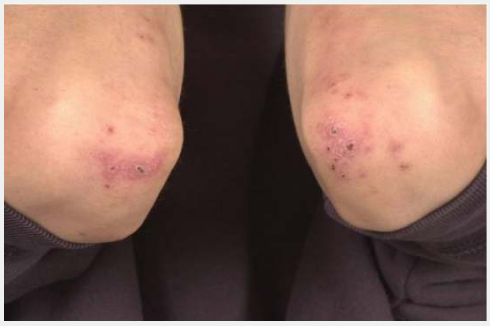


Figure **12.7.1**: Pustules and crusts around the elbows in a patient with Crohn's disease and bowel-associated dermatosis-arthritis syndrome (BADAS).

## INFLAMMATORY BOWEL DISEASE

**Inflammatory bowel disease** is a collection of inflammatory conditions primarily affecting the intestines. The two principal inflammatory bowel diseases are Crohn's disease and ulcerative colitis. Unlike Crohn's disease, which may affect any part of the GI tract and the joints as well as the skin, ulcerative colitis mainly affects just the colon and rectum. Both diseases occur when the body's own immune system attacks the digestive system. Both diseases also typically first appear in the late teens or early twenties and occur equally in all sexes and genders.

### CROHN'S DISEASE

**Crohn's disease** is a type of inflammatory bowel disease that may affect any part of the GI tract from the mouth to the anus, among other body tissues. The most commonly affected region is the ileum, which is the final part of the small intestine. Signs and symptoms of Crohn's disease typically include abdominal pain, diarrhea (with or without blood), fever, and weight loss. Malnutrition because of faulty absorption of nutrients may also occur. Potential complications of Crohn's disease include obstructions and abscesses of the bowel. People with Crohn's disease are also at a slightly greater risk than the general population of developing bowel cancer. Although there is a slight reduction in life expectancy in people with Crohn's disease, if the disease is well managed, affected people can live full and productive lives.

Crohn's disease is caused by a combination of genetic and environmental factors that lead to impairment of the generalized immune response (called innate immunity). The chronic inflammation of Crohn's disease is thought to be the result of the immune system "trying" to compensate for the impairment. Dozens of genes are likely to be involved, only a few of which have been identified. Because of the genetic component, close relatives such as siblings of people with Crohn's disease are many times more likely to develop the disease than people in the general population. Environmental factors that appear to increase the risk of the disease include smoking tobacco and eating a diet high in animal proteins. Crohn's disease is typically diagnosed on the basis of a colonoscopy, which provides a direct visual examination of the inside of the colon and the ileum of the small intestine.

People with Crohn's disease typically experience recurring periods of flare-ups followed by remission. There are no medications or surgical procedures that can cure Crohn's disease, although medications such as anti-inflammatory or immune-suppressing drugs may alleviate symptoms during flare-ups and help maintain remission. Lifestyle changes, such as dietary modifications and smoking cessation, may also help control symptoms and reduce the likelihood of flare-ups. Surgery may be needed to resolve bowel obstructions, abscesses, or other complications of the disease.

### ULCERATIVE COLITIS

**Ulcerative colitis** is an inflammatory bowel disease that causes inflammation and ulcers (sores) in the colon and rectum. Unlike Crohn's disease, other parts of the GI tract are rarely affected in ulcerative colitis. The primary symptoms of the disease are lower abdominal pain and bloody diarrhea. Weight loss, fever, and anemia may also be present. Symptoms typically occur intermittently with periods of no symptoms between flare-ups. People with ulcerative colitis have a considerably increased risk of colon cancer and should be screened for colon cancer more frequently than the general population. However, ulcerative colitis seems to reduce primarily the quality of life and not the lifespan.

The exact cause of ulcerative colitis is not known. Theories about its cause involve immune system dysfunction, genetics, changes in normal gut bacteria, and lifestyle factors such as a diet high in animal protein and the consumption of alcoholic beverages. Genetic involvement is suspected in part because ulcerative colitis tends to "run" in families. It is likely that multiple genes are involved. Diagnosis is typically made on the basis of colonoscopy and tissue biopsies.

Lifestyle changes, such as reducing the consumption of animal protein and alcohol, may improve symptoms of ulcerative colitis. A number of medications are also available to treat symptoms and help prolong remission. These include anti-inflammatory drugs and drugs that suppress the immune system. In cases of severe disease, removal of the colon and rectum may be required and can cure the disease.

## DIVERTICULITIS

**Diverticulitis** is a digestive disease in which tiny pouches in the wall of the large intestine become infected and inflamed. Symptoms typically include lower abdominal pain of sudden onset. There may also be fever, nausea, diarrhea or constipation, and blood in the stool. Having large intestine pouches called diverticula (Figure 12.7.2) that are not inflamed is called **diverticulosis.** Diverticulosis is thought to be due to a combination of genetic and environmental factors and is more common in people who are obese. Infection and inflammation of the pouches (diverticulitis) occur in about 10 to 25 percent of people with diverticulosis and is more common at older ages. The infection is generally caused by bacteria.



Figure **12.7.2**: Multiple pouches called diverticula in the wall of the large intestine

Diverticulitis can usually be diagnosed with a CT scan. Mild diverticulitis may be treated with oral antibiotics and a short-term liquid diet. For severe cases, intravenous antibiotics, hospitalization, and complete bowel rest (no nourishment via the mouth) may be recommended. Complications such as abscess formation or perforation of the colon require surgery.

## PEPTIC ULCER

A **peptic ulcer** is a sore in the lining of the stomach or the duodenum (the first part of the small intestine). If the ulcer occurs in the stomach, it is called a gastric ulcer; if it occurs in the duodenum, it is called a duodenal ulcer. The most common symptoms of peptic ulcers are upper abdominal pain that often occurs at night and improves with eating. Other symptoms may include belching, vomiting, weight loss, and poor appetite. However, many people with peptic ulcers, particularly older people, have no symptoms. Peptic ulcers are relatively common, with about 10 percent of people developing a peptic ulcer at some point in their life.

The most common cause of peptic ulcers is infection with the bacterium *Helicobacter pylori*, which may be transmitted by food, contaminated water, or human saliva (for example, by kissing or sharing eating utensils). Surprisingly, the bacterial cause of peptic ulcers was not discovered until the 1980s. The scientists who made the discovery are Australians Robin Warren and Barry J. Marshall. Although the two scientists eventually won a Nobel Prize for their discovery, their hypothesis was poorly received at first. To demonstrate the validity of their discovery, Marshall used himself in an experiment. He drank a culture of bacteria from a peptic ulcer patient and developed symptoms of peptic ulcer in a matter of days. His symptoms resolved on their own within a couple of weeks, but he took antibiotics to kill any remaining bacteria at his wife's urging (apparently because bad breath is also one of the symptoms of *H. pylori* infection). Marshall's self-experiment was published in the Australian Medical Journal and is among the most cited articles ever published in the journal.

Another relatively common cause of peptic ulcers is the chronic use of non-steroidal anti-inflammatory drugs (NSAIDs), such as aspirin or ibuprofen. Additional contributing factors may include tobacco smoking and stress, although these factors have not been demonstrated conclusively to cause peptic ulcers independent of *H. pylori* infection. Contrary to popular belief, diet does not appear to play a role in either causing or preventing peptic ulcers. Eating spicy foods and drinking coffee and alcohol were once thought to cause peptic ulcers. These lifestyle choices are no longer thought to have much if any effect on the development of peptic ulcers.

Peptic ulcers are typically diagnosed on the basis of symptoms or the presence of *H. pylori* in the GI tract. However, endoscopy (Figure 12.7.3), which allows direct visualization of the stomach and duodenum with a camera, may be required for a definitive diagnosis. Peptic ulcers are usually treated with antibiotics to kill *H. pylori*, along with medications to temporarily decrease stomach acid and aid in healing. Unfortunately, *H. pylori* have developed resistance to commonly used antibiotics, so treatment is not always effective. If a peptic ulcer has penetrated so deep into the tissues that it causes perforation of the wall of the stomach or duodenum, then emergency surgery is needed to repair the damage.



Figure **12.7.3**: A doctor inserts a tiny camera through a tube (called an endoscope) to examine a patient's upper GI tract for peptic ulcers. He views the image created by the camera on a screen above the patient's head.

## GASTROENTERITIS

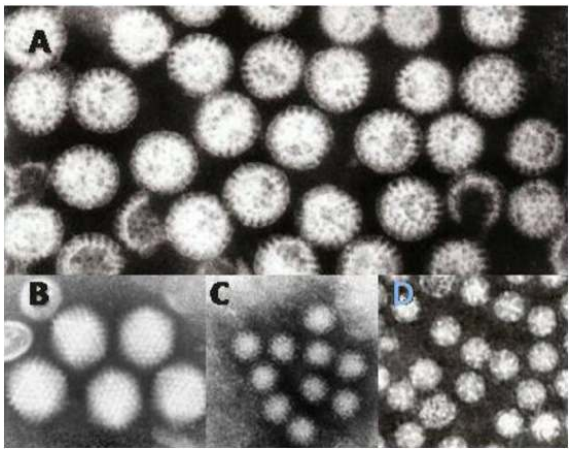



Figure **12.7.4**: These micrographs show four types of viruses that commonly cause gastroenteritis in humans: A. rotavirus, B. adenovirus, C. norovirus, and D. astrovirus.

**Gastroenteritis,** also known as infectious diarrhea, is an acute and usually self-limiting infection of the GI tract by pathogens. Symptoms typically include some combination of diarrhea, vomiting, and abdominal pain. Fever, lack of energy, and dehydration may also occur. The illness generally lasts less than two weeks, even without treatment, but in young children, it is potentially deadly. Gastroenteritis is very common, especially in poorer nations. Worldwide, up to five billion cases occur each year, resulting in about 1.4 million deaths. In the United States, infectious diarrhea is the second most common type of infection after the common cold.

Commonly called "stomach flu," gastroenteritis is unrelated to the influenza virus, although viruses are the most common cause of the disease (Figure **12.7.4**). In children, rotavirus is most often the cause, whereas norovirus is more likely to be the cause in adults. Besides viruses, other potential causes of gastroenteritis include fungi, protozoa (including *Giardia lamblia*, described below), and bacteria (most often *Escherichia coli* or *Campylobacter jejuni*). Transmission of pathogens may occur due to eating improperly prepared foods or foods left to stand at room temperature, drinking contaminated water, or having close contact with an infected individual.

Gastroenteritis is less common in adults than children, partly because adults have acquired immunity after repeated exposure to the most common infectious agents. Adults also tend to have better hygiene than children. If children have frequently repeated incidents of gastroenteritis, they may suffer from malnutrition, stunted growth, and developmental delays. Many cases of gastroenteritis in children can be avoided by giving them a rotavirus vaccine. Frequent and thorough hand washing can cut down on infections caused by other pathogens.

Treatment of gastroenteritis generally involves increasing fluid intake to replace fluids lost in vomitus or diarrhea. Oral rehydration solution, which is a combination of water, salts, and sugar, is often recommended. In severe cases, intravenous fluids may be needed. Antibiotics are not usually prescribed because they are ineffective against viruses that cause most cases of gastroenteritis.

## GIARDIASIS



Figure **12.7.5**: Giardia lamblia is a single-celled organism that parasitizes the GI tract of humans as well as many other animal species. It is a eukaryotic cell with tentacle-like extensions.

**Giardiasis,** popularly known as beaver fever, is a type of gastroenteritis caused by a GI tract parasite, the single-celled protozoan *Giardia lamblia* (Figure **12.7.5**). The parasite inhabits the digestive tract of a wide variety of domestic and wild animal species in addition to human beings, including cows, rodents, and sheep as well as beavers (hence its popular name). Giardiasis is one of the most common parasitic infections in people the world over, with hundreds of millions of people infected worldwide each year.

Transmission of *G. lamblia* is via a fecal-oral route. Those at greatest risk include travelers to countries where giardiasis is common, people who work in child-care settings, backpackers and campers who drink untreated water from lakes or rivers, and people who have close contact with infected people or animals in other settings. In the United States, giardiasis occurs more often during the summer than in other seasons, probably because people spend more time outdoors and in wild settings at that time of year.

Symptoms of giardiasis can vary widely. About a third of people with the infection have no symptoms, whereas others have severe diarrhea with poor absorption of nutrients. Problems with absorption occur because the parasites inhibit intestinal digestive enzyme production, cause detrimental changes in microvilli lining the small intestine, and kill off small intestinal epithelial cells. The illness can result in weakness, loss of appetite, stomach cramps, vomiting, and excessive gas. Without treatment, symptoms may continue for several weeks. Treatment with an antibiotic may be needed if symptoms persist longer or are particularly severe.

## REVIEW

1. What is inflammatory bowel disease?
2. Describe typical symptoms of inflammatory bowel disease.
3. Compare and contrast Crohn's disease and ulcerative colitis.
4. What is diverticulosis? How is it related to diverticulitis?
5. Identify the locations and causes of peptic ulcers.
6. Define and describe gastroenteritis.
7. Identify the cause of giardiasis. Why may it cause malabsorption?
8. Which of the following does not normally affect the small intestine?

A. Peptic ulcers

B. Crohn's disease

C. Giardiasis

D. Ulcerative colitis

9. Name three disorders of the GI tract that can be due to bacteria.
10. *True or False.* A colonoscopy can be used to examine the small intestine.
11. *True or False.* Peptic ulcers are mainly due to diet.
12. Name one disorder of the GI tract that can be *helped* by anti-inflammatory medications and one that can be *caused* by chronic use of anti-inflammatory medications.
13. People with ulcerative colitis should be frequently screened for _____ cancer.
14. Describe one reason why it can be dangerous to drink untreated water.
15. Do you think the “stomach flu” can be prevented by an influenza vaccine? Why or why not?

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# 12.8: CASE STUDY CONCLUSION- CELIAC AND CHAPTER SUMMARY

## CASE STUDY CONCLUSION: PLEASE DON'T PASS THE BREAD

The garlic bread stuffed with spaghetti shown in Figure **12.8.1** may or may not look appetizing to you, but for people with celiac disease, it is certainly off-limits. Bread and pasta are traditionally made with wheat, which contains proteins called gluten. As you learned in the beginning of the chapter, even trace amounts of gluten can damage the digestive system of people with celiac disease. When Rania and Tui met for lunch, Rania chose a restaurant that she knew could provide her with gluten-free food because she has this disease.



Figure **12.8.1**: Spaghetti Stuffed Garlic Bread

When people with celiac disease eat gluten, it causes an autoimmune reaction that results in inflammation and flattening of the villi of the small intestine. What do you think happens if the villi are inflamed and flattened? Think about what you have learned about the functions of the villi and small intestine. The small intestine is where most chemical digestion and absorption of nutrients occurs in the body. The villi increase the surface area in the small intestine to maximize the digestion of food and absorption of nutrients into the blood and lymph. If the villi are inflamed and flattened, there is less surface area where digestion and absorption can occur. Therefore, damage from celiac disease can result in inadequate absorption of nutrients, called malabsorption.

Malabsorption explains why there can be so many different types of symptoms of celiac disease, ranging from diarrhea and other forms of digestive distress to anemia, nutritional deficiencies, skin rashes, osteoporosis, bone pain, depression, anxiety, and rarer but potentially serious complications such as cancer. Our bodies need to digest and absorb adequate amounts of nutrients in order to function properly and stay healthy. Lack of nutrients can affect and damage cells, tissues, and organs throughout the body, sometimes seriously and irreversibly. A person with celiac disease can limit and often heal intestinal damage just by not eating gluten. In fact, eliminating all gluten from the diet is the main treatment for celiac disease. In some people with celiac disease, a gluten-free diet may not be enough, and steroids and other medications may be used to reduce the inflammation in the small intestine.

Celiac disease is an autoimmune disorder in which the body's immune system attacks its own tissues. It is thought to be caused by the presence of particular genes in combination with exposure to gluten. What are some other autoimmune disorders that you read about in this chapter that affect the digestive system? The two main inflammatory bowel diseases, Crohn's disease and ulcerative colitis are both due to the body's immune system attacking the digestive system, resulting in inflammation. Crohn's disease can affect any part of the GI tract, most commonly the ileum of the small intestine, while ulcerative colitis mainly affects the colon and rectum. Similar to celiac disease, treatments for these diseases also focus on reducing GI tract damage through lifestyle changes and medications.

Gluten is clearly dangerous for people with celiac disease, but should people who do not have celiac disease or other diagnosed medical problems with gluten also eliminate gluten from their diet? Many medical experts say no; because gluten-free diets are so restrictive, they may cause nutritional deficiencies without providing any proven health benefits. They can also be expensive and, as Tui's cousin found out, difficult to maintain given that gluten is present in so many foods. It is estimated that only 1% of the population has celiac disease. Most people should enjoy a varied diet and consult with their doctor if they are concerned about celiac disease, other types of gluten intolerance, or food allergies.

## CHAPTER SUMMARY

In this chapter, you learned about the digestive system, which allows the body to obtain needed nutrients from food. Specifically, you learned that:

- The digestive system consists of organs that break down food, absorb its nutrients, and expel any remaining food waste.
- Most digestive organs form a long, continuous tube through which food passes, called the gastrointestinal (GI) tract. It starts at the mouth, which is followed by the pharynx, esophagus, stomach, small intestine, and large intestine.
- Organs of the GI tract have walls that consist of several tissue layers that enable them to carry out digestion and/or absorption. For example, the inner mucosa has cells that secrete digestive enzymes and other digestive substances and also cells that absorb nutrients. The muscle layer of the organs enables them to contract and relax in waves of peristalsis to move food through the GI tract.
- Digestion is a form of catabolism, in which food is broken down into small molecules that the body can absorb and use for energy, growth, and repair. Digestion occurs when food moves through the GI tract. The digestive process is controlled by both hormones and nerves.
    - Mechanical digestion is a physical process in which food is broken into smaller pieces without becoming chemically changed. It occurs mainly in the mouth and stomach.
    - Chemical digestion is a chemical process in which macromolecules including carbohydrates, proteins, lipids, and nucleic acids in food are changed into simple nutrient

molecules that can be absorbed into body fluids. Carbohydrates are chemically digested to sugars, proteins to amino acids, lipids to fatty acids, and nucleic acids to individual nucleotides. Chemical digestion requires digestive enzymes. Gut flora carries out additional chemical digestion.

- Absorption occurs when the simple nutrient molecules that result from digestion are absorbed into blood or lymph. They are then circulated through the body.
- Organs of the upper gastrointestinal (GI) tract include the mouth, pharynx, esophagus, and stomach.
  - The mouth is the first organ of the GI tract. It has several structures that are specialized for digestion, including salivary glands, tongue, and teeth. Both mechanical digestion and chemical digestion of carbohydrates and fats begin in the mouth.
  - The pharynx and esophagus move food from the mouth to the stomach but are not directly involved in the process of digestion or absorption. Food moves through the esophagus by peristalsis.
  - Mechanical and chemical digestion continue in the stomach. Acid and digestive enzymes secreted by the stomach start the chemical digestion of proteins. The stomach turns masticated food into a semi-fluid mixture called chyme.
- The lower GI tract includes the small intestine and large intestine. The small intestine is where most chemical digestion and virtually all absorption of nutrients occur. The large intestine contains huge numbers of beneficial bacteria and removes water and salts from food waste before it is eliminated.
  - The small intestine consists of three parts: the duodenum, jejunum, and ileum. All three parts of the small intestine are lined with mucosa that is very wrinkled and covered with villi and microvilli, giving the small intestine a huge surface area for digestion and absorption.
    - The ileum carries out any remaining digestion and absorption of nutrients, but its main function is to absorb vitamin B12 and bile salts.
    - The jejunum carries out most of the absorption of nutrients in the small intestine, including the absorption of simple sugars, amino acids, fatty acids, and many vitamins.
    - The duodenum secretes digestive enzymes and also receives bile from the liver or gallbladder and digestive enzymes and bicarbonate from the pancreas. These digestive substances neutralize acidic chyme and allow for the chemical digestion of carbohydrates, proteins, lipids, and nucleic acids in the duodenum.
- The large intestine consists of the colon (which in turn includes the cecum, ascending colon, transverse colon, descending colon, and sigmoid colon), rectum, and anus. The vestigial organ called the appendix is attached to the cecum of the colon.
  - The main function of the large intestine is to remove water and salts from chyme for recycling within the body and eliminating the remaining solid feces from the body through the anus. The large intestine is also the site where trillions of bacteria help digest certain compounds, produce vitamins, stimulate the immune system, and break down toxins, among other important functions.
- Accessory organs of digestion are organs that secrete substances needed for the chemical digestion of food, but through which food does not actually pass as it is digested. The accessory organs include the liver, gallbladder, and pancreas. These organs secrete or store substances that are carried to the duodenum of the small intestine as needed for digestion.
  - The liver is a large organ in the abdomen that is divided into lobes and smaller lobules, which consist of metabolic cells called hepatic cells, or hepatocytes. The liver receives oxygen in the blood from the aorta through the hepatic artery. It receives nutrients in blood from the GI tract and wastes in blood from the spleen through the portal vein.
    - The main digestive function of the liver is the production of the alkaline liquid called bile. Bile is carried directly to the duodenum by the common bile duct or to the gallbladder first for storage. Bile neutralizes acidic chyme that enters the duodenum from the stomach and also emulsifies fat globules into smaller particles (micelles) that are easier to digest chemically.
    - Other vital functions of the liver include regulating blood sugar levels by storing excess sugar as glycogen, storing many vitamins and minerals, synthesizing numerous proteins and lipids, and breaking down waste products and toxic substances.
- The gallbladder is a small, pouch-like organ near the liver. It stores and concentrates bile from the liver until it is needed in the duodenum to neutralize chyme and help digest lipids.
- The pancreas is a glandular organ that secretes both endocrine hormones and digestive enzymes. As an endocrine gland, the pancreas secretes insulin and glucagon to regulate blood sugar. As a digestive organ, the pancreas secretes digestive enzymes into the duodenum through ducts. Pancreatic digestive enzymes include amylase (starches); trypsin and chymotrypsin (proteins); lipase (lipids); and ribonucleases and deoxyribonucleases (RNA and DNA).
- Inflammatory bowel disease is a collection of inflammatory conditions primarily affecting the intestines. The diseases involve the immune system attacking the GI tract, and they have multiple genetic and environmental causes. Typical symptoms include abdominal pain and diarrhea, which show a pattern of repeated flare-ups interrupted by periods of remission. Lifestyle changes and medications may control flare-ups and extend remission. Surgery is sometimes required.
- The two principal inflammatory bowel diseases are Crohn's disease and ulcerative colitis. Crohn's disease may affect any part of the GI tract from the mouth to the anus, among other body tissues. Ulcerative colitis affects the colon and/or rectum.

- Some people have little pouches, called diverticula, in the lining of their large intestine, a condition called diverticulosis. People with diverticulosis may develop diverticulitis, in which one or more of the diverticula become infected and inflamed. Diverticulitis is generally treated with antibiotics and bowel rest; sometimes surgery is required.
- A peptic ulcer is a sore in the lining of the stomach (gastric ulcer) or duodenum (duodenal ulcer). The most common cause is infection with the bacterium *Helicobacter pylori*. NSAIDs such as aspirin can also cause peptic ulcers, and some lifestyle factors may play contributing roles. Antibiotics and acid reducers are typically prescribed; surgery is not often needed.
- Gastroenteritis, or infectious diarrhea, is an acute and usually self-limiting infection of the GI tract by pathogens, most often viruses. Symptoms typically include diarrhea, vomiting, and/or abdominal pain. Treatment includes replacing lost fluids; antibiotics are not usually effective.
- Giardiasis is a type of gastroenteritis caused by infection of the GI tract with the protozoa parasite *Giardia lamblia*. It may cause malnutrition. It is generally self-limiting, but severe or long-lasting cases may require antibiotics.

## CHAPTER SUMMARY REVIEW

1. Explain how the accessory organs of digestion interact with the GI tract.
2. In which of the following organs is food actually digested?
   A. Pancreas
   B. Small intestine
   C. Gallbladder
   D. A and B
3. *True or False.* Bile is one of the digestive fluids secreted in the stomach.
4. *True or False.* The smell of food can stimulate the release of digestive enzymes.
5. If the pH in the duodenum was too low (acidic), what effect do you think this would have on the processes of the digestive system?
6. Is the stomach involved in chemical digestion, mechanical digestion, or both? Explain your answer.
7. Absorption of most nutrients occurs in the:
   A. Duodenum
   B. Ileum
   C. Cecum
   D. Jejunum
8. Is food passing through the GI tract generally more solid in the small intestine or the large intestine? Explain your answer.
9. What is another name for the colon?
10. Discuss whether digestion occurs in the large intestine.
11. The appendix is attached to:
    A. The large intestine
    B. The small intestine
    C. The pancreas
    D. The liver
12. What is lacteal? In your answer, be sure to describe both its location and function in the digestive system.
13. Lipids are digested at different points in the digestive system. Describe how lipids are digested at two of these points.
14. Describe two different functions of stomach acid.
15. *True or False*. Proteins are only digested in the stomach.
16. *True or False*. A peptic ulcer can occur in the small intestine.
17. Match each of the following organs of the digestive system with the description that best fits it. Each organ is used only once: Organs: pancreas; liver; gallbladder
    A. A small, pouch-like organ that stores and concentrates bile produced by a different organ.
    B. Produces insulin as well as digestive enzymes and other needed substances.
    C. Processes wastes in addition to aiding in digestive functions.
18. What is the name of the rhythmic muscle contractions that move food through the GI tract?
19. What are the major roles of the upper GI tract?
20. Diverticulitis causes infected and inflamed pouches in the:
    A. stomach
    B. small intestine
    C. jejunum
    D. large intestine
21. What is the physiological cause of heartburn?
22. Which disease most commonly affects the ileum of the small intestine?
    A. Crohn's disease
    B. Peptic ulcer
    C. Ulcerative colitis
    D. Gastroenteritis
23. *True or False.* Smoking does not contribute to digestive system disorders.
24. *True or False.* In addition to obtaining nutrients, the digestive system plays a role in protecting the body from pathogens.
25. What are two ways in which the tongue participates in digestion?
26. Where is the epiglottis located?
27. If the epiglottis were to not close properly, what might happen?
28. The GI tract goes from the mouth to which structure?

## ATTRIBUTIONS

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# CHAPTER OVERVIEW

## 13: NUTRITION

This chapter describes nutrients, nutrient needs, and healthy eating to achieve good nutrition. It also discusses eating disorders, problems of obesity and malnutrition, and causes and prevention of foodborne diseases.


13.1: Case Study- Fueling Our Bodies Properly
13.2: Nutrients
13.3: Healthy Eating
13.4: Eating Disorders
13.5: Obesity
13.6: Undernutrition
13.7: Foodborne Diseases
13.8: Case Study Conclusion- Fast Food and Chapter Summary


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# 13.1: CASE STUDY- FUELING OUR BODIES PROPERLY

## CASE STUDY: WHAT'S WRONG WITH FAST FOOD?

Like many Americans, 20-year-old Abdul eats fast food several times a week. After a long day of classes and work, it's easy for him to pick up fast food for dinner from a drive-through window on his way home. He also often has fast food for lunch on his short break. He knows that fast food probably isn't the healthiest choice, but it is convenient and he likes it. Besides, he is young and only slightly overweight, with no major health problems, so he is not too concerned about it affecting his health.



Figure **13.1.1**:Fast Food Menu

One day, Abdul gives his friend Carlos a ride home and suggests they pick up some fast food on the way. Carlos says, "Nah, I don't eat that stuff very often. It's not good for you." Abdul feels a little defensive and asks Carlos what exactly is wrong with it. Carlos says, "Well, it has a lot of calories and it's not exactly fresh food." Abdul says he doesn't think it has any more calories than other types of meals, and he eats some fresh fruit and vegetables at other times — is it really that bad for his health to eat fast food five or six times a week?

Carlos thinks about this. He has heard many times that fast food is not good for your health, but he is not sure of the exact reasons. When he gets home, he decides to do some research. He visits the website of Abdul's favorite fast food restaurant and looks up the nutritional information for Abdul's typical meal of a cheeseburger, large fries, and a large soda. Some of the information he finds is shown in Table **13.1.1** and Table **13.1.2**.

Table **13.1.1**: Nutritional Information for a Typical Fast Food Meal

| Food | Calories | Total Fat (%DV) | Saturated Fat (%DV) | Trans Fat | Carbohydrates (%DV) |
|---|---|---|---|---|---|
| Burger | 540 | 43% | 49% | 1 g | 15% |
| Fries | 510 | 37% | 17% | 0 g | 22% |
| Soda | 300 | 0% | 0% | 0 g | 27% |
| **Total** | **1,350** | **80%** | **66%** | **1 g** | **64%** |

Table **13.1.2**: Percentage of the adult recommended daily value (%DV) for each nutrient, based on a 2,000 Calorie a day diet.

| Food | Sodium (%DV) | Iron (%DV) | Vitamin A (%DV) | Vitamin C (%DV) | Calcium (%DV) |
|---|---|---|---|---|---|
| Burger | 40% | 25% | 10% | 2% | 15% |
| Fries | 15% | 6% | 0% | 30% | 2% |
| Soda | 1% | 0% | 0% | 0% | 0% |
| **Total** | **56%** | **31%** | **10%** | **32%** | **17%** |

What does this nutritional information mean? How can it help Carlos understand the potential health impact of Abdul frequently eating meals like this?

## CHAPTER OVERVIEW: NUTRITION

In this chapter, you will learn about nutrients, proper nutrition, and the negative health consequences of bad nutrition and improperly prepared food. Specifically, you will learn about:

- The six major classes of nutrients — carbohydrates, proteins, lipids, water, vitamins, and minerals — are substances the body needs for energy, building materials, and body processes.
- Essential nutrients, which must be obtained from food, and nonessential nutrients, which can be synthesized by the body.
- Macronutrients, which the body needs in relatively large quantities, and micronutrients, which the body needs in relatively small quantities.
- The functions of specific nutrients in the body and sources of these nutrients.
- Phytochemicals and their potential role in maintaining normal body functions and good health.
- Guidelines for healthy eating and good nutrition, and why a healthy diet can reduce the risk of many diseases.
- Energy homeostasis, which is the balance between calories consumed and those that are used by the body.
- Types of malnutrition, including undernutrition, overnutrition, and unbalanced nutrition.
- Nutrient and energy density and how knowledge of these factors can be used to make healthier food choices.
- How appetite is regulated.
- Eating disorders including anorexia nervosa, bulimia nervosa, and binge eating disorder and their causes, health effects, and treatments.
- Obesity and how it is defined, its causes, health consequences, ways to prevent and treat it, and the impact on public health.
- Undernutrition and how it is defined, its causes, specific undernutrition syndromes, and the often irreversible effects on children.
- The impact of undernutrition around the world, including richer nations, and public health approaches to treat and prevent undernutrition.
- The causes of foodborne diseases, including microorganisms and toxins; symptoms of the foodborne diseases; and ways to prevent

foodborne disease including good hygiene and proper food preparation and storage.

As you read this chapter, think about the following questions related to the tables above that contain nutritional information for Abdul's typical fast food meal:

1. Which nutrients might Abdul consume too much of if he eats meals like this frequently? Why would these nutrients be a concern? What health issues could be caused by consuming them in excess?
2. Which nutrients might Abdul not get enough of if he eats meals like this frequently? What health issues could this cause?
3. What are some ways Abdul can make better food choices, even at a fast-food restaurant? Why would these choices improve his diet and health?

## ATTRIBUTIONS


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# 13.2: NUTRIENTS

## FIGHTING PHYTOCHEMICALS

Many wars have been fought to acquire these spices from India. Chemicals and oils in the spices infuse specific smells and tastes in Indian cuisine. Food and culture are intertwined, and people bring their culture with them when they settle in a foreign country. Sometimes their culture is accepted, and sometimes it becomes a cause of discrimination that people have to face for embracing their culture.

This colorful display of Indian spices is not just pretty to look at, the items pictured are also rich in phytochemicals. **Phytochemicals** are a large group of recently discovered chemicals, such as oils and colors, that occur naturally in plants. Many of them are known to protect plants by fighting off insect attacks and infectious diseases. Phytochemicals in the food we eat may also be needed to help keep us healthy. If so, some nutritionists think they should be classified as nutrients.



Figure **13.2.1**: Indian Spices

## WHAT ARE NUTRIENTS?

**Nutrients** are substances the body needs for energy, building materials, and control of body processes. There are six major classes of nutrients based on biochemical properties: carbohydrates, proteins, lipids, water, vitamins, and minerals. Fiber, which consists largely of nondigestible carbohydrates, is sometimes added as the seventh class of nutrients.

Besides the biochemical classification of nutrients, nutrients are also categorized as either essential or nonessential nutrients. **Essential nutrients** cannot be synthesized by the human body, at least not in sufficient amounts for normal functioning, so these nutrients must be obtained from food. **Nonessential nutrients,** in contrast, can be synthesized in the body in sufficient quantities for normal functioning, although they are generally obtained from food as well. Except for dietary fiber, all dietary carbohydrates are considered nonessential. Every other major class of nutrients contains multiple essential compounds. For example, there are nine essential amino acids, at least two essential fatty acids, and many essential vitamins and minerals. Water and fiber are also essential nutrients.

The major classes of nutrients are also categorized as macronutrients or micronutrients depending on how much of them the body needs.

## MACRONUTRIENTS

**Macronutrients** are nutrients that the body needs in relatively large amounts. They include carbohydrates, proteins, lipids, and water. All macronutrients except water are used by the body for energy, although this is not their sole physiological function. The energy provided by macronutrients in food is measured in kilocalories, commonly called **Calories,** where 1 Calorie is the amount of energy needed to raise 1 kilogram of water by 1 degree Celsius.

### CARBOHYDRATES

Carbohydrates are organic compounds made up of simple sugars (as in the cotton candy pictured in Figure **13.2.2**). Carbohydrates are classified by the number of sugars they contain as monosaccharides (one sugar), such as glucose and fructose; disaccharides (two sugars), such as sucrose and lactose; and polysaccharides (three or more sugars), including starch, glycogen, and cellulose (the main component of dietary fiber). Dietary carbohydrates come mainly from grains, fruits, and vegetables. All digestible carbohydrates in the diet are used by the body for energy. One gram of dietary carbohydrates provides 4 Calories of energy. **Fiber,** such as the cellulose in plant foods, cannot be digested by the human digestive system, so most of it just passes through the digestive tract. Although it does not provide energy as other carbohydrates do, it is nonetheless considered an essential nutrient for its physiological roles. There are two types of fiber in many plant foods: soluble fiber and insoluble fiber.



Figure **13.2.2**: This cotton candy may look like a big cotton ball made of real cotton, which consists mostly of cellulose, but it actually consists almost entirely of simple sugars.

**Soluble fiber** consists of nondigestible complex plant carbohydrates that dissolve in water, forming a gel. This type of dietary fiber thickens and slows the movement of chyme through the small intestine and thereby slows the absorption of glucose into the blood. The consistency of food after it has been mechanically digested in the stomach is referred to as chyme. This may lessen insulin spikes

and the risk of type 2 diabetes. Soluble fiber can also help lower blood cholesterol. Good dietary sources of soluble fiber include oats, apples, and beans.

**Insoluble fiber** consists mainly of cellulose and does not dissolve in water. As insoluble fiber moves through the large intestine, it stimulates peristalsis. Peristalsis is the involuntary constriction of the smooth muscle of the GI tract that pushes the food content in the tract. This keeps food wastes moving and helps prevent constipation. The insoluble fiber in the diet may also lessen the risk of colon cancer. Good dietary sources of insoluble fiber include cabbage, bell peppers, and grapes.

## PROTEINS

Proteins are organic compounds made up of amino acids. You may think of meat and fish as major sources of dietary proteins — and they are — but there are many good plant sources as well, including soybeans (see the figure below) and other legumes. Proteins in food are broken down during digestion to provide the amino acids needed for protein synthesis. Proteins in the human body are the basis of many body structures, including muscles and skin. Proteins also function as enzymes that catalyze biochemical reactions, hormones that regulate body functions in other ways, and antibodies that help fight pathogens. Any amino acids from food that are not needed for these purposes are excreted in the urine, converted to glucose for energy, or stored as fat. One gram of protein provides 4 Calories of energy.

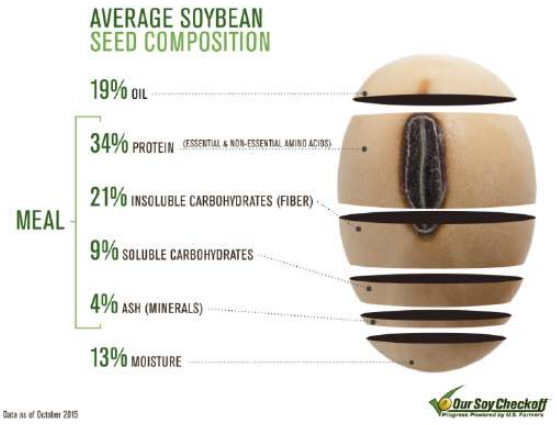



Figure **13.2.3**: Average soybean seed composition: 19% oil, 34% protein (essential and non-essential amino acids), 21% insoluble carbohydrates (fiber), 9% soluble carbohydrates, 4% ash (minerals), 13% moisture.

The most important aspect of protein structure from a nutritional standpoint is amino acid composition. About 20 amino acids are commonly found in the human body, of which about 11 are nonessential because they can be synthesized internally. The other 9 amino acids are essential amino acids that must be obtained from dietary sources. Essential amino acids are phenylalanine, valine, threonine, tryptophan, methionine, leucine, isoleucine, lysine, and histidine. Animal proteins such as meat and fish are concentrated sources of all 9 essential amino acids, whereas plant proteins may have only trace amounts of one or more essential amino acids.

## LIPIDS

Lipids, commonly called fats, are organic compounds made up mainly of fatty acids. Fats in foods (Figure **13.2.4**), as well as fats in the human body, are typically triglycerides (three fatty acids attached to a molecule of glycerol). Fats provide the body with energy and serve other vital functions, including helping to make and maintain cell membranes and functioning as hormones. When used for energy, one gram of fat provides 9 Calories of energy.



Figure **13.2.4**: A variety of forms of fat are commonly used in food preparation. Fatty food sources shown here include butter, mayonnaise, vegetable oil, and salad dressing.

### *SATURATED VS UNSATURATED FATS*

Fats are classified as either saturated or unsaturated depending on the type of bonds in their fatty acids.

- In saturated fats, carbon atoms share only single bonds, so each carbon atom is bonded to as many hydrogen atoms as possible. Saturated fats tend to be solids at room temperature. Most saturated fat in the diet comes from animal foods, such as meat and butter.
- In unsaturated fats, at least one pair of carbon atoms share a double bond, so these carbon atoms are not bonded to as many hydrogen atoms as possible. Unsaturated fats with just one double bond are called monounsaturated fats. Those with multiple double bonds are called polyunsaturated fats. Unsaturated fats tend to be liquids at room temperature. Unsaturated fats in the diet come mainly from certain fish such as salmon and from plant foods such as seeds and nuts.

### *ESSENTIAL FATTY ACIDS*

Most fatty acids are not essential. The body can make them as needed, generally from other fatty acids, although this takes energy. Only two fatty acids are known to be essential, called omega-3 and omega-6 fatty acids. They cannot be synthesized in the body, so they must be obtained from food. The most commonly used cooking oils in processed foods are rich in omega-6 fatty acids, so most people get plenty of these fatty acids in their diet. Omega-3 fatty acids are not as prevalent in foods, and most people do not get enough of them in food. Good food sources of omega-3 fatty acids include oily fish such as salmon, walnuts, and flax seeds.

### TRANS FATS

**Trans fats** are unsaturated fats that contain types of bonds that are rare in nature. Trans fats are typically created in an industrial process called partial hydrogenation. They may be used in a variety of processed foods (such as those shown in Figure **13.2.5**) because they tend to have a longer shelf life without going rancid. Trans fats are known to be detrimental to human health.



Figure **13.2.5**: All of the foods pictured here contain harmful trans fats.

## WATER

Water is essential to life because biochemical reactions take place in water. Water is continuously lost from the body in multiple ways, including in urine and feces, during sweating, and as water vapor in exhaled breath. This constant loss of water makes water an essential nutrient that must be replenished often.

Too little water is called dehydration. It can cause weakness, dizziness, and heart palpitations. Severe dehydration can lead to death. It is easy to become dehydrated in hot weather, especially when exercising. It is more difficult to consume too much water, but overhydration is also possible. It can result in water intoxication, a serious and potentially fatal condition.

# MICRONUTRIENTS

**Micronutrients** are nutrients the body needs in relatively small amounts. Micronutrients do not provide energy. Instead, they are necessary for the biochemical reactions of metabolism, among other vital functions. They include vitamins, minerals, and possibly phytochemicals as well.

## VITAMINS

**Vitamins** are organic compounds that generally function as coenzymes. A coenzyme is a “helper” molecule that is required for a protein enzyme to work. In this capacity, vitamins play many roles in good health, ranging from maintaining normal vision (vitamin A) to help the blood clot (vitamin K). Some functions of these and several other vitamins are listed in the table below. Most vitamins are essential nutrients and must be obtained from food. Fruits, vegetables, meat, and fish are all high in one or more essential vitamins. There are only a few nonessential vitamins. Vitamins $B_7$ and K are produced by bacteria in the large intestine, and vitamin D is synthesized in the skin when it is exposed to UV light

Table **13.2.1**: Selected Vitamins and Some of Their Functions

| Vitamin | Function |
|---|---|
| A | normal vision |
| $B_1$ (thiamin) | production of cellular energy from food |
| $B_3$(niacin) | cardiovascular health |
| $B_7$ (biotin) | support of carbohydrate, protein, and fat metabolism |
| $B_9$ (folic acid) | fetal health and development |
| $B_{12}$ | normal nerve function and production of red blood cells |
| C | making connective tissue |
| D | healthy bones and teeth |
| E | normal cell membranes |
| K | blood clotting |

## MINERALS

**Minerals** are inorganic chemical elements that are necessary for normal body processes and good health. Because they are inorganic and not synthesized biologically, all nutrient minerals are considered essential nutrients.

Several minerals are needed in relatively large quantities (> 150 mg/day), so they are sometimes referred to as macrominerals or bulk minerals. They include:

- calcium, which is needed for bone strength, neutralizing acidity in the digestive tract, and nerve and cell membrane functions. Dairy products are good sources of calcium.
- magnesium, which is needed for strong bones, maintaining pH, processing ATP, and other functions. Green leafy vegetables, bran, and almonds are high in magnesium.
- phosphorus, which is needed for bone strength, energy processing, pH regulation, and phospholipids in cell membranes. Milk and meat are good sources of phosphorus.
- sodium, which is needed to regulate blood volume, blood pressure, water balance, and pH. Most processed foods have added sodium. A salt shaker is another common source of sodium.
- chloride, which is needed for the production of hydrochloric acid in the stomach and for cell membrane transport. Chloride in table salt added to processed foods provides plenty of chloride in most diets.
- potassium, which is needed for the proper functioning of the heart and nerves, water balance, and pH. Many fruits and vegetables are high in potassium.
- sulfur, which is needed for the synthesis of many proteins. Meat and fish are good sources of sulfur.

Other minerals are needed in much smaller quantities (≤150 mg/day), so they are often referred to as trace minerals. The table below lists several trace minerals and some of their functions. Good dietary sources of trace minerals include whole grains, seafood, fruits, vegetables, nuts, and legumes.

Table 13.2.2: Selected Trace Minerals and Some of Their Functions

| Trace Mineral | Function |
|---|---|
| Cobalt | synthesis of vitamin $B_{12}$ by gut bacteria |
| Copper | component of many enzymes |
| Chromium | metabolism of sugar |
| Iodine | synthesis of thyroid hormones |
| Iron | component of hemoglobin and many enzymes |
| Manganese | processing of oxygen |
| Molybdenum | component of several enzymes |
| Selenium | component of oxidases (antioxidants) |
| Zinc | component of several enzymes |

## PHYTOCHEMICALS

The naturally occurring, disease- and pest-fighting plant chemicals known as phytochemicals are commonly consumed in plant foods, particularly spices and fresh vegetables and fruits. Besides fighting attacks on plants, many phytochemicals give plants their distinctive colors and characteristic flavors and aromas. Phytochemicals are the reason that blueberries are blue (Figure 13.2.6) and that garlic has its characteristically strong, pungent taste and smell. There are known to be as many as 4,000 different phytochemicals in plants. Preliminary evidence suggests that certain phytochemicals in the diet help protect human health. For example, some phytochemicals may act as antioxidants that counter cancer-causing free radicals. Research on phytochemicals is still relatively young, so time will tell whether they will eventually be classified as micronutrients.



Figure 13.2.6: The colors of berries and other fruits are attributable to phytochemicals.

## REVIEW

1. What are the nutrients?
2. List the six major classes of nutrients based on biochemical properties.
3. Compare and contrast essential and nonessential nutrients.
4. Identify macronutrients.
5. Which nutrients are classified as micronutrients? Why?
6. Describe carbohydrates, state how much energy they provide, and list good food sources of carbohydrates.
7. If fiber in food cannot be digested, why is it considered a nutrient?
8. Describe proteins, state their general uses in the human body, and identify food sources that are high in proteins. How much energy do proteins provide?
9. Describe lipids, identify how much energy they provide, and state their general uses in the human body.
10. Distinguish between saturated, unsaturated, and trans fats.
11. Water provides no energy or materials the body needs for building or controlling body processes. Why is it considered a nutrient?
12. What are vitamins? What is the general role of most vitamins? Which vitamins are not essential nutrients? Why?
13. What are the dietary minerals? Give examples of macrominerals and trace minerals.
14. What are phytochemicals? What are good food sources of phytochemicals?
15. Which of the following are inorganic substances?

    A. Vitamins
    B. Minerals
    C. All micronutrients
    D. A and B

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# 13.3: HEALTHY EATING

## BALANCING ACT

If you practice yoga, then you know that yoga positions such as the headstand demonstrated here can help you develop a good balance. Having good balance, in turn, can reduce your risk of falls and injuries. Another kind of balance is important to ensure that you have good health and prevent disease, and that kind of balance is a balance in your diet. Achieving a dietary balance requires healthy eating.



Figure **13.3.1**: Yoga

## BENEFITS OF HEALTHY EATING

It sounds like something a snake-oil salesman would say, but it's true: healthy eating is a panacea for many human ailments. A healthy diet reduces risk of obesity, cardiovascular disease, type 2 diabetes, osteoporosis, and cancer. Not surprisingly, it also extends the length of life. In fact, an unhealthy diet is one of the leading preventable causes of death. A healthy diet also has mental health benefits. It may stall or reduce the risk of dementia and have a positive effect on memory.

## DIET AND NUTRITION

If you adopt healthy eating habits and get enough exercise, you are likely to have good nutrition. **Nutrition** is the process of taking in nutrients in food and using them for growth, metabolism, and repair. Good nutrition requires eating foods rich in nutrients with the right amount of food energy (Calories) to balance energy use.

### NUTRIENT BALANCE AND NUTRIENT DENSITY

Eating a wide range of foods, especially fruits and vegetables, is the basis of healthy eating. This helps ensure that you are eating a wide range of nutrients. However, there is only a limited amount of food you can eat in a single day without consuming too many Calories. In order to maximize the number of nutrients you take in, you need to spend your "Calorie budget" wisely by choosing foods that have high **nutrient density.** Nutrient density refers to how much of a given nutrient is provided by a particular food, relative to the mass of the food or the number of Calories it provides. Consider vitamin K as an example. The recommended daily value of vitamin K for adults is 90 µg. Both kale and iceberg lettuce provide vitamin K. A cup of iceberg lettuce provides about 50 µg vitamin K; a cup of kale provides more than 1000 µg of vitamin K. Therefore, kale has about 20 times the nutrient density for vitamin K as lettuce. Black beans, pictured below, are another good example of nutrient-dense food.



Figure **13.3.2**: Black beans, prepared here in a salad with corn and other veggies, are nutrient-dense in both protein and fiber. One cup of cooked black beans provides about 30 percent of the protein and 60 percent of the fiber needed by a typical adult while providing virtually no fat, sodium, or sugar. Black beans are also nutrient-dense sources of many micronutrients, including folate, thiamin, manganese, magnesium, phosphorus, and iron.

### ENERGY HOMEOSTASIS AND ENERGY DENSITY

Good nutrition also requires achieving energy homeostasis. **Energy homeostasis** is a balance between the energy consumed in food and the energy expended in metabolism and physical activity. If more energy is taken in as food than is used for metabolism and activity, then the extra energy is stored as fat. An extra 3,500 Calories of food energy results in the storage of almost half a kilogram (1 lb) of body fat. If less energy is taken in than is used, then stored fat may be used for energy. The human brain, particularly the hypothalamus, plays a central role in regulating energy homeostasis. Based on biochemical signals from the body, the hypothalamus generates a sense of hunger or satiation as needed to maintain energy balance.

Energy homeostasis depends on more than hunger and satiation. It also depends on dietary choices, eating habits, and activity levels. To achieve energy balance, it is important to consider the energy density of the food. **Energy density** refers to the number of Calories a food provides per gram (or ounce). Foods high in carbohydrates or proteins are generally less energy-dense than foods high in lipids. Carbohydrates and proteins provide 4 Calories of energy per gram, whereas lipids provide 9 Calories of energy per gram. However, within nutrient classes, there is considerable variation in the energy density of foods. For example, fruits are high in carbohydrates that the body uses for energy. Both casaba melons and figs are fruits and provide energy, but an ounce of casaba melon provides only about 8 Calories of energy, whereas an ounce of figs provides about 80 Calories of energy. This means that figs have 10 times the energy density of casaba melons.

### MALNUTRITION

Bad nutrition is referred to as **malnutrition.** The word malnutrition may make you think of starving children in Africa who do not have

enough food to eat. This type of malnutrition is called undernutrition, and it is a major nutritional problem in developing countries. Undernutrition is typically caused by inadequate energy intake, often coupled with frequent bouts of infectious disease. It usually results in people being underweight for their height, and it commonly leads to growth failure in children.

Undernutrition is just one type of malnutrition. Excessive food intake can also cause malnutrition, in this case, overnutrition. This is the major nutritional problem in developed countries. Overnutrition is typically caused by excessive energy intake coupled with inadequate energy expenditure in physical activity. Overnutrition usually leads to people becoming overweight or obese (see Figure **13.3.3**). Obesity is associated with a host of health problems and diseases, including metabolic syndrome, cardiovascular disease, type 2 diabetes, and some types of cancer, among others.

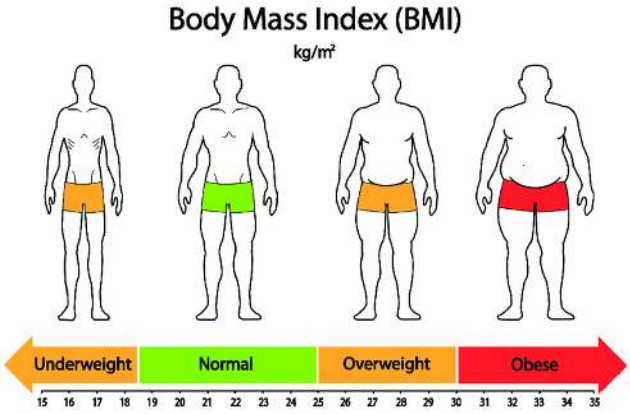



Figure **13.3.3**: Body Mass Index is a measure that can be used to help determine if a person is obese. A simple BMI scale compares height vs. weight. A BMI below 18 is generally considered to be underweight; a BMI over 25 is overweight and over 30 is obese.

Unbalanced nutrition is another type of malnutrition. In this case, the diet contains too much or not enough of specific nutrients other than energy. This type of malnutrition often occurs with undernutrition. However, a person doesn't have to be undernourished to lack specific nutrients. People with adequate food intake and even people with overnutrition may have unbalanced nutrition. Getting either too much or not enough of particular nutrients may cause diseases or other health problems. For example, inadequate vitamin A intake may cause blindness, whereas too much vitamin A can be toxic. Likewise, dietary calcium deficiency may contribute to osteoporosis, whereas too much calcium can cause kidney stones.

## NUTRIENT NEEDS

The goal of healthy eating is to take in the proper amount of each nutrient to meet nutrient and energy needs. The FDA identifies the recommended adult daily values (DV) for a wide variety of nutrients, based on a 2,000 Calorie daily diet. The values in the table are average values. The exact amount of each nutrient that a given individual needs may differ, depending on factors, such as age and gender. Different stages of adulthood have different nutrient needs for several nutrients, and males have somewhat higher needs for many nutrients than do females at most ages, mainly because of gender differences in body size. Other factors that influence individual nutrient needs include health status and activity level. People in poor health may need some nutrients in greater quantities. People who are very active need to obtain more energy from macronutrients in their diet.

## TOOLS AND TIPS FOR HEALTHY EATING

There are so many nutrients and daily values. Eating to meet all these nutrient needs may seem like an overwhelming challenge. Do you need to keep track of the nutrient content of everything you eat to guarantee that you are meeting your nutrient needs? Fortunately, the answer is no. Healthy eating is much easier than that. Just use MyPlate and nutrition facts labels and follow the tips below. This approach will help ensure that you are meeting your nutrient needs.

### MYPLATE

One of the most useful tools for healthy eating is **MyPlate,** which is shown below. This is a visual guide to healthy eating that was developed by the United States Department of Agriculture (USDA) in 2011. MyPlate replaces the previous MyPyramid guide from the USDA and is easier to apply to daily eating. MyPlate depicts the relative proportions of different types of foods you should eat at each meal (or cumulatively by the end of the day). The foods are selected from five different food groups: vegetables, fruits, grains (such as cereal, bread, or pasta), proteins (such as meat, fish, or legumes), and dairy (such as milk, cheese, or yogurt).

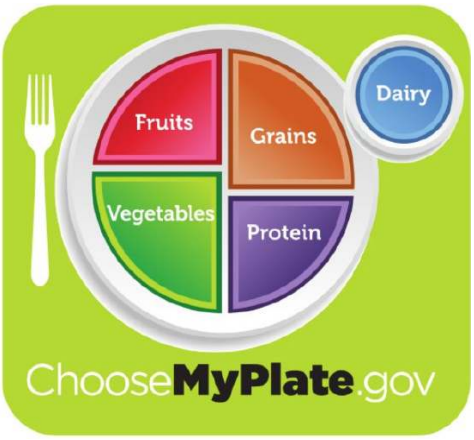


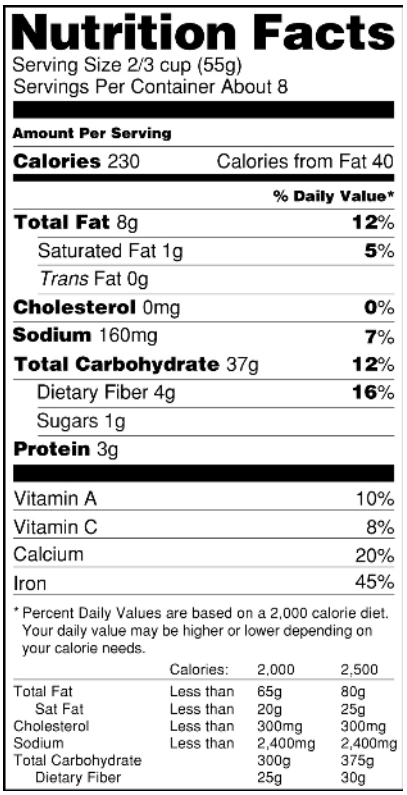

Figure **13.3.4**: MyPlate makes it relatively simple to eat balanced meals that meet nutrition needs.

According to MyPlate, about half of the food on your plate should be vegetables and fruits, and the other half should be grains and proteins. A serving of a dairy product should also accompany each meal. A meal based on MyPlate might include a serving of kale, an apple, a turkey sandwich, and a glass of milk. Think about some of your own typical meals. Do they match MyPlate? If not, how could you modify them to get the right proportions of foods from each food group?

### NUTRITION FACTS LABELS

If you are like most Americans, you rely heavily on packaged and processed foods. Although limiting these foods in your diet is a good aim, in the meantime, make use of the nutrition facts labels on these

foods. A nutrition facts label, like the one shown above, gives the nutrient content and ingredients in food and makes it easy to choose the best options. A quick look at the nutrition facts can help you choose foods that are high in nutrients you are likely to need more of (such as fiber and protein) and low in nutrients you probably need less of (such as sodium and sugar). Checking the ingredients list on labels can help you choose food items that contain the most nutritious ingredients, such as whole grains instead of processed grains.



**Nutrition Facts**

Serving Size 2/3 cup (55g)
Servings Per Container About 8

**Amount Per Serving**

| | |
|---|---|
| **Calories** 230 | Calories from Fat 40 |
| | **% Daily Value*** |
| **Total Fat** 8g | **12%** |
| Saturated Fat 1g | **5%** |
| *Trans* Fat 0g | |
| **Cholesterol** 0mg | **0%** |
| **Sodium** 160mg | **7%** |
| **Total Carbohydrate** 37g | **12%** |
| Dietary Fiber 4g | **16%** |
| Sugars 1g | |
| **Protein** 3g | |
| Vitamin A | 10% |
| Vitamin C | 8% |
| Calcium | 20% |
| Iron | 45% |

* Percent Daily Values are based on a 2,000 calorie diet. Your daily value may be higher or lower depending on your calorie needs.

| | Calories: | 2,000 | 2,500 |
|---|---|---|---|
| Total Fat | Less than | 65g | 80g |
| Sat Fat | Less than | 20g | 25g |
| Cholesterol | Less than | 300mg | 300mg |
| Sodium | Less than | 2,400mg | 2,400mg |
| Total Carbohydrate | | 300g | 375g |
| Dietary Fiber | | 25g | 30g |

Figure **13.3.5**: Nutrition facts labels like this one can help you make good food choices.

The sample nutrition label in Figure **13.3.5** indicates that a serving of this food is 55 g (with about 8 servings in the package). Each serving contains:

- 230 calories (with 40 calories from fat)
- 8 g total fat (making up 12% of the recommended fats per day)
  - 1 g of this total fat is saturated fat (making up 5% of the daily value)
  - 0 g is trans fat
- 0 mg cholesterol (0% of the daily value)
- 160 mg sodium (7% of the daily value)
- 37 g total carbohydrates (12% of daily value)
  - 4 g of that is dietary fiber (16% of daily value)
  - 1 g sugars
- 3 g proteins
- 10% of the recommended daily value of vitamin A
- 8% of the recommended daily value of vitamin C
- 20% of the recommended daily value of calcium
- 45% of the recommended daily value of Iron

## TIPS FOR HEALTHY EATING

The following tips can help you attain energy homeostasis while meeting your nutrient needs.

- Eat several smaller meals throughout the day rather than a few larger meals. Eating more frequently keeps energy, blood glucose, and insulin levels stable.
- Make healthy food choices. Try to eat whole foods rather than processed foods. Whole foods have more nutrients than processed foods. Raw foods also generally retain more nutrients than cooked foods. Overall, try to eat more plant foods and fewer animal foods.
- Make healthy grain choices. Try to make at least half your grains whole grains. Choose food items with whole grains listed as the main ingredient. Avoid foods that contain mainly or only processed grains, such as white flour or white rice. Include a variety of grains, such as rice, oats, and wheat.
- Make healthy fruit and vegetable choices. Include a variety of green, yellow, red, and orange fruits and vegetables, like those pictured below. These foods are high in vitamins and phytochemicals. Consume whole fruits instead of juices. Whole fruits are higher in fiber and more filling and may also have less sugar. The highest fiber fruits include plums and prunes.
- Combine amino acids in plant foods. The right combinations, such as beans and rice, make complete proteins with all nine essential amino acids. The two foods do not have to be eaten at the same meal to be used together by the body.
- Limit sugar and salt intake. Fresh foods generally have less of these two nutrients than processed foods. For packaged foods, read nutrition facts labels and choose options that are lower in sodium and sugars. Keep in mind that sugar may come in many forms, including high fructose corn syrup. Put away the salt shaker and sugar bowl so you won't be tempted to add extra sodium or sugar at the table.
- Limit saturated fats. Eat more fish and legumes and less red meat. Use nut and vegetable oils instead of butter or other fats derived from animals.
- Always check for trans fats on nutrition facts labels. Try to avoid these harmful artificial fats completely.
- Increase omega-3 fatty acids. Foods that contain these essential fatty acids include salmon, walnuts, flax seeds, and canola oil.
- Stay hydrated. Eat foods high in water, such as fruits and vegetables. Also, try to drink 2 liters (about 8 cups) of fluids each day. Choose water or unsweetened beverages such as tea or coffee instead of sweetened beverages. Sweetened drinks such as soft drinks contain no nutrients except sugar. Frequent consumption of sweetened beverages is a major risk factor for metabolic syndrome, obesity, type 2 diabetes, and cardiovascular disease.
- Engage in at least 30 minutes of physical activity most days of the week. Besides all the other benefits of exercise to human

health, such as strong bones and muscles, exercise uses energy that helps to balance the Calories in food.

## FEATURE: MY HUMAN BIOLOGY

The Zone Diet, Blood Type Diet, Paleo Diet, grapefruit diet — no doubt, you've heard of them all. Such diets — often referred to as fad diets — certainly feature prominently in the media, and many people try them. If you want to lose weight, you may be thinking about trying a fad diet yourself. And why not? Fad diets are certainly appealing. They often promise quick weight loss without exercise. They also generally spell out exactly what you can and cannot eat. This makes it easier for some people to consume less in the short term. But do fad diets really work, and are they healthy ways to lose weight?

In reality, most fad diets do not lead to significant, long-term weight loss. People may lose a lot of weight initially, but the weight loss is likely to be due to loss of water rather than fat. In addition, many fad diets are unhealthy because they are unbalanced. They typically restrict or eliminate foods — such as fruits, dairy, or whole grains — that should be the basis of a healthy eating plan because they are dense in critical nutrients. At the same time, such diets may recommend overconsumption of certain nutrients that can actually compromise health when eaten in excess. For example, high-protein diets can put a strain on the kidneys and potentially lead to kidney stones and gout. Fad diets that are restricted to certain foods also quickly become boring and difficult to stick with. They generally are not intended to become a healthy, lifetime eating plan. Once the weight is lost (if it is), dieters usually go back to their old ways of eating and regain the weight.

How can you tell if a diet is a fad diet? Ask these questions about it:

1. Does the diet promise rapid weight loss (> 2 pounds a week)?
2. Does the diet claim that the weight loss will be from certain parts of the body (such as "stubborn belly fat")?
3. Does the diet claim to work even without exercise?
4. Does the diet help sell a product, such as prepackaged meals, pills, or books?
5. Does the diet lack well-validated scientific evidence to back its claims?
6. Does the diet use "before and after" photos or testimonials from individual dieters to "prove" that the diet works?
7. Does the diet identify "bad" foods and "good" foods?
8. Does the diet require following a rigid menu or meal plan?
9. Does the diet sound too good to be true?

If you can answer "yes" to even one of these questions, then the diet is likely to be a fad diet. If you are serious about losing weight safely and permanently, avoid fad dieting. Instead, follow the general eating and physical activity recommendations made in this concept as well as the following specific tips.

- Practice portion control. This means knowing serving sizes, which are generally smaller than most people think. You can use nutrition facts labels and the table below to avoid super-sizing your food.

Table **13.3.1**: Serving Size Comparisons for Selected Types of Food

| Type of Food | Serving Size Comparison |
|---|---|
| Raw leafy vegetables<br>Baked potato | small fist |
| Milk or yogurt<br>Fresh fruit | baseball |
| Cereal<br>Bread | hockey puck |
| Meat<br>Poultry | computer mouse |
| Fish | checkbook |
| Cheese | six stacked dice |
| Margarine<br>Butter | one die |

- Eat breakfast every day and do not skip meals. This will keep your metabolism fired up so you use more energy. If you go long periods without eating, your body goes into starvation mode and starts "hoarding" Calories.
- Get off the couch. Choose physical activities that you enjoy so you will do them regularly. The only exercise that works is the one you will actually do. Also, include more physical activity throughout each day. Park farther from your destination and walk the rest of the way. Take the stairs whenever you can. Wearing a pedometer may challenge you to reach the recommended 10,000 steps a day.
- Follow MyPlate but use a smaller plate. If you use a salad plate instead of a dinner plate, for example, the same-sized serving of food will look larger. You will eat less without feeling deprived.

Following the healthy-eating guidelines in this concept and the specific tips above should lead to a slow but steady weight loss of a pound or two a week. Losing weight slowly may be frustrating, but it is more likely to stay off than weight that is lost rapidly. It took you time to gain excess weight so it will take time to lose it. The only way to keep it off is to establish a healthy pattern of eating and physical activity that you can live with lifelong.

## REVIEW

1. Why is healthy eating important for good health?
2. Define nutrition. What does good nutrition depend on?
3. Define malnutrition, and identify types of malnutrition.
4. Briefly describe what healthy eating means.
5. What is nutrient density? How is it related to nutritious food choices?

6. Define energy homeostasis, and identify factors that regulate or influence energy homeostasis.
7. What is energy density, and how is it related to energy homeostasis?
8. What are the recommended daily values of nutrients?
9. List factors that influence nutrient needs of individuals.
10. Describe MyPlate. What food groups is it based on?
11. What information do nutrition facts labels provide? How can the information be used to choose the most nutritious food options?
12. Give two tips for healthy eating.
13. If there are 100 Calories per 100 grams of a baked potato, and 5.5 Calories per 1 gram of potato chips, which has a higher energy density — a baked potato or potato chips? Explain your answer.
14. When comparing two multivitamins in the store, you see that one has 500% of the daily value for a particular vitamin, while the other has 100% of the daily value for that vitamin. Is the one with 500% of the daily value necessarily better for your health? Explain your answer.
15. Explain why it is better for your health to eat whole fruits instead of drinking fruit juices.

## EXPLORE MORE

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## ATTRIBUTIONS


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# 13.4: EATING DISORDERS

## BEFORE AND AFTER

The child on the left in this sketch is in the throes of a serious disorder. They are extremely emaciated and on the brink of death. The same child is depicted on the right after being treated for their disorder. They have gained weight and appear to be healthy. What disease wreaked such havoc on this child's health? Was it cancer? Some terrible parasitic infection? The answer may surprise you. The disease that caused such serious health consequences is a mental health disorder, specifically, the eating disorder anorexia nervosa.

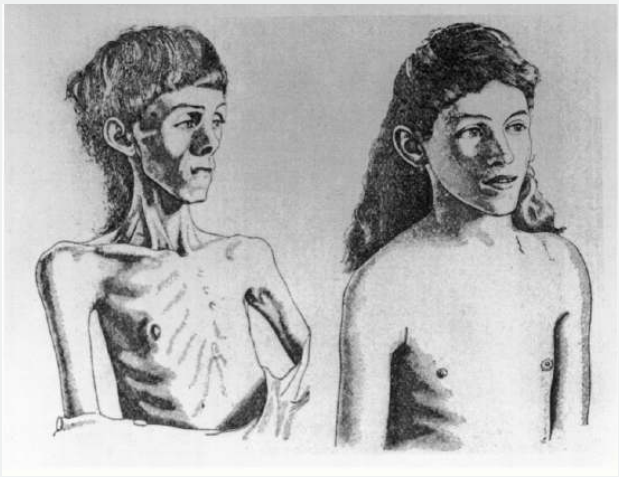


Figure **13.4.1** Anorexia Nervosa

## WHAT ARE EATING DISORDERS?

**Eating disorders** are mental health disorders defined by abnormal eating habits that adversely affect health. Eating disorders typically begin during late childhood, adolescence, or early adulthood. In developed countries such as the United States, they occur in about 4 percent of people. In a study of 9,713 participants showed that about 5.5% of young males (adolescents and young adults from 12 colleges and universities) manifested elevated eating disorder risk in the United States (Mariusz Jaworski et al., 2019). In developing countries, they are less common but increasing in frequency. Eating disorders are serious diseases and can even be fatal. In fact, they result in about 7,000 deaths a year in the United States, making them the mental disorders with the highest mortality rate.

## MAJOR EATING DISORDERS

Common eating disorders in the United States include anorexia nervosa, bulimia nervosa, and binge eating disorder. They differ in the patterns of disordered eating that characterize them, but all of them can have life-threatening health consequences. They may also have similar causes.

### ANOREXIA NERVOSA

**Anorexia nervosa** is an eating disorder in which people consistently eat very little even though they may be obsessed with food. They typically have an obsessive fear of gaining weight. They also usually have an unrealistic perception of their own low body weight and see themselves as fat even when they are very thin. This misperception of one's true body size and shape, along with dissatisfaction with that misperception, is called body dysmorphic disorder. It is very common in people with eating disorders such as anorexia nervosa. In fact, the majority of people with body dysmorphic disorder also have an eating disorder.

The food restriction in anorexia nervosa results in excessive weight loss and often amenorrhea (cessation of menses) in females. Other serious consequences of this pattern of eating include loss of bone mass; weakening of the heart and other muscles; abnormally low heart rate and blood pressure; and weakness, dizziness, and fainting. Because of such consequences, there is a significant risk of heart failure, and this can result in death.

### BULIMIA NERVOSA

**Bulimia nervosa** is an eating disorder in which people recurrently binge on large amounts of food. Because of the extreme fear of gaining weight, each binge is usually followed by trying to purge the food from the body. This may be done — more or less successfully — by vomiting, using laxatives or enemas, taking diuretics, or exercising excessively.

People with bulimia nervosa may or may not have an abnormal weight, but they are likely to develop an electrolyte imbalance due to the repeated binging and purging. This imbalance may cause an irregular heartbeat, which can lead to heart failure and death. Frequent vomiting can also cause rupture of the stomach or esophagus, which can be fatal, as well as erode dental enamel.

### BINGE EATING DISORDER

**Binge eating disorder** is an eating disorder in which people repeatedly binge on large amounts of food, and each binge is followed by feelings of guilt but not by purging. Adverse health impacts of binge eating disorder include excessive weight gain, obesity, high blood pressure, and high cholesterol. People with binge eating disorder are also at increased risk of gallbladder disease, cardiovascular disease, and type 2 diabetes.

## CAUSES OF EATING DISORDERS

The causes of eating disorders are not fully understood and are likely to vary among individuals. However, in virtually all cases, both biological and environmental factors appear to play a role.

### BIOLOGICAL FACTORS

Genes are likely to be involved in the development of eating disorders because having a close biological relative with an eating disorder increases one's own risk tenfold or more. At a biochemical level, eating disorders are thought to be caused in part by the

deregulation of neurotransmitters such as serotonin and dopamine. Serotonin normally has an inhibitory effect on eating and dopamine regulates the rewarding property of food. Imbalance in these neurotransmitters is likely to affect appetite and eating behavior. Deregulation of the hormones leptin and ghrelin may also be involved in eating disorders. These two hormones normally help maintain the body's energy balance by increasing or decreasing food intake. This occurs through the regulation of appetite and eating behavior. **Leptin** is produced mainly by fat cells in the body. It normally inhibits appetite by inducing a feeling of satiety. **Ghrelin** is produced in the stomach and small intestine. Its normal role is to stimulate the appetite. If these hormones are out of balance, the imbalance will affect appetite and may lead to disordered eating.

### ENVIRONMENTAL FACTORS

A number of environmental factors have also been shown to increase the risk of developing eating disorders. One of the most salient is abuse suffered as a child, including physical, psychological, or sexual abuse. Child abuse has been shown to triple the risk of developing an eating disorder. Parental pressure to control a child's eating habits can also increase the risk, as can having a fragile sense of self-identity. In older individuals, social isolation increases the risk of eating disorders.

For women, cultural ideal relates to slenderness, and for men to the musculature that is thought to be a major contributing cause of anorexia and bulimia nervosa. Dancers (like the one pictured below), jockeys, and athletes such as gymnasts are the groups of young individuals who may feel exceptional pressure to be thin. Up to 12 percent of dancers develop anorexia or bulimia, compared with about 2 percent of individuals in the general population.



Figure **13.4.2**: Eating disorders are very common in dancers and elite athletes, who may feel a great deal of pressure to remain thin.

## TREATMENT AND RECOVERY

Treatment of eating disorders varies according to the type and severity of the eating disorder. Usually, more than one treatment option is used. Treatment typically includes mental health counseling, which can take place in a variety of settings, such as a community program, private practice, or hospital. Treatment may also include the use of antidepressants or other medications because many people with eating disorders also suffer from depression or other mental health disorders. Nutritional counseling is often recommended as well. Hospitalization is occasionally required, in many cases to treat the adverse physical health consequences of the disordered eating.

The goal of treatment is recovery, including gaining control of eating, adopting normal eating habits, and attaining a normal weight. About 50 to 85 percent of people with eating disorders recover with treatment. However, some may have to struggle to maintain normal eating behaviors throughout the rest of their life.

### FEATURE: RELIABLE SOURCES

People with anorexia nervosa, as with many other health problems, may seek information and advice online before or instead of contacting a healthcare professional. The web offers a plethora of useful information on eating disorders, including anorexia nervosa, but some websites, blogs, and social media pages actually have the agenda of promoting disordered eating. The term *pro-ana* (from "pro-anorexia") refers to organizations, websites, and other sources that promote anorexia nervosa. Their mission is to normalize or even glamorize anorexia nervosa. They defend it as a lifestyle choice and an accomplishment of self-control rather than as a mental disorder. Research has shown that visiting pro-ana sites can have a negative impact on eating behavior in people both with and without eating disorders. After visiting such sites, people tend to decrease their Caloric intake, although most of them do not actually perceive that they have reduced their intake of Calories.

Following a 2001 episode of the *Oprah Winfrey Show* that focused on pro-ana, the mainstream press started covering the issue. Pressure from the public and pro-recovery organizations led to some social media and other websites adopting policies of blocking pro-ana pages or labeling them with warning messages. As a result, many pro-ana groups have taken steps to conceal themselves. For example, they may claim that they are simply providing a nonjudgmental forum for people with anorexia nervosa to discuss their disorder. They may also claim that they exist in part to provide support for those who choose to enter recovery.

Some clues that a website or page may be pro-ana include providing information on topics such as:

- crash dieting techniques and recipes.
- socially acceptable pretexts for refusing food, such as veganism.
- ways to hide weight loss from parents and doctors.
- reducing the adverse health effects of anorexia.
- ways to ignore or suppress hunger pangs.

Do you think you can tell the difference between pro-ana websites and legitimate pro-recovery websites, which are designed to encourage the development and maintenance of healthy behaviors and cognition? Go online and try to find at

least one pro-ana website and at least one pro-recovery website. Then write a brief explanation of how you made your choices.

## REVIEW

1. What are eating disorders? How serious are they?
2. What demographic group is most likely to be diagnosed with eating disorders?
3. Describe anorexia nervosa and its adverse effects on health.
4. What is bulimia nervosa? How does it affect health?
5. Define binge eating disorder, and identify its health consequences.
6. Why are genes likely to be involved in the development of eating disorders?
7. Explain how the deregulation of biochemicals may be involved in eating disorders.
8. Discuss environmental factors that may increase the risk of eating disorders.
9. Identify types of treatment for eating disorders. How effective is the treatment likely to be
10. What is a common ultimate cause of death in people with anorexia nervosa and bulimia nervosa?
11. True or False. Someone who is a normal weight cannot have an eating disorder.
12. True or False. The neurotransmitter serotonin normally has an inhibitory effect on eating.
13. When you are feeling hungry, what do you think are the relative levels of your ghrelin and leptin hormones? Explain your answer.
14. Which disorder is most likely to affect teeth enamel?
    A. Anorexia nervosa
    B. Binge eating disorder
    C. Bulimia nervosa
    D. None of the above
15. A. Female dancers are how many times as likely to develop anorexia or bulimia than women in the general population.
    B. half
    C. just
    D. two times
    E. six times

## REFERENCES:

Mariusz Jaworski, Mariusz Panczyk, Andrzej Śliwczyński, Melania Brzozowska, Katarzyna Janaszek, Piotr Małkowski, Joanna Gotlib. Eating Disorders in Males: An 8-Year Population-Based Observational Study; First Published July 3, 2019 Research Article Find in PubMed https://doi.org/10.1177/1557988319860970. CC BY-NC 4.0

## EXPLORE MORE

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In the following video, the speaker touches on the fact that eating disorders are about control in a very sober and balanced way.



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# 13.5: OBESITY

## TOO MUCH OF A GOOD THING

Everybody needs food energy just to stay alive, but too much energy consumption, coupled with too little energy use, is too much of a good thing. People who consistently consume more food energy than they use may become obese like the woman pictured here.



Figure **13.5.1**: Obesity

## WHAT IS OBESITY?

**Obesity** is a disease in which excess body fat has accumulated to the extent that it is likely to have negative effects on health. Obesity is commonly diagnosed on the basis of the body mass index (BMI). **BMI** is an estimate of body fatness based on a person's weight relative to their height. BMI is calculated by dividing a person's weight (in kilograms) by the square of the person's height (in meters). The graph below shows how BMI is used to categorize obesity and other body mass classes for adults. A BMI value of 18.5 to 25 kg/m$^2$ is considered normal. A BMI below 18.5 kg/m$^2$ is considered underweight. A BMI between 25 and 30 kg/m$^2$ places a person in the overweight range. A BMI greater than 30 kg/m$^2$ classifies a person as obese.

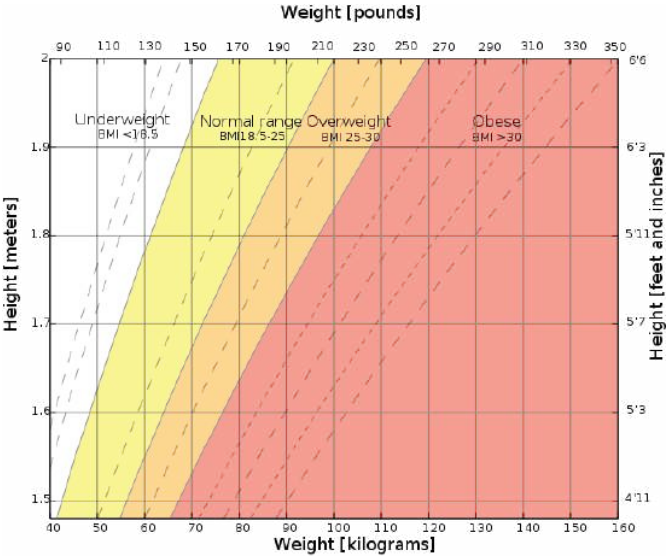



Figure **13.5.2**: BMI estimates body fatness on the basis of weight and height. This graph shows weight on the X-axis (pounds on the top and kilograms on the bottom. The Y-axis is height (feet on the right and meters on the left). This graph can be used to calculate BMI.

Obesity in children and adolescents is generally defined not simply by BMI but by comparison of BMI with reference values. Obesity is diagnosed when a child has a BMI that is greater than the 95th percentile of the reference values for children of the same age. This means that the child's BMI is higher than that of 95 percent of same-aged children in the reference sample. The reference values are based on large samples of children from the mid-to-late 20th century, before the recent rise in childhood obesity.

### CATEGORIES OF OBESITY

The medical profession breaks down obesity into additional categories, although the exact delineation of the categories is not universally agreed upon. Commonly accepted categories include:

- severe obesity, which is diagnosed when a person has a BMI ≥ 35 kg/m$^2$.
- morbid obesity, which is diagnosed when a person has a BMI ≥ 35 kg/m$^2$ and obesity-related health problems, or when a person has a BMI ≥ 40 kg/m$^2$ but < 45 kg/m$^2$.
- super obesity, which is diagnosed when a person has a BMI ≥ 45 kg/m$^2$

### FAT DISTRIBUTION IN OBESITY

Obesity can also be categorized in terms of fat distribution, as measured by waist-to-hip ratio (waist circumference divided by hip circumference). A waist-to-hip ratio greater than 0.85 for women or 0.90 for men is diagnostic of **central obesity,** in which most of the excess fat is stored in the abdomen. This type of fat distribution gives a person an apple shape, like the man pictured above. People with central obesity are at greater risk of the adverse health consequences of obesity than people who store most of their excess fat around the hips (giving them a pear shape). Because it accounts for the elevated risks associated with central obesity, waist-to-hip ratio is a better predictor than BMI of mortality in older obese patients

## CAUSES OF OBESITY

Like many other diseases, most cases of obesity are the result of an interplay between genetic and environmental factors. Obesity is most commonly caused by a combination of excessive food intake, inadequate physical activity, and genetic susceptibility.

### GENETIC INFLUENCES ON OBESITY

Various genes that control appetite and metabolism predispose people to develop obesity when sufficient food energy is present. It is likely that dozens of such genes exist. Family studies reveal the strength of the genetic influence on obesity. When both parents are obese, 80 percent of their offspring will also be obese. For comparison, when both parents are of normal weight, less than 10 percent of their offspring will be obese.

## DIET AND OBESITY

From 1971 to 2000 in the United States, the average amount of food consumed by women actually increased by 335 Calories per day, and by men by 168 Calories per day. During the same period, the rate of obesity in U.S. adults increased from about 15 to 31 percent. Most of the extra food energy came from an increase in carbohydrate consumption. Primary sources of these extra carbohydrates were sugar-sweetened beverages, like those pictured below. Sugary beverages include not only soft drinks but also fruit drinks, sweetened iced tea and coffee, and energy and vitamin water drinks. Such drinks now account for almost 25 percent of daily food energy in young adults in the United States. This is an alarming statistic, given that these drinks provide no other nutrients except energy.

## ACTIVITY LEVELS AND OBESITY

A sedentary lifestyle plays a significant role in obesity. Worldwide, there has been a large shift toward less physically demanding work. There has also been an increased reliance on cars and labor-saving devices at home. Currently, an estimated 30 percent of the world's population gets insufficient exercise.

## OTHER CAUSES OF OBESITY

A minority of cases of obesity are caused by certain medications or by other diseases. Medications that may increase the risk of obesity include antidepressant and antipsychotic drugs, steroids such as prednisone, and some forms of hormonal contraception, among others. Diseases that increase the risk of obesity include hypothyroidism, Cushing's disease, binge eating disorder, and Prader-Willi syndrome.

Consider Prader-Willi syndrome as an example. A young child with this syndrome is shown in Figure **13.5.3**. The syndrome occurs due to the loss of function of specific genes on chromosome 15. Symptoms of the syndrome include constant hunger, which typically leads to severe obesity in childhood. Prader-Willi syndrome is caused by genetic defects but it is not generally inherited. Instead, the genetic changes happen during the formation of the egg or sperm or during embryonic development.



Figure **13.5.3**: This super-obese eight-year-old child has Prader-Willi syndrome.

## PATHOPHYSIOLOGY OF OBESITY

A recently proposed physiological mechanism for the development of obesity is leptin resistance. Leptin is called the satiety hormone. It is secreted by fat cells and helps to regulate appetite based on the body's fat reserves. When fat reserves are high, more leptin is secreted and appetite is inhibited, so you eat less. The opposite occurs when fat reserves are low. In obesity, decreased sensitivity to leptin occurs, resulting in an inability to detect satiety despite high-fat reserves. As a consequence, people with leptin resistance never feel satiated and are likely to overeat and gain more weight.

## HEALTH CONSEQUENCES OF OBESITY

As shown in Figure **13.5.4**, obesity increases the risk of many health problems and diseases, including:

- sleep apnea
- lung disease, asthma, pulmonary blood clots
- liver disease, fatty liver, cirrhosis
- gallstones
- cancer of breast, uterus, colon, esophagus, pancreas, kidney, prostate
- stroke
- heart disease, abnormal lipid profile, high blood pressure
- diabetes
- pancreatitis
- abnormal periods and infertility
- arthritis
- inflamed veins often with blood clots
- gout

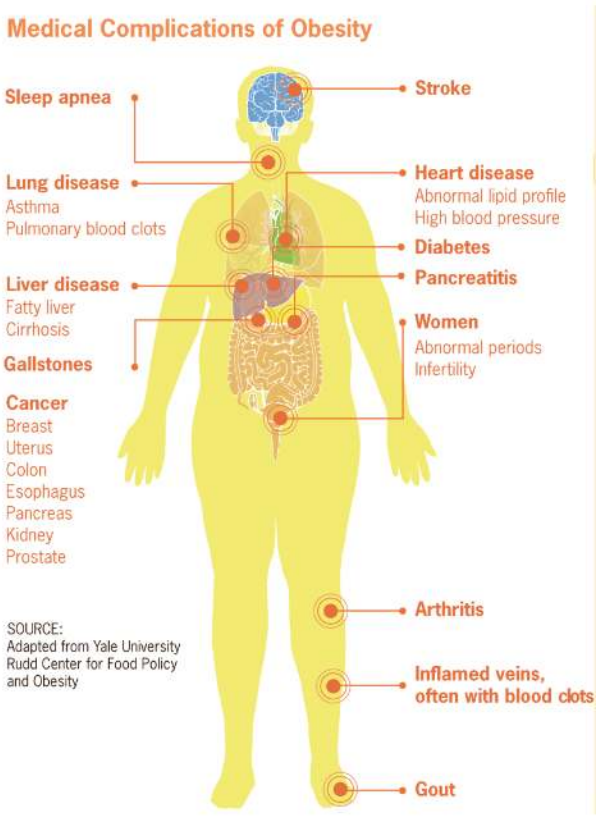



Figure **13.5.4**: Obesity has a detrimental effect on most body systems, both because of the added mass of fat and because of the increased number of fat cells.


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The health consequences of obesity are mainly due to the effects of either increased fat mass or increased numbers of fat cells. Extra weight from excess body fat places a lot of stress on the body and its organ systems, causing diseases such as osteoarthritis and obstructive sleep apnea. An increased number of fat cells increases inflammation and the risk of blood clots. It also changes the body's metabolism, altering the body's response to insulin and potentially leading to insulin resistance and type 2 diabetes. This explains why the link between obesity and type 2 diabetes is so strong. Obesity is thought to be the root cause of 64 percent of cases of type 2 diabetes in men and 77 percent of cases in women.

Not surprisingly, obesity has been found to reduce life expectancy. On average, obesity reduces life expectancy by six or seven years. Super obesity reduces life expectancy by as much as ten years.

## TREATING AND PREVENTING OBESITY

Most cases of obesity are treatable or preventable through changes in diet and physical activity that restore energy balance to the body. In fact, obesity is one of the leading preventable causes of disease and death worldwide. The amount of energy provided by the diet can be reduced by decreasing consumption of energy-dense (high-Calorie) foods, such as foods high in fat and sugar, and increasing consumption of high-fiber foods. The fiber in the diet cannot be digested, so it adds bulk and a feeling of fullness without adding Calories. All types of low-carbohydrate and low-fat diets appear equally beneficial in reducing obesity and its health risks. In some cases, medications may be prescribed to help control obesity by reducing appetite or fat absorption.

### BARIATRIC SURGERY

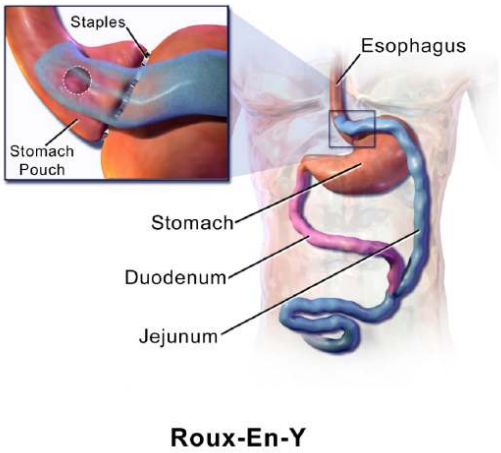



Figure **13.5.5**: Modifying the digestive tract with bariatric surgery is the most effective medical treatment for obesity. In this procedure, the main section of the stomach is closed off from the digestive tract. Instead, a small pouch is formed and the jejunum is directly attached to that pouch. The stomach and the duodenum are bypassed. The changes limit the intake of food and the absorption of nutrients from food.

If changes in diet and exercise and even medications are not effective, bariatric surgery may be recommended as a treatment for obesity. Bariatric surgery is the single most effective medical treatment for obesity. There are several different types of bariatric surgery, one of which is illustrated in figure **13.5.5**. In this particular type of surgery, the size of the stomach is greatly reduced so less food can be eaten at a time. The length of the small intestine is also reduced so fewer nutrients can be absorbed from food.

### PUBLIC HEALTH APPROACHES

Public health approaches to the problem of obesity include efforts to understand and correct the environmental factors responsible for increasing obesity rates. The goals are to reduce food energy consumption and promote energy expenditure in physical activity. Efforts to reduce energy consumption include promoting healthy meals and limiting access to sugary beverages and junk foods in schools. Efforts to promote physical activity include increasing access to parks and developing pedestrian routes in urban environments.

## REVIEW

1. Define obesity.
2. How is obesity generally diagnosed in adults? In children?
3. Compare and contrast severe obesity, morbid obesity, and super obesity.
4. What is central obesity? What is its relationship to the adverse health consequences of obesity?
5. Give examples of medications and disorders that may cause obesity.
6. Discuss factors that cause most cases of obesity.
7. What is leptin resistance, and what is its connection with obesity?
8. Identify some of the health consequences of obesity.
9. Describe types of treatments available for obesity.
10. Describe public health approaches to treating and preventing obesity.
11. Which is likely to be worse for a person's health — having their hip circumference be larger than their waist circumference, or vice versa? Explain your answer.
12. What factors is BMI based on?
13. Why is the recent increase in childhood obesity a public health concern?

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# 13.6: UNDERNUTRITION

THEN AND NOW

This photo was taken in the late 1960s. It shows an American volunteer nurse and their patients at an orphanage in Nigeria. The children's distended bellies are signs of kwashiorkor, a severe form of undernutrition caused by inadequate Calorie and protein intake, usually exacerbated by frequent bouts of infectious disease. Kwashiorkor and other forms of undernutrition still occur at high rates in Nigeria and many other places in the world. Today, one out of every seven people on our planet goes to bed hungry, and 25,000 people a day die of hunger-related diseases. Clearly, undernutrition is still a major problem now as it was then.



Figure **13.6.1**: Kwashiorkor

## DEFINING UNDERNUTRITION

**Undernutrition** is defined as an insufficient intake of nutritious foods. People who are undernourished are likely to have low body fat reserves, so one indicator of undernutrition in individuals is a low body mass index (BMI). Adults are considered underweight if their body mass index (BMI) is less than 18.5 $kg/m^2$. Children are considered underweight if their BMI is less than the 5th percentile of the reference values for children of the same age.

## UNDERNUTRITION IN CHILDREN

The effects of undernutrition are particularly important during childhood when energy and other nutrients are needed for normal growth and development. Children are more likely than adults to become severely undernourished as well as to suffer permanent effects from undernutrition. They may become dangerously thin, with loss of muscle as well as fat. This is called **wasting** (see figure **13.6.2**). If they lack adequate energy for growth, they will stop growing. If they are chronically undernourished, the growth deficits may cause them to be too short for their age. This is called **stunting.** Unless adequate nutrition becomes available later so they can make up their growth deficits, stunted children will end up shorter than their genetic potential for height by the time they are adults.



Figure **13.6.2**: In this photo, a public health worker is measuring the arm circumference of a young child in order to assess their nutritional status. Their virtual absence of body fat and very limited.

### UNDERNUTRITION AND INFECTION

Undernutrition and infectious diseases in children have a positive synergistic relationship. Each increases the risk of the other and makes the other worse. Children who are undernourished may be weakened and have a less than robust immune system. This makes them more susceptible to infectious diseases and likely to become sicker when they have infectious diseases. Children who are sick with infectious diseases may need more nutrients to defend against infection. At the same time, they may have reduced intake or absorption of nutrients due to symptoms such as vomiting and diarrhea. In these ways, infectious disease increases the risk of undernutrition or makes existing undernutrition worse.

### UNDERNUTRITION AND LOW BIRTHWEIGHT

Many children are born with the disadvantage of low birth weight (< 2.5 kg, or 5.5 lb.) caused by maternal undernutrition and intrauterine growth restriction. Babies with low birth weight are more susceptible to disease and more likely to die in infancy. In children that survive infancy, low birthweight may result in slow growth and developmental delays throughout early childhood.

## UNDERNUTRITION SYNDROMES

Severe cases of undernutrition may develop into life-threatening syndromes such as kwashiorkor, as in the Nigerian orphans pictured above. Another common severe undernutrition syndrome is called marasmus.

### KWASHIORKOR

**Kwashiorkor** was first described in the medical literature in the 1930s. The name comes from a West African word meaning "disease of the deposed child." The original meaning of the term is a clue to the cause of this syndrome. If a young child is weaned from the breast so a new baby can be breastfed, the "deposed child" is likely to go from a mostly breastmilk diet, which is high in protein, to a mostly plant-food diet, which is low in protein. Although Kwashiorkor may occur in a child who lacks protein but not Calories, it occurs more often when the diet is also deficient in

Calories. That's why kwashiorkor is commonly called protein-Calorie malnutrition.

The defining sign of kwashiorkor in an undernourished child is edema (swelling) of the ankles and feet and often a distended belly, both of which are clearly visible in the child pictured below. The lack of protein causes osmotic imbalances that prevent tissue fluids from being returned to the bloodstream. This mechanism accounts for the accumulation of fluid in the ankles, feet, and abdomen. Other common signs of kwashiorkor include enlarged liver (which contributes to the abdominal distension), thinning hair, loss of teeth, skin rash, and skin and hair depigmentation. Children with kwashiorkor may also be irritable and lose their appetite. Kwashiorkor can have a long-term impact on a child's physical and mental development and frequently leads to death without treatment.

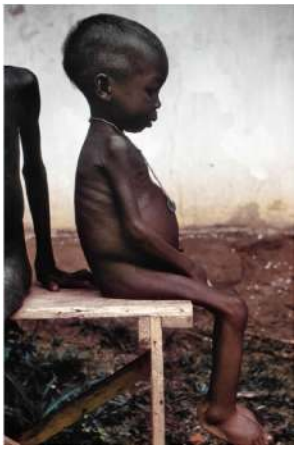


Figure **13.6.3**: This African child shows several characteristic signs of kwashiorkor, including edema of the ankles and feet, distended abdomen, and loss of hair.

### MARASMUS

Marasmus comes from a Greek word meaning "wasting away." It is a severe undernutrition syndrome caused by extremely low intakes of food energy. Signs and symptoms of marasmus include wasting (as depicted above, low body temperature, anemia, dehydration, weak pulse, and cold extremities. Without treatment, marasmus is often fatal, although it generally has a better prognosis than untreated kwashiorkor.

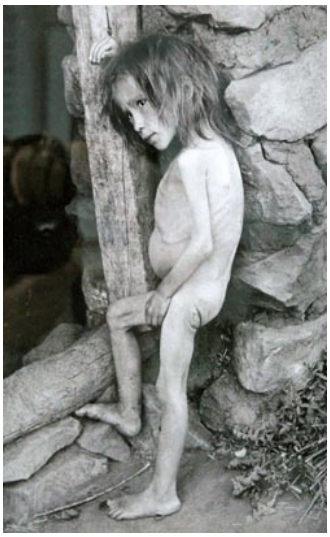


Figure **13.6.4**: This Russian child shows the characteristic emaciation of marasmus but lacks the edema and abdominal distension typical of kwashiorkor.

## MICRONUTRIENT DEFICIENCIES

Besides deficiencies in food energy and protein, many undernourished people suffer from deficiencies of specific vitamins or minerals. Some of the most common micronutrient deficiencies worldwide are iron, vitamin A, and iodine deficiencies.

### IRON DEFICIENCY

Iron deficiency is the single most common micronutrient deficiency worldwide, affecting about 2 billion people. Iron deficiency, in turn, causes anemia, which is especially common in women and children under the age of five years. Anemia can lead to increased mortality in infancy and poor cognitive and motor development in early childhood. The problems caused by iron-deficiency anemia in childhood cannot be reversed.

### VITAMIN A DEFICIENCY

Vitamin A deficiency is also very common in developing countries. In young children, vitamin A plays an essential role in the development of the immune system, so vitamin A deficiency adversely affects the ability of the immune system to fight off infections. Vitamin A deficiency also contributes to anemia and causes visual impairments, ranging from night blindness (inability to see well at low light levels) to total blindness.

### IODINE DEFICIENCY

Since the early 1900s, iodine has been added to salt in many countries, including the United States and most of Europe, virtually eliminating iodine deficiency in these countries. However, inadequate iodine intake is still a public health problem in dozens of countries, and about 30 percent of the world's people are iodine deficient.



Figure **13.6.5**: Before salt was iodized in North America and Europe starting in the early 1900s, goiters caused by iodine deficiency were far more common.

Iodine is needed for thyroid hormone production. In adults, iodine deficiency causes reversible signs and symptoms of inadequate thyroid hormone. These may include an enlarged thyroid gland, called a goiter (see the photo above), and a sluggish metabolism. In children, iodine deficiency is much more serious. It causes permanent intellectual disability because thyroid hormone is needed for normal brain growth and development, from the fetal stage through early childhood. Iodine deficiency is the most important cause of preventable intellectual disability in the world.

## CAUSES OF UNDERNUTRITION

A small percentage of undernutrition occurs because of diseases such as cancer, anorexia nervosa, celiac disease, and cystic fibrosis (all of which you can read about in other concepts). However, the vast majority of undernutrition globally occurs because people simply don't have enough nutritious food to eat. They take in less energy than the minimum daily energy requirement so they are underweight, and they are likely to have other nutritional deficiencies as well.

Worldwide food supplies are adequate to provide food to all if the food supplies were equally distributed and accessible to everyone. Unfortunately, that is not the case. Adequate food is not available to people over large areas of Africa and Asia. Even if food supplies were equally distributed, most undernutrition would still occur in these areas because of the inability of many people to access food due to poverty. Poverty is a consequence as well as a cause of undernutrition, and the two form a self-perpetuating cycle. Impoverished individuals are less likely to have access to enough nutritious food for good health and for normal growth and development. As a result, they are more likely to be undernourished. Undernutrition, in turn, makes them less likely to attend or perform well in school and as adults to be less productive workers, thus limiting their income.

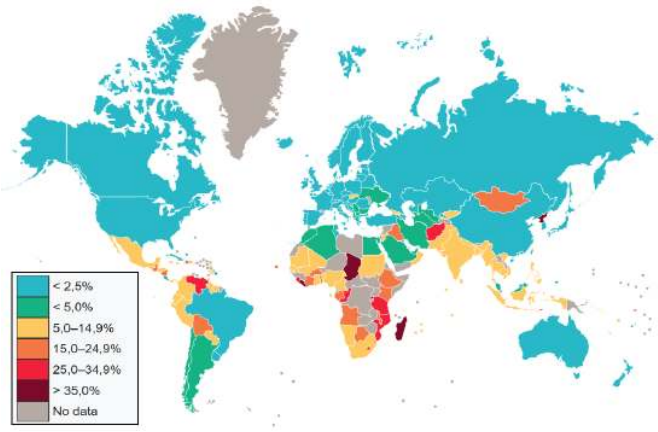



Figure **13.6.6**: Based on data from the United Nations World Food Program in 2020, this map shows that much of the global north has less than 2.5% of the population suffering from chronic hunger. The global south has a greater percentage of the population suffering from chronic hunger. The highest rates of chronic hunger (over 35% of the population) are found in Chad, Madagascar, Liberia, Rowanda, Haiti, and North Korea.

Although undernutrition is not as common in the richer nations of the world as it is elsewhere, it still occurs in significant proportions of people. Even in a land of plenty like the United States, socioeconomic disparities result in some people being undernourished due to lack of access to sufficient nutritious food. The photo below, taken in New York City, shows a woman searching for edible food in a garbage dumpster. Besides lacking adequate money to buy nutritious foods, many poor people in the United States live in areas that are considered "food deserts," defined as areas with limited access to nutritious foods. In these food deserts, supermarkets with fresh produce and other nutritious food choices are typically too far away for people to utilize. Instead, they must rely on small neighborhood stores that stock mainly over-priced processed foods or on fast food restaurants that offer primarily high-fat and high-sugar food options. With social inequalities on the rise in the United States and some other rich nations, problems of food access and undernutrition may worsen.



Figure **13.6.7**: An impoverished woman in New York City scavenges food from a dumpster. (CC BY 2.0; Carlos. A. Martinez via Wikimedia Commons)

## TREATMENT AND PREVENTION OF UNDERNUTRITION

Treating and preventing undernutrition is a huge and complex problem requiring multifaceted approaches. Potential solutions must target both individual and public health. Meeting individual needs is generally achieved through direct nutrition interventions (like the one illustrated in the photo above). In such interventions, the health-care sector typically delivers nutritional supplements directly to acutely malnourished people who might otherwise require hospitalization. Public health interventions may focus on improvements in agriculture, water, sanitation, or education, among other public health targets. Some of the most successful public health interventions have been those aimed at eliminating specific micronutrient deficiencies. For example, in the early 1990s, iodine deficiency was addressed by a global campaign to iodize salt. This campaign reduced the rate of iodine deficiency from about 70 percent to 30 percent.



Figure **13.6.8**: The United States Agency for International Development (USAID) provides therapeutic foods to treat and prevent malnutrition among children in some of the poorest nations in the world. These young Ethiopian children are being fed a ready-to-eat, peanut-based protein supplement called Plumpy'nut.

## REVIEW

1. Define undernutrition.
2. How is underweight status determined in adults? How is it determined in children?
3. Why is undernutrition a more significant problem in children than adults?
4. What are wasting and stunting?
5. Describe kwashiorkor.
6. What is marasmus?
7. List three of the most common micronutrient deficiencies worldwide. Describe how each deficiency affects health.
8. Why do the vast majority of cases of undernutrition occur?
9. Explain how undernutrition and poverty are related.
10. Why does undernutrition occur even in the richer nations of the world?
11. How should the problem of global undernutrition be tackled?
12. Which best describes the relationship between undernutrition and infectious disease?
    A. Undernutrition can increase the risk of infectious disease.
    B. Infectious disease can increase the risk of undernutrition.
    C. Undernutrition and infectious disease are independent of one another.
    D. A and B
13. *True or False.* A diet that has enough energy but is deficient in protein can result in a type of undernutrition syndrome.
14. *True or False.* The distended belly seen in kwashiorkor is due primarily to the stomach expanding in response to lack of food in it.

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# 13.7: FOODBORNE DISEASES

## PICNIC FUN

Picnics like this one can be a lot of fun. Food always seems to taste better when eaten outdoors. Ants and other insects can be attracted to picnic foods and be annoying. However, a greater potential hazard may lurk within the picnic foods themselves: microorganisms that cause foodborne disease.



Figure **13.7.1**: A picnic

## WHAT IS FOODBORNE DISEASE?

**Foodborne disease,** commonly called food poisoning, is any disease that is transmitted via food. Picnic foods create a heightened risk of foodborne disease mainly because of problems with temperature control. If hot foods are not kept hot enough or cold foods are not kept cold enough, foods may enter a temperature range in which microorganisms such as bacteria can thrive.

Many people do not think about food safety until a foodborne disease affects them or a family member. While the food supply in the United States is one of the safest in the world, the CDC estimates that 76 million Americans a year get a foodborne disease, of whom more than 300,000 are hospitalized and 5,000 die. Preventing foodborne disease remains a major public health challenge.

## CAUSES OF FOODBORNE DISEASE

Most foodborne diseases are caused by microorganisms in food. Some are caused by toxins in food or adulteration of food by foreign bodies.

### MICROORGANISMS

Microorganisms that cause foodborne diseases include bacteria, viruses, parasites, and prions. The four most common foodborne pathogens in the United States are a virus called norovirus and three genera of bacteria: *Salmonella* species (such as *Salmonella typhimurium*, pictured below), *Clostridium perfringens*, and *Campylobacter jejune*. Although norovirus causes many more cases of foodborne disease, *Salmonella* species are the pathogens in food that are most likely to be deadly. Parasites that cause human foodborne diseases are mostly **zoonoses** — animal infections that can be transmitted to humans. Parasites such as pork tapeworm *(Taenia solium)* are ingested when people eat inadequately cooked infected animal tissue. The prions that cause mad-cow disease have been transmitted to people through the ingestion of contaminated beef.



Figure **13.7.2**: Salmonella bacteria, shown here in red, cause potentially deadly foodborne disease.

### TOXINS

Toxins are another common cause of foodborne disease. Toxins may come from a variety of sources. Foods may be contaminated with toxins in the environment. Pesticides applied to farm fields are common examples of environmental food toxins. Toxins may be produced by microorganisms in food. An example is botulism toxin that is produced by the bacterium *Clostridium botulinum*. Some toxins occur naturally in certain plants and fungi. A common example is mushrooms. Dozens of species are poisonous and some are deadly, like the aptly named death-cap mushroom pictured below. Many deadly mushrooms look similar to edible species, making them even more dangerous. Food plants can also be infected with fungi that make people sick when they eat the plants. Fungi in the genus *Aspergillus* are frequently found in nuts, maize, and corn. They produce a toxin called aflatoxin, which targets the liver, potentially causing cirrhosis of the liver and liver cancer.



Figure **13.7.3**: The death-cap mushroom (Amanita phalloides) contains toxins that are not affected by cooking. More than half of the people who accidentally eat these mushrooms die from the poison.

### ADULTERATION BY FOREIGN BODIES

Another potential cause of the foodborne disease is the adulteration of foods by foreign bodies. Foreign bodies refer to any substances or particles that are not meant to be foods. They can include pests such as insects, animal feces such as mouse droppings, hairs (human or nonhuman), cigarette butts, and wood chips, to name just a few. Some foods are at risk of contamination with lead or other toxic chemicals because they are stored or cooked in unsafe containers, such as ceramic pots with lead-based glaze.

## CHARACTERISTICS OF FOODBORNE DISEASES

Foodborne diseases differ in specific characteristics but they share some commonalities, often including similar symptoms.

### SYMPTOMS AND INCUBATION PERIOD

Foodborne diseases commonly cause gastrointestinal symptoms such as vomiting and diarrhea. They also frequently cause fevers, aches, and pains. The length of time between the consumption of contaminated food and the first appearance of symptoms is called the **incubation period.** This concept is illustrated in the figure below. The incubation period for a foodborne disease can range from a few hours to several days or even longer, depending on the cause of the disease. Toxins generally cause symptoms sooner than microorganisms. When symptoms do not appear for days, it is difficult to connect them with the agent that caused them.

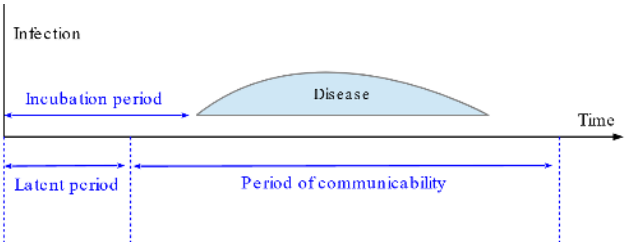



Figure **13.7.4**: This graph shows the incubation period of a disease, which is the time between infection and the first appearance of symptoms. It also shows the period of communicability, which is the time during which infected individuals can spread the disease. This period may begin before symptoms appear and infected individuals know they are sick

During the incubation period, microbes generally pass through the stomach and into the small intestine. Once in the small intestine, they attach to cells lining the intestinal walls and begin to multiply. Some types of microbes stay in place in the intestine, although they may produce toxins that are absorbed into the bloodstream and carried to cells throughout the body. Other types of microbes directly invade deeper body tissues.

### INFECTIOUS DOSE

Whether a person becomes ill from a microbe or a toxin depends on how much of the agent was consumed. The amount that must be consumed to cause disease is called the **infectious dose.** It varies by disease agent and also by host factors, such as age and overall health.

### SPORADIC CASES VS. OUTBREAKS

The vast majority of reported cases of foodborne disease occur as sporadic cases in individuals. The origin of most sporadic cases is never determined. Only a small number of foodborne disease cases happen as part of **disease outbreaks.** An outbreak of a foodborne disease occurs when two or more people experience the same disease after consuming food from a common source. The majority of foodborne disease outbreaks originate in restaurants, but they also originate in nursing homes, hospitals, schools, and summer camps.

An example of a foodborne disease outbreak in the United States is the *Salmonella* outbreak shown in Figure **13.7.5**. The CDC map below shows where most of the cases occurred. The reported cases began in July and were traced back to onions produced in California. Within 2 weeks the onions were recalled. The outbreak was over by October. Overall, a total of 1,127 people across 48 states, were infected with the outbreak strain of *Salmonella* Newport. There were 167 hospitalizations and no deaths reported.

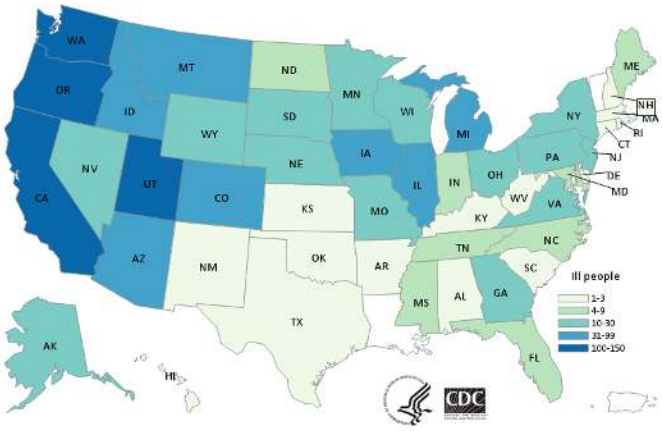



Figure **13.7.5**: This map shows the distribution of cases in a 2020 Salmonella outbreak in the United States.

## FACTORS THAT INCREASE THE RISK OF FOOD CONTAMINATION

The foodborne disease usually arises from food contamination through improper handling, preparation, or storage of food. Food can become contaminated at any stage from the farmer's field to the consumer's plate.

### POOR HYGIENE

Many foods become contaminated by microorganisms because of poor hygienic practices, such as handling or preparing foods with unwashed hands. Consider norovirus, the leading cause of foodborne disease in the United States. The virus can easily contaminate food because it is very tiny and highly infective. People sick with the virus shed billions of virus particles. Unfortunately, It takes fewer than 20 virus particles to make someone else sick. Food can become contaminated with virus particles when infected people get stool or vomit on their hands and then fail to wash their hands before handling food. People who consume food can ingest the virus particles and get sick.

### CROSS-CONTAMINATION

Another major way that foods become contaminated is through **cross-contamination.** This occurs when microbes are transferred from one food to another. Some raw foods commonly contain bacteria such as *Salmonella*, including eggs, poultry, and meat. These foods should never come into contact with ready-to-eat foods, such as raw fruits and vegetables or bread. If a cutting board, knife, or counter-top is used to prepare contaminated foods, it should not be used to prepare other foods without proper cleaning in between.

## FAILURE OF TEMPERATURE CONTROL

Foods contaminated with bacteria or other microorganisms may become even more dangerous if failure of temperature control allows the rapid multiplication of microorganisms. Bacteria generally multiply most rapidly at temperatures between about 4 and 60 degrees C (40 and 140 degrees F). Perishable foods that remain within that temperature range for more than two hours may become dangerous to eat because of rapid bacterial growth.

# PREVENTION OF FOODBORNE DISEASE

Preventing foodborne disease is both a personal and a society-wide problem. Both governments and individuals must work to solve it.

## THE GOVERNMENT'S ROLE

In the United States, the prevention of foodborne disease is mainly the role of government agencies such as the Food and Drug Administration and local departments of health. Such government agencies are responsible for setting and enforcing strict rules of hygiene in food handling in stores and restaurants (see the sign below). Government agencies are also responsible for enforcing safety regulations in food production, from the way foods are grown and processed to the way they are shipped and stored. Government regulations require that food to be traceable to their point of origin and date of processing. This helps epidemiologists identify the source of foodborne disease outbreaks.




Figure **13.7.6**: This historic sign was created by the Minnesota Department of Health in the 1930s. It instructs food service workers to wash their hands frequently. It was part of a campaign to reduce foodborne diseases.

## FOOD SAFETY AT HOME

At home, the prevention of foodborne disease depends mainly on good food safety practices.

- Regular handwashing is one of the most effective defenses against the spread of foodborne diseases. Always wash hands before and after handling or preparing food and before eating.
- Rotate food in your pantry so older items are used first. Make sure foods have not expired before you consume them. Be aware that perishable foods such as unpreserved meats and dairy products have a relatively short storage life, usually just a few days in the refrigerator.
- Rinse fresh produce before eating. This is especially important if the produce is to be eaten raw. Even if you do not plan to eat the outer skin or rind, wash it because microbes or toxins on the surface can contaminate the inside when the food is cut open or peeled.
- Many bacteria in food can be killed by thorough cooking, but food must reach an internal temperature of at least 74 degrees C (165 degrees F) to kill any bacteria the food contains. Use a cooking thermometer like the one pictured below to ensure food gets hot enough to make it safe to eat.
- Foods meant to be eaten hot should be kept hot until served, and foods meant to be eaten cold should be kept refrigerated until served. Perishable leftovers should be refrigerated as soon as possible. Any perishable foods left at a temperature between 4 and 60 degrees C (40 and 140 degrees F) for more than two hours should be thrown out.




Figure **13.7.7**: To be on the safe side, use a thermometer to make sure food reaches a high enough temperature to kill any bacteria it contains.

- Make sure the temperature in the refrigerator is kept at or below 4 degrees C (40 degrees F) to inhibit bacterial growth in refrigerated foods. If your refrigerator does not have a built-in thermometer, you can buy one to monitor the temperature. This is especially important in a power outage. If the temperature stays below 40 degrees F until the power comes back on, the food is safe to eat. If the temperature goes above 40 degrees F for two hours or more, the food may no longer be safe and should not be consumed.
- Keep the temperature of the freezer below 18 degrees C (0 degrees F). Foods frozen at this temperature will keep indefinitely, although they may gradually deteriorate in quality.
- Do not thaw foods at room temperature. Freezing foods does not kill microbes; it preserves them. They will become active again as soon as they thaw. Either thaw frozen foods slowly in the refrigerator or thaw them quickly in the microwave, cool water, or while cooking. Never refreeze food once it has thawed.

### FEATURE: MYTHS VS. REALITY

Myths about foodborne diseases abound. Some of the most common myths are debunked below.

**Myth:** It must have been the mayonnaise.

**Reality:** Mayonnaise is acidic enough that it does not provide a good medium for the growth of bacteria unless it becomes heavily contaminated by a dirty utensil or is mixed with other foods that decrease its acidity. Mayo may have gotten a bad rap because it is often consumed at picnics, where temperature control may be poor and lead to bacterial growth in other, non-acidic foods.

**Myth:** Foodborne disease is caused by food that has "gone bad."

**Reality:** Eating spoiled or rotten food is seldom the cause of foodborne disease. Most cases of foodborne disease are caused by contamination of food by unwashed hands or cross-contamination of food by unwashed utensils or cutting boards.

**Myth:** Foodborne disease is caused by eating restaurant foods.

**Reality:** Foodborne disease is caused by contamination of foods in the home as well as in restaurants. Restaurant kitchens must be regularly inspected to ensure sanitary conditions for food preparation. There are no such inspections of home kitchens.

**Myth:** Foodborne disease is caused by the last food eaten.

**Reality:** Symptoms of the foodborne disease may not strike for several hours to several days following infection, so the last meal eaten may not be the culprit. This makes it very difficult to know which food caused the symptoms.

## REVIEW

1. What is a foodborne disease?
2. How common are foodborne diseases in the United States?
3. What are the main causes of foodborne disease? Give examples of each cause.
4. Define the incubation period and infectious dose.
5. Discuss similarities and differences among foodborne diseases.
6. Compare and contrast sporadic cases and disease outbreaks of foodborne disease.
7. What are the three main ways that food becomes contaminated?
8. List three food safety practices that can help prevent transmission of foodborne disease in the home.
9. If you store cooked leftovers at room temperature (about 68 degrees F) for more than two hours, are they safe to eat if you heat them up well first? Explain your answer.
10. *True or False*. There is no need to wash a melon before cutting it because you will not be eating the rind.
11. *True or False*. Foodborne diseases can sometimes cause a form of cancer.
12. Explain why it can be hard to trace the source of a foodborne disease if it has a long incubation period.
13. Which are a bacterial species that can cause foodborne disease?
    A. *Clostridium perfringens*
    B. Norovirus
    C. *Taenia solium*
    D. All of the above
14. Why do you think the incubation period for a foodborne disease is generally shorter when the agent is a toxin compared to a microorganism?
15. Why do you think it is often recommended to rapidly cool a large quantity of homemade soup by putting the pot in an ice water bath before storing it in the refrigerator?

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# 13.8: CASE STUDY CONCLUSION- FAST FOOD AND CHAPTER SUMMARY

## CASE STUDY CONCLUSION: WHAT'S WRONG WITH FAST FOOD?

What is wrong with fast food? That is the question that Carlos, who you read about at the beginning of the chapter, asked after learning that his friend Abdul eats it five or six times a week and thinks that this diet is not necessarily that bad. In order to find some answers, Carlos went to the website of Abdul's favorite fast food restaurant and found nutritional information for Abdul's typical meal of a cheeseburger, large fries, and a large soda. Some of the information that Carlos found is shown in the tables below. Knowing what you now know about nutrition, what aspects of this meal could potentially be harmful to Abdul's health if he eats like this frequently?



Figure **13.8.1**: Eating a burger

As Carlos already said to Abdul, fast food meals are often very high in calories. This meal has 1,350 Calories. A typical adult should consume around 2,000 Calories a day, so this single meal has more than half the calories typically needed by a person in one day. Some fast-food meals have even more calories. The cheeseburger in this meal has 540 Calories, which is typical for a moderately-sized fast-food cheeseburger. But some larger fast-food burgers, or burgers with more toppings, can have over 1,000 Calories! As you can see, it can be quite easy to exceed your calorie recommendation for the day if you eat a typical fast food meal, considering that you will probably eat two other meals that day as well.

What is the problem with consuming excess calories? As you have learned, it is important to maintain energy homeostasis — that is, a balance between the energy you consume and what your body uses. If you eat more calories than your body needs, you will store that extra food energy as fat, which can cause you to become obese. Obesity raises the risk of many diseases and health problems, including cardiovascular disease, type 2 diabetes, stroke, liver disease, cancer, pancreatitis, osteoarthritis, sleep apnea, and asthma. Many of these medical conditions can be deadly, which is why obesity can shorten a person's lifespan. Although Abdul is only slightly overweight at this point, if he regularly consumes more calories than he uses (which is likely with a diet high in fast food) he will gain excess body fat, raising his risk of obesity and its associated diseases.

Table **13.8.1**: Nutritional Information for a Typical Fast Food Meal

| Food | Calories | Total Fat (%DV) | Saturated Fat (%DV) | Trans Fat | Carbohydrates (%DV) |
|---|---|---|---|---|---|
| Burger | 540 | 43% | 49% | 1 g | 15% |
| Fries | 510 | 37% | 17% | 0 g | 22% |
| Soda | 300 | 0% | 0% | 0 g | 27% |
| **Total** | **1,350** | **80%** | **66%** | **1 g** | **64%** |

| Food | Sodium (%DV) | Iron (%DV) | Vitamin A (%DV) | Vitamin C (%DV) | Calcium (%DV) |
|---|---|---|---|---|---|
| Burger | 40% | 25% | 10% | 2% | 15% |
| Fries | 15% | 6% | 0% | 30% | 2% |
| Soda | 1% | 0% | 0% | 0% | 0% |
| **Total** | **56%** | **31%** | **10%** | **32%** | **17%** |

*% DV = percentage of the adult recommended daily value (DV) for each nutrient, based on a 2,000 Calorie a day diet.*

Why do typical fast-food meals have so many calories even if they don't appear to be particularly large? For one, these foods are typically high in fat. Notice that this meal contains 80% of the recommended daily value (DV) of total fat — close to the limit for the entire day! As you have learned, fat is energy-dense. One gram of fat has nine Calories, while one gram of protein or carbohydrate has only four Calories. This means that meals high in fat, like this one, will generally have more calories than a lower fat meal of equivalent size. A large amount of fat in the burger and fries contributes to the high energy density of this meal.

But fat isn't the only reason this meal is so high in calories. The soda contains 300 Calories — about the same number of calories as three apples! For most people, three apples would be more satiating than a soda. This is in part because apples have fiber, which is filling. As you have learned, sodas and other sugary beverages generally have no other nutrients besides carbohydrates. You can see from the tables that the soda is the largest contributor of carbohydrates to this meal, with very few other nutrients. If Abdul is frequently drinking large sodas, he is getting a significant percentage of his calories from a substance that is not giving him a feeling of fullness, which may cause him to consume more calories overall. In fact, many scientists think that the increase in consumption of sugary beverages has been a major contributor to the obesity epidemic.

Besides excess calories, what nutrients in this meal could cause health problems? This meal has both a high percentage of saturated fat (66% DV) as well as some trans fat. The American Heart Association recommends that people limit their consumption of saturated fat since it has been shown to raise the risk of heart disease. Trans fats are particularly dangerous and can increase the

risk of heart disease, stroke, and type 2 diabetes. In fact, in 2015 the U.S. Food and Drug Administration (FDA) ruled that trans fats have not been shown to be safe for human consumption, and ordered food producers to remove them from the food supply by 2018. While some fast-food restaurants voluntarily removed trans fats from their food prior to this time, as of early 2017 some restaurants still had items containing trans fats on their menus —like the burger from Abdul's favorite restaurant.

Another nutrient that fast food meals tend to have too much of is sodium. This meal has over half the sodium you should eat in a day, mostly from the burger. And this burger isn't the worst one around — some fast food burgers have *double* the recommended DV for sodium! Burgers with bacon are particularly high in sodium. Consumption of excess sodium can lead to high blood pressure, cardiovascular disease, and stroke.

Consumption of excess nutrients is not the only concern when a person frequently eats fast food. As you can see from the tables, this meal is relatively low in some vitamins and minerals such as vitamin A (10% DV) and calcium (17% DV). As you have learned, vitamin A is important for maintaining normal vision and, in young children, the development of the immune system, among other functions. Calcium is a macromineral needed for bone strength, neutralizing acidity in the digestive tract, and nerve and cell membrane functions. Eating a diet low in specific nutrients can cause a form of malnutrition called unbalanced nutrition. If Abdul eats meals like this frequently, he would have to make sure to get plenty of essential nutrients from other sources in order to maintain his health, which may be difficult if fast food takes the place of healthier foods in his diet. Carlos was correct to be concerned about the lack of fresh food in most fast food meals. Fresh fruits and vegetables contain fiber, phytochemicals, and many vitamins and minerals that are important for maintaining health.

But as Abdul brought up, is fast food worse than other types of food? While it tends to be particularly high in calories, fat, and sodium, it is not very nutrient-dense. The same is true for many other types of meals eaten outside the home. Many chain restaurants have nutritional information listed on their website — you can look up some of your favorites. You might be surprised to learn that some restaurant entrees contain more than 2,000 Calories for a single meal, combined with an excessive amount of saturated fat and sodium. These items are just as bad or worse for your health than some fast food meals.

The keys to healthy eating are to know what you are consuming and to make good choices. Preparing fresh food at home is usually healthier than eating out, but most restaurants have some healthier options. After Carlos tells Abdul what Carlos found out about Abdul's favorite meal, Abdul decides to make some changes. Abdul does not want to face a future of obesity and potentially life-threatening health conditions. He decides to pack a healthy lunch to take with him during the day and will eat more dinners at home. When he does occasionally eat fast food, he will make better choices. Skipping the soda will easily save them 300 Calories. Abdul loves fries but he realizes that if he orders small fries instead of large, he can save 280 Calories and 20% DV of total fat. If he orders a smaller cheeseburger, he can save an additional 240 Calories and 25% DV total fat. Then if he is still hungry, he can add a piece of fruit from home for additional nutrients. He will also try other options at fast-food restaurants, such as salads or grilled chicken sandwiches, which may be healthier. However, he should check the nutritional information first, since some seemingly healthy options can still be high in calories, fat, and salt due to added dressings, sauces, and cheese. Healthy eating and good nutrition don't have to be difficult if you are armed with information and make good choices with your long-term health in mind.

## CHAPTER SUMMARY

In this chapter, you learned how nutrition relates to the functioning of your body and your health. Specifically, you learned that:

- Nutrients are substances the body needs for energy, building materials, and control of body processes. There are six major classes of nutrients: carbohydrates, proteins, lipids, water, vitamins, and minerals.
- Essential nutrients cannot be synthesized by the human body, so they must be consumed in food. Nonessential nutrients can be synthesized by the human body, so they need not be obtained directly from food.
- Macronutrients are nutrients that are needed in relatively large amounts. They include carbohydrates, proteins, lipids, and water. All macronutrients except water provide energy, which is measured in Calories. Micronutrients are nutrients that are needed in relatively small amounts. They do not provide energy. They include vitamins and minerals.
    - Carbohydrates are organic compounds made of simple sugars. Besides sugars, they include starches, glycogen, and cellulose. Dietary carbohydrates come mainly from grains, fruits, and vegetables. They are used for energy, and one gram of carbohydrates provides 4 Calories of energy. Fiber consists of nondigestible carbohydrates that help control blood glucose and cholesterol (soluble fiber) or that stimulate peristalsis and prevent constipation (insoluble fiber).
    - Proteins are organic compounds made of amino acids. Dietary proteins come from sources such as meat, fish, and legumes. Amino acids from foods that are not needed for synthesizing new proteins by the body may be used for energy. One gram of proteins provides 4 Calories of energy. Of the 20 amino acids the human body needs, 9 amino acids are essential.
    - Lipids are organic compounds made of fatty acids. Fatty acids are needed by the body for energy, cell membranes, and other functions. One gram of lipids provides 9 Calories of energy. Only two fatty acids (omega-3 and omega-6) are essential in the diet. Animal fats are mainly saturated fats, whereas plant fats are mainly unsaturated fats. Artificial trans fats are added to many foods and are known to be harmful to human health.

- Water is essential to life. It is continuously lost from the body in urine, sweat, and exhaled breath, so it must be replenished often. Too little or too much water consumption can be dangerous to health.
- Vitamins are organic compounds that generally function as coenzymes. As such, they are needed for a wide range of normal body functions and necessary for good health. Most vitamins are essential. Exceptions include vitamins $B_7$ and K, which are made by intestinal bacteria; and vitamin D, which is made in the skin when it is exposed to UV light.
- Minerals are inorganic chemical elements that are necessary for many body processes and needed for good health. Minerals are not synthesized biologically, so they are essential nutrients. Macrominerals, which are needed in relatively large quantities, include calcium, magnesium, phosphorus, and sodium. Trace minerals, which are needed in much smaller quantities, include cobalt, iodine, iron, and zinc.

- Healthy eating is fundamentally important for good health. A healthy diet reduces the risk of obesity, cardiovascular disease, cancer, and many other diseases. It also extends life.
- Nutrition refers to the process of taking in nutrients in food and using them for growth, metabolism, and repair. Good nutrition depends on meeting nutrient needs while maintaining energy balance, called energy homeostasis.
- The opposite of good nutrition is malnutrition. Malnutrition includes undernutrition, in which there is inadequate energy intake; overnutrition, in which there is excessive energy intake; and unbalanced nutrition, in which there is too much or not enough of specific nutrients, such as vitamin A or calcium.
- Good nutrition requires healthy eating. This means eating a wide range of nutritious foods that provide the correct balance of nutrients. It also means taking in the correct amount of food energy to balance energy use.
- Nutrient density refers to how much of a given nutrient a particular food provides, relative to the mass of the food or the number of Calories it provides. Foods vary greatly in nutrient density — making informed food choices is important for achieving nutrient balance.
- Energy homeostasis is regulated by the hypothalamus, which controls appetite and satiation, but it also depends on dietary choices and activity levels. Energy density refers to the amount of energy a food provides per unit of mass or volume. Choosing foods with lower or higher energy density as needed to balance energy expenditure can help maintain energy homeostasis.
- Recommended daily values of nutrients can be used as a general guide to nutrient needs. At the level of individuals, requirements for many nutrients may vary based on age, gender, health status, activity level, and other factors.
- Tools such as MyPlate and nutrition facts labels are invaluable for healthy eating. MyPlate is a visual guide to the relative proportions of foods in five different food groups (vegetables, fruits, grains, protein, and dairy) that you should eat at each meal. Nutrition facts labels give the nutrient content and ingredients in packaged foods, which can help you choose the most nutritious options.
- Eating disorders are mental health disorders defined by abnormal eating habits that adversely affect health. They generally begin by young adulthood and are much more common in females than males. Eating disorders are mental disorders with the highest mortality rate.
  - Anorexia nervosa is an eating disorder in which people consistently eat very little and become extremely thin. They may also develop amenorrhea and other serious health problems. People with anorexia nervosa often fail to appreciate how thin they are and how severe their illness is.
  - Bulimia nervosa is an eating disorder in which people recurrently binge on large amounts of food, followed by purging the food from the body through vomiting, using laxatives, exercising excessively, or other methods. People with bulimia nervosa may have normal weight but often have serious health problems such as electrolyte imbalances and irregular heartbeat.
  - Binge eating disorder is an eating disorder in which people repeatedly binge on large amounts of food, followed by feelings of guilt but not by purging. This generally leads to excessive weight gain, obesity, and other serious disorders.
- Genes are likely to be involved in the development of eating disorders because eating disorders tend to "run in families." At a biochemical level, eating disorders may be caused in part by dysregulation of neurotransmitters or the hormones leptin and ghrelin, which normally help maintain the body's energy homeostasis.
- Environmental factors that increase the risk of eating disorders include being abused as a child, tight parental control over eating habits, fragile sense of self-identity, and social isolation. Cultural idealization of thinness in females may be a major cause of anorexia nervosa and bulimia nervosa in particular.
- Treatment of an eating disorder depends on the type and severity of the disorder. Treatment options include mental health counseling, medications, nutritional counseling, and hospitalization. The majority of people with eating disorders recover with treatment.
- Obesity is a disease in which excess body fat has accumulated to the extent that it is likely to have negative effects on health. Obesity is diagnosed in adults when their body mass index (BMI), which is an estimate of body fatness, is greater than 30 $kg/m^2$. Obesity is diagnosed in children when their BMI is greater than the $95^{th}$ percentile for children of that age.
  - Obesity may be further categorized by the medical profession as severe obesity, morbid obesity, and super obesity. Obese people who store most of their excess fat in the abdomen have central obesity, putting them at greater risk of adverse health consequences of obesity.

- Dozens of genes that control appetite and metabolism may predispose people to develop obesity when sufficient food energy is present. While rates of obesity have risen, diets have increased in Calories, mainly from excess carbohydrates (often in the form of sugary drinks), and activity levels have declined due to changes in work and technology.
- Leptin resistance has been proposed as a physiological mechanism underlying obesity. A decreased sensitivity to leptin results in an inability to detect satiety despite high-fat reserves. This causes people to never feel satiated and to overeat and gain weight.

- Obesity increases the risk of many other health problems and diseases, including cardiovascular disease, type 2 diabetes, certain types of cancer, osteoarthritis, and obstructive sleep apnea. The health consequences of obesity are due to the effects of either increased fat mass or increased numbers of fat cells.
- Most cases of obesity are treatable or preventable through changes in diet and physical activity that restore energy balance to the body. All types of low-carbohydrate and low-fat diets appear equally beneficial in reducing obesity and its health risks. Other treatments may include medications to control appetite or reduce nutrient absorption and bariatric surgery to modify the digestive tract in ways that limit the intake of food and absorption of nutrients from food.
- Undernutrition is defined as an insufficient intake of nutritious foods. People who are undernourished are usually underweight. Adults are considered underweight if their BMI is less than 18.5 $kg/m^2$. Children are considered underweight if their BMI is less than the $5^{th}$percentile of the reference values for children of the same age.
- Undernutrition is a more significant problem in children who need nutrients for growth and development. They may become dangerously thin (called wasting) or stop growing so they are too short for their age (stunting). Growth deficits often begin in utero due to maternal undernutrition, resulting in low birthweight and its associated risks.
- Severe undernutrition may develop into life-threatening syndromes, such as kwashiorkor or marasmus, both of which can be fatal without treatment. Kwashiorkor occurs when the diet is especially deficient in protein, causing edema and other characteristic signs of the syndrome. Marasmus occurs when the diet is especially deficient in food energy, causing extreme emaciation and other abnormalities.
- Some of the most common micronutrient deficiencies worldwide are iron, vitamin A, and iodine deficiencies. Iron deficiency causes anemia, which in childhood can lead to permanent cognitive and motor deficits. Vitamin A deficiency can weaken the immune system, contribute to anemia, and cause blindness. Iodine deficiency leads to inadequate thyroid hormone, causing goiter and hypothyroidism in adults and intellectual disability in children.
- The vast majority of undernutrition globally occurs because people do not have enough nutritious food to eat. Although there is enough food to meet the needs of the global human population, the food is unevenly distributed and for many people inaccessible because of poverty. Caused by poverty, undernutrition also contributes to poverty because of its effects on health, growth, development, and ultimately on the ability to work and earn income.
- Undernutrition is less common in the richer nations than it is elsewhere, but it still occurs because of wealth inequalities and the existence of food deserts, which are areas with limited access to nutritious foods.
- Treating and preventing undernutrition is a huge and complex problem requiring multifaceted approaches. They include direct nutritional interventions, generally provided through the health-care sector to people who are acutely malnourished, as well as public health interventions that focus on improvements in agriculture, water, sanitation, education, or the like. The most successful interventions have been those that address deficiencies of specific micronutrients such as iodine.
- Foodborne disease is any disease that is transmitted via food. As many as 76 million Americans a year get a foodborne disease, and thousands of them die from it.
- Foodborne diseases are caused by microorganisms, toxins, or adulteration of food by foreign bodies. Norovirus and several genera of bacteria cause most foodborne diseases. Toxins that cause foodborne disease may come from the environment or from microorganisms in food. Alternatively, they may be consumed in toxic plants or fungi. Foreign bodies such as cigarette butts and insects can accidentally get into food at any stage.
- Many foodborne diseases share some of the same symptoms, such as vomiting and diarrhea, but they are quite variable in other ways. The incubation period (time from infection to first symptoms) of foodborne disease can range from a few hours to many days. The infectious dose (an amount that must be consumed to cause disease) can vary greatly depending on the agent of disease.
- The vast majority of reported cases of foodborne disease occur as sporadic cases in individuals. Only a minority of cases occur as part of a disease outbreak, in which two or more people get the same foodborne disease from a common source, such as the same restaurant.
- The foodborne disease usually arises from food contamination through improper handling, preparation, or storage of food. The main ways food becomes contaminated are through poor hygiene, cross-contamination, and failure of temperature control.
- Government agencies such as the Food and Drug Administration are responsible for keeping the food supply safe. Food safety at home depends mainly on following good food safety practices. These range from regular handwashing to maintaining the correct refrigerator temperature.

## CHAPTER SUMMARY REVIEW

1. Imagine you are a nurse who is assessing the BMI of patients. For each of the patients below, identify whether they are underweight, normal weight, overweight, or obese (and the subcategories of severe obesity, morbid obesity, and super obesity). If you cannot determine BMI category based on the information given, explain why. Then discuss whether each patient may have a health/nutritional concern, or whether this cannot be determined from the information given. Finally, if they do have a health/nutritional concern, list some ways they may be able to improve their health. Patients:
   A. An adult with a BMI of 41 kg/m2
   B. An adult with a BMI of 24 kg/m2
   C. An adult with a BMI of 17 kg/m2
   D. A child with a BMI of 27 kg/m2
2. Which nutrients provide energy for the body?
   A. Vitamins
   B. Minerals
   C. Proteins
   D. All of the above
   E. None of the above
3. For each of the statements below, choose whether it applies to soluble fiber, insoluble fiber, both, or neither.
   A. Stimulates movement of food wastes through the large intestine
   B. Slows movement of chyme through the small intestine
   C. Classified as a carbohydrate
   D. Nonessential nutrient
4. Sometimes one type of nutrient can be converted to another type of nutrient in the body. Give one example of this, and describe when it occurs.
5. True or False. Trans fat is a type of unsaturated fat.
6. True or False. Bulimia nervosa always involves vomiting to purge food from the body.
7. Which is the best definition of essential nutrients?
   A. Nutrients that are needed in large quantities by the body.
   B. Nutrients that must be obtained from food.
   C. Nutrients that provide energy for the body.
8. Which typically has the highest energy density?
   A. Proteins
   B. Carbohydrates
   C. Sugars
   D. Lipids
9. If you are reading the nutrition facts label on a food item and see that “partially hydrogenated” oil is one of the ingredients, what type of fat is likely to be present? Is this fat a healthy choice? Why or why not?
10. Identify two ways in which processed foods are typically less healthy than whole foods.
11. The table below contains nutritional information listed on a bag of tortilla chips. Read the table and then answer the following questions.
    A. If you eat 16 of these tortilla chips, how many Calories have you consumed?
    B. A palm-sized (4 oz) serving of grilled, boneless, skinless chicken breast has about 190 Calories. How does this compare to the Calories in 16 tortilla chips? Which is more energy-dense? Explain your answer.
    C. What is the percentage DV of fat, sodium, and dietary fiber in 16 of these chips? If you wanted to maintain a healthy diet, following the DV recommendations, what percentage DV of fat, sodium, and fiber would you have left for the rest of the day after eating a snack of 16 of these chips?

    Table **13.8.2**: nutritional information listed on a bag of tortilla chips

| Serving size | 1 oz (28 g) | About 8 chips |
|---|---|---|
| Calories per serving | 140 | |
| Total fat per serving | 7 g | 10% Daily Value (DV) |
| Sodium per serving | 115 mg | 5% DV |
| Dietary fiber per serving | 1 g | 5% DV |

12. Can you eat too many calories but still be malnourished? Why or why not?
13. Explain why one person with a BMI of 35 kg/m2 could be considered severely obese, while another person with the same BMI could be considered morbidly obese.
14. Explain how leptin normally regulates appetite, in the absence of leptin resistance.
15. Central obesity refers to:
    A. obesity that is due to genetic causes.
    B. obesity that occurs in the middle of the U.S.
    C. a body fat distribution where most of the excess body fat is stored in the abdomen as opposed to the hips.
    D. obesity that has resulted in type 2 diabetes.
16. Name the demographic group that is more likely to be obese and have eating disorders.
17. Match each of the statements below with the eating disorder that best matches it. Eating disorder choices are anorexia nervosa, bulima nervosa, or binge eating disorder. Each disorder is used only once.
    A. People with this disorder often develop an electrolyte imbalance.
    B. People with this disorder typically eat very little.
    C. People with this disorder are at risk of developing type 2 diabetes.
18. If an undernourished child has a distended abdomen, are they more likely to have kwashiorkor or marasmus? Explain your answer and describe the nutritional deficits that likely caused this undernutrition syndrome.
19. Do you think foodborne disease can exacerbate or even cause undernutrition? Explain your answer.
20. *True or False*. Micronutrient deficiencies in children can cause long-term cognitive deficits.
21. *True or False*. The risk of getting a foodborne disease can be eliminated by adopting a vegetarian diet.

## ATTRIBUTIONS

1. Man eats burger by Nick Taylor, licensed CC BY 2.0 via Flickr

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# CHAPTER OVERVIEW

## 14: THE URINARY SYSTEM

This chapter discusses the concept of excretion and explains the excretory functions of the skin, liver, large intestine, lungs, and kidneys. It also describes the other organs of the urinary system and several urinary system disorders.


14.1: Case Study- Waste Management

14.2: Introduction to the Urinary System

14.3: Kidneys

14.4: Ureters, Urinary Bladder, and Urethra

14.5: Disorders of the Urinary System

14.6: Case Study Conclusion- Alcohol and Chapter Summary


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# 14.1: CASE STUDY- WASTE MANAGEMENT

## CASE STUDY: DRINK AND FLUSH

"Wow, this line for the restroom is long!" Bintou says to Maeva, anxiously bobbing from side to side to ease the pressure in her bladder. Maeva nods and says, "It's always like this at parties. It's the alcohol."

Bintou and Maeva are 21-year-old college students at a party. They and many other people have been drinking alcoholic beverages over the course of the evening. As the night has gotten later, the line for the restroom has gotten longer and longer. You may have noticed this phenomenon if you have been to places where large numbers of people are drinking alcohol, like at the ballpark below.




Figure **14.1.1**: A line stretching out of a restroom door at a ballpark.

Bintou says, "I wonder why alcohol makes you have to pee?" Maeva learned about this in her Human Biology class and tells Bintou that alcohol inhibits a hormone that helps you retain water. So instead of your body retaining water, you urinate more out. This could lead to dehydration, so she suggests that after their trip to the restroom, they start drinking water instead of alcohol.

For people who drink occasionally or moderately, this effect of alcohol on the excretory system—the system that removes wastes such as urine—is usually temporary. However, in people who drink excessively, alcohol can have serious, long-term effects on the excretory system. For example, heavy drinking on a regular basis can cause liver and kidney disease.

As you will learn in this chapter, the liver and kidneys are important organs of the excretory system, and impairment of the functioning of these organs can cause serious health consequences. At the end of the chapter, you will learn which hormone Maeva was referring to, and some of the ways alcohol can affect the excretory system, both after the occasional drink and in cases of excessive alcohol use and abuse.

## CHAPTER OVERVIEW: EXCRETORY SYSTEM

In this chapter, you will learn about the excretory system, which rids the body of toxic waste products and helps maintain homeostasis. Specifically, you will learn about:

- The organs of the excretory system, which include the skin, liver, large intestine, lungs, and kidneys, eliminate waste and excess water from the body.
- How wastes are eliminated through sweat, feces, urine, and exhaled gases; and how toxic substances in the blood are broken down by the liver.
- The urinary system, which includes the kidneys, ureters, bladder, and urethra.
- The main function of the urinary system, which is to filter the blood and eliminate wastes, mineral ions, and excess water from the body in the form of urine.
- How the kidneys filter the blood, retain needed substances, produce urine, and help maintain homeostasis, such as proper ion and water balance.
- How urine is stored, transported, and released from the body.
- Disorders of the urinary system, including bladder infections, kidney stones, polycystic kidney disease, urinary incontinence, and kidney damage due to factors such as uncontrolled diabetes and high blood pressure.

As you read the chapter, think about the following questions:

1. Which hormone do you think Maeva was referring to? Remember that this hormone causes the urinary system to retain water and excrete less water out in the urine.
2. How and where does this hormone work?
3. Long-term, excessive use of alcohol can affect the liver and kidneys. How do these two organs of excretion interact and work together?

## ATTRIBUTIONS


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2. Line at ballpark by Dorothy, CC BY 2.0 via Flickr.com
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# 14.2: INTRODUCTION TO THE URINARY SYSTEM

## SCULPTURE GARDEN

In Figure **14.2.1**, this interesting outdoor art installation can be viewed at the Hague in the Netherlands. It's a colorful piece with an unusual subject. The wrinkled structures on each side of the sculpture represent the kidneys, and the striped structure in the distance represents the urinary bladder. The red and blue tubes are blood vessels, and the tan tubes are ureters. In short, the installation is a three-dimensional depiction of the human urinary system. Only one urinary system organ is not visible in the photo. Do you know what it is?



Figure **14.2.1**: Nier met blaas (Kidney with bladder)

The actual human **urinary system**, also known as the renal system, is shown in Figure **14.2.2**. The system consists of the kidneys, ureters, bladder, and urethra, which is the only structure not visible in the sculpture above. The main function of the urinary system is to eliminate the waste products of metabolism from the body by forming and excreting **urine.** Between 1 and 2 liters of urine are normally produced every day in a healthy individual.

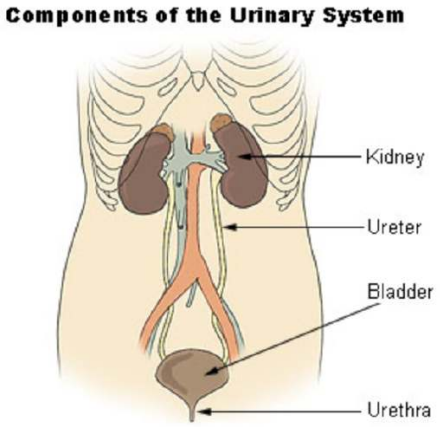



Figure **14.2.2**: The components of the urinary system include the two kidneys which lead to two tubes called ureters which lead to a holding structure called the bladder which leads to a tube called the urethra.

## ORGANS OF THE URINARY SYSTEM

The urinary system is all about urine. It includes organs that form urine and also those that transport, store, or excrete urine.

### KIDNEYS

Urine is formed by the kidneys, which filter many substances out of blood, allow the blood to reabsorb needed materials, and use the remaining materials to form urine. The human body normally has two paired kidneys, although it is possible to get by quite well with just one kidney. The anatomy and function of the kidney are discussed in detail in the next section.

### URETERS, BLADDER, URETHRA

After urine forms in the kidneys, it is transported through the ureters (one per kidney) to the sac-like bladder, which stores the urine until urination. During urination, the urine is released from the bladder and transported by the urethra to be excreted outside the body through the external urethral opening.

## FUNCTIONS OF THE URINARY SYSTEM

Waste products removed from the body with the formation and elimination of urine include many water-soluble metabolic products. The main waste products are urea, a by-product of protein catabolism, and uric acid, a by-product of nucleic acid catabolism. Excess water and mineral ions are also eliminated in urine.

Besides the elimination of waste products such as these, the urinary system has several other vital functions. These include:

- maintaining homeostasis of mineral ions in extracellular fluid. These ions are either excreted in urine or returned to the blood as needed to maintain the proper balance.
- regulating the acid-base balance in the body. For example, when pH is too low (blood is too acidic), the kidneys excrete less bicarbonate (which is basic) in the urine. When pH is too high (blood is too basic), the opposite occurs and more bicarbonate is excreted in the urine.
- controlling the volume of extracellular fluids, including the blood, which helps maintain blood pressure. The kidneys control fluid volume and blood pressure by excreting more or less salt and water in urine.

## CONTROL OF THE URINARY SYSTEM

The formation of urine must be closely regulated to maintain body-wide homeostasis. Several endocrine hormones help control this function of the urinary system, including antidiuretic hormone, parathyroid hormone, and aldosterone.

- Antidiuretic hormone, also called vasopressin, is secreted by the hypothalamus. One of its main roles is conserving body water. It is released when the body is dehydrated and causes the kidneys to excrete less water in urine.
- Parathyroid hormone is secreted by the parathyroid glands. It works to regulate the balance of mineral ions in the body through its effects on several organs, including the kidneys. Parathyroid hormone stimulates the kidneys to excrete less calcium and more phosphorus in the urine.

- Aldosterone is secreted by the cortex of the adrenal glands, which rest atop the kidneys, as shown in Figure **14.2.3**. It plays a central role in regulating blood pressure through its effects on the kidneys. It causes the kidneys to excrete less sodium and water in urine.

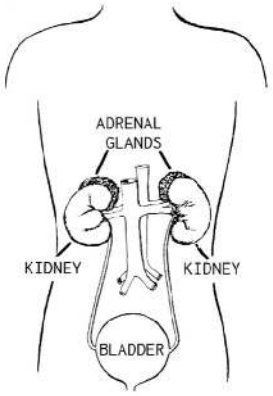



Figure **14.2.3**: The adrenal glands are located on top of the kidneys. They secrete aldosterone into the bloodstream, which carries it to the kidneys.

Once urine forms, it is excreted from the body in the process of urination. This process is controlled by both the autonomic and the somatic nervous systems. As the bladder fills with urine, it causes the autonomic nervous system to signal a muscle in the bladder wall to contract and the sphincter between the bladder and urethra to relax and open. This forces urine out of the bladder and through the urethra. Another sphincter at the distal end of the urethra is under voluntary control. When it relaxes under the influence of the somatic nervous system, it allows urine to leave the body through the external urethral opening.

## REVIEW

1. What organs make up the urinary system?
2. State the main function of the urinary system.
3. What is the primary function of the kidneys?
4. Describe how blood enters and leaves the kidneys.
5. What are nephrons?
6. What happens to urine after it forms in the kidneys?
7. Identify the functions of the urinary system besides the elimination of waste products.
8. How is the formation of urine regulated?
9. Explain how the process of urination is controlled.
10. What function do the adrenal glands carry out that is related to urine?

    A. They form urine and transport it to the kidneys

    B. They excrete concentrated urine into the ureters

    C. They secrete a hormone that affects the composition of urine

    D. They store urine when water and salts need to be retained by the body
11. Explain why it is important to have voluntary control over the sphincter at the end of the urethra.
12. Compare the aldosterone to antidiuretic hormones in terms of how they affect the kidneys.
13. If your body needed to retain more calcium, which of the hormones described in this concept is the most likely to rise in the level? Explain your reasoning.
14. *True or False.* Urine is composed of water, urea, and minerals only.
15. *True or False.* The renal artery contains blood that was filtered by the kidney.

## EXPLORE MORE

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## ATTRIBUTIONS

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# 14.3: KIDNEYS

## KIDNEYS ON THE MENU

Pictured here amidst a bed of mixed veggies are a steak and kidney pudding. More often made into a pie, this savory dish is a British favorite. Kidneys on the menu typically come from sheep, pigs, or cows. In these animals as in the human animal, kidneys are the main organs of excretion.



Figure **14.3.1**: Steak and kidney pudding

## LOCATION OF THE KIDNEYS

The two bean-shaped **kidneys** are located high in the back of the abdominal cavity, one on each side of the spine. Both kidneys sit just below the diaphragm, the large breathing muscle that separates the abdominal and thoracic cavities. As you can see in Figure **14.3.2**, the right kidney is slightly smaller and lower than the left kidney. The right kidney is behind the liver, and the left kidney is behind the spleen. The location of the liver explains why the right kidney is smaller and lower than the left.

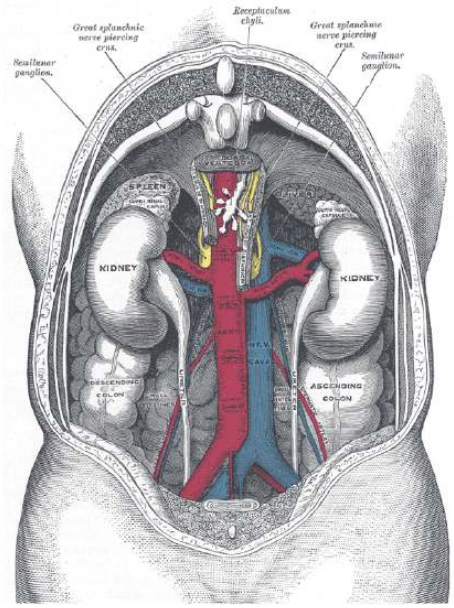



Figure **14.3.2**: This classic illustration of the abdominal cavity provides a view of the internal organs from the back of the body. It clearly shows the locations of the right and left kidney, as well as the large blood vessels that connect the kidneys to the body's main artery (aorta) and vein (inferior vena cava). The ureter exiting each kidney is also shown in the diagram.

## KIDNEY ANATOMY

The shape of each kidney gives it a convex side and a concave side. You can see this clearly in the detailed diagram of kidney anatomy shown in Figure **14.3.3**. The concave side is where the renal artery enters the kidney and the renal vein and ureter leave the kidney. This area of the kidney is called the hilum. The entire kidney is surrounded by tough fibrous tissue, called the renal capsule, which in turn is surrounded by two layers of protective, cushioning fat.

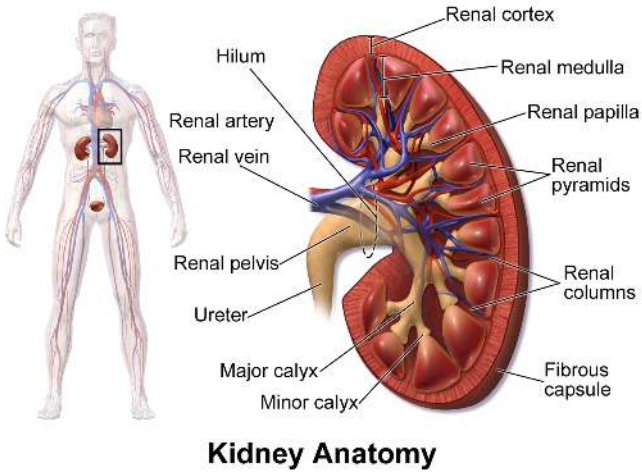



Figure **14.3.3**: This diagram shows the location and relative size of the two kidneys as well as the internal structure of each kidney.

Internally, each kidney is divided into two major layers: the outer renal cortex and the inner renal medulla (see Figure **14.3.3**). These layers take the shape of many cone-shaped renal lobules, each containing a renal cortex surrounding a portion of the medulla called a renal pyramid. Within the renal pyramids are the structural and functional units of the kidneys, the tiny nephrons. Between the renal pyramids are projections of cortex called renal columns. The tip or papilla of each pyramid empties urine into a minor calyx (chamber). Several minor calyces empty into a major calyx, and the latter empties into the funnel-shaped cavity called the renal pelvis, which becomes the ureter as it leaves the kidney.

## RENAL CIRCULATION

The renal circulation is an important part of the kidney's main function of filtering waste products from the blood. Blood is supplied to the kidneys via the renal arteries. The right renal artery supplies the right kidney, and the left renal artery supplies the left kidney. These two arteries branch directly from the aorta, which is the largest artery in the body. Each kidney is only about 11 cm (4.4 in.) long and has a mass of just 150 grams (5.3 oz), yet it receives about 10 percent of the total output of blood from the heart. Blood is filtered through the kidneys about 20 times each hour, 24 hours a day, day after day.

As indicated in Figure **14.3.4**, each renal artery carries blood with waste products into the kidney. Within the kidney, the renal artery branches into increasingly smaller arteries that extend through the

renal columns between the renal pyramids. These arteries, in turn, branch into arterioles that penetrate the renal pyramids. Blood in the arterioles passes through nephrons, the structures that actually filter the blood. After blood passes through the nephrons and is filtered, the clean blood moves through a network of venules that converge into small veins. Small veins merge into increasingly larger ones and ultimately into the renal vein, which carries clean blood away from the kidney to the inferior *vena cava*.

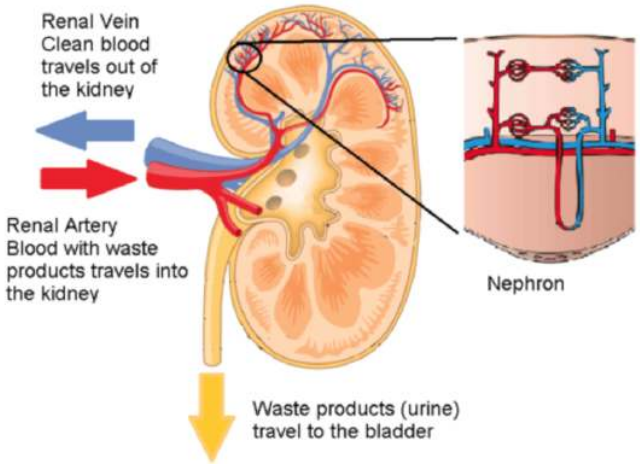



Figure **14.3.4**: The renal artery and renal vein carry blood to and from the kidney, respectively. As blood passes through the capillaries surrounding nephrons within the kidney, it is filtered and substances filtered from the blood are eventually excreted via ureter to the bladder.

## NEPHRON STRUCTURE AND FUNCTION

The illustration above gives an indication of the complex structure of a nephron. The **nephron** is the basic structural and functional unit of the kidney, and each kidney typically contains at least a million of them. As blood flows through a nephron, many materials are filtered out of the blood, needed materials are returned to the blood, and the remaining materials form urine. Most of the waste products removed from the blood and excreted in the urine are byproducts of metabolism. At last half of the waste is urea, a waste product produced by protein catabolism. Another important waste is uric acid, produced in nucleic acid catabolism.

### COMPONENTS OF A NEPHRON

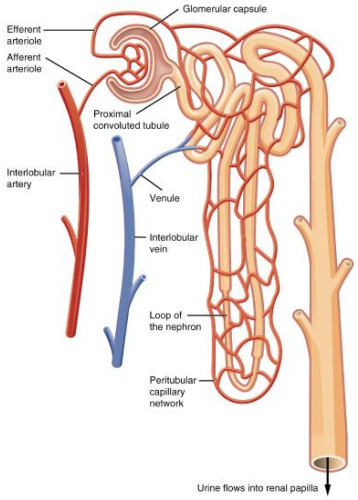



Figure **14.3.5**: This model of an individual nephron shows each of the structures that are involved in filtering blood, returning needed materials to blood, or excreting wastes that form urine. The arrows indicate the direction in which fluids flow through the nephron.

The diagram in Figure **14.3.5** shows in greater detail the components of a nephron. The renal corpuscle is a filtering structure that is consists of a network of capillaries called the glomerulus (plural, glomeruli) and the Bowman's capsule, a space surrounding the glomerulus. Bowman's capsule is the initial structure of a nephron. Extending from Bowman’s capsule is the renal tubule. The proximal end (nearest Bowman’s capsule) of the renal tubule is called the proximal convoluted (coiled) tubule. From here, the renal tubule continues as a loop (known as the loop of Henle), which in turn becomes the distal convoluted tubule. The latter finally joins with a collecting duct. As you can see in the diagram, peritubular capillaries surround the total length of the renal tubule.

### THE FUNCTION OF A NEPHRON

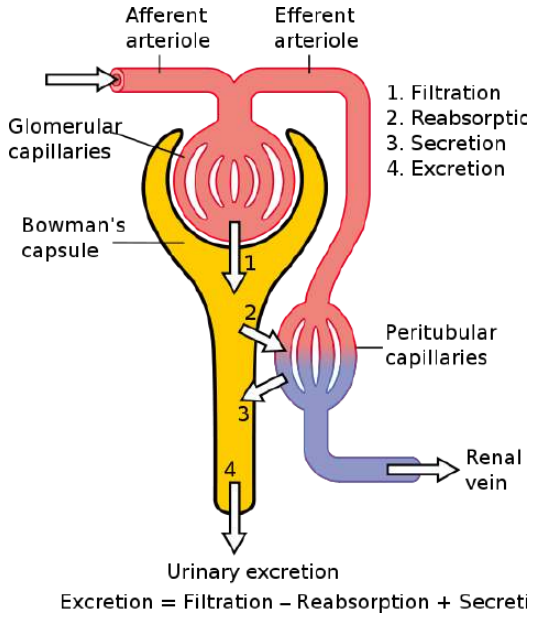



Figure **14.3.6**: This diagram of a nephron shows the parts of the nephron where different stages of nephron function take place. Filtration (1) occurs in the Renal corpuscle, Reabsorption (2) occurs in the proximal tubule, Secretion (3) occurs in the distal tubule, and Excretion (4) occurs in the collecting duct.

The simplified diagram of a nephron in Figure **14.3.6** shows how the nephron functions. Blood enters the nephron through an arteriole called the afferent arteriole. Some of the blood next passes through the capillaries of the glomerulus. Any blood that doesn't pass through the glomerulus, as well as blood after it passes through the glomerular capillaries, continues on through an arteriole called the efferent arteriole. The efferent arteriole follows the renal tubule of the nephron, where it continues to play roles in nephron functioning.

### *FILTRATION*

As blood from the afferent arteriole flows through the glomerular capillaries, it is under pressure. Because of the pressure, water and solutes are filtered out of the blood and into the space made by Bowman's capsule. This is the filtration stage of nephron function. The filtered substances, called filtrate, pass into Bowman's capsule and from there into the proximal end of the renal tubule. At this stage, filtrate includes water, salts, organic solids such as nutrients, and waste products of metabolism such as urea.

### *REABSORPTION AND SECRETION*

As filtrate moves through the renal tubule, some of the substances it contains are reabsorbed from the filtrate back into the blood in the efferent arteriole (via peritubular capillaries). This is the reabsorption stage of nephron function. About two-thirds of the filtered salts and water and all of the filtered organic solutes (mainly glucose and amino acids) are reabsorbed from the filtrate by the blood in the peritubular capillaries. Reabsorption occurs mainly in the proximal convoluted tubule and the loop of Henle.

At the distal end of the renal tubule, some additional reabsorption generally occurs. This is also the region of the tubule where other substances from the blood are added to the filtrate in the tubule. The addition of other substances to the filtrate from the blood is called secretion. Both reabsorption and secretion in the distal convoluted tubule are largely under the control of endocrine hormones that maintain homeostasis of water and mineral salts in the blood. These hormones work by controlling what is reabsorbed into the blood from the filtrate and what is secreted from the blood into the filtrate to become urine. For example, the parathyroid hormone causes more calcium to be reabsorbed into the blood and more phosphorus to be secreted into the filtrate.

### COLLECTION OF URINE AND EXCRETION

By the time the filtrate has passed through the entire renal tubule, it has become the liquid waste known as urine. Urine empties from the distal end of the renal tubule into a **collecting duct**. From there, the urine flows into increasingly larger collecting ducts. As urine flows through the system of collecting ducts, more water may be reabsorbed from it. This will occur in the presence of antidiuretic hormone from the hypothalamus. This hormone makes the collecting ducts permeable to water, allowing water molecules to pass through them into capillaries by osmosis while preventing the passage of ions or other solutes. As much as three-fourths of the water may be reabsorbed from urine in the collecting ducts, making the urine more concentrated.

Urine finally exits the largest collecting ducts through the renal papillae. It empties into the renal calyces and finally into the renal pelvis (see Figure **14.3.3**. From there, it travels through the ureter to the urinary bladder for eventual excretion from the body. An average of about 1.5 liters of urine is excreted each day. Normally, urine is yellow or amber in color (Figure **14.3.7**). The darker the color, generally the more concentrated the urine is.



Figure **14.3.7**: Fresh urine is typically yellow or amber in color.

## OTHER FUNCTIONS OF THE KIDNEYS

Besides filtering blood and forming urine for the excretion of soluble wastes, the kidneys have several vital functions in maintaining body-wide homeostasis. Most of these functions are related to the composition or volume of urine formed by the kidneys. These functions include maintaining the proper balance of water and salts in the body, normal blood pressure, and the correct range of blood pH. Through the processes of absorption and secretion by nephrons, more or less water, salt ions, acids, or bases are returned to the blood or excreted in urine as needed to maintain homeostasis.

### KIDNEY HORMONES

- **Aldosterone** is secreted by the adrenal cortex. Aldosterone causes the kidneys to increase the reabsorption of sodium ions and water from the filtrate into the blood. This returns the

concentration of sodium ions in the blood to normal. The increased water in the blood also increases blood volume and blood pressure.

- **Calcitriol** is secreted by the kidneys in response to low levels of calcium in the blood. This hormone stimulates the uptake of calcium by the intestine, thus raising blood levels of calcium.
- **Erythropoietin** is secreted by the kidneys in response to low levels of oxygen in the blood. This hormone stimulates **erythropoiesis**, which is the production of red blood cells in the bone marrow. Extra red blood cells increase the level of oxygen carried in the blood.

### FEATURE: HUMAN BIOLOGY IN THE NEWS

Kidney failure is a complication of common disorders including diabetes mellitus and hypertension. Almost half a million Americans have end-stage kidney disease and need to either receive a donated kidney or have frequent hemodialysis, a medical procedure in which the blood is artificially filtered through a machine. Transplant generally has better outcomes than hemodialysis but demand for organs far outstrips the supply. At any given time, more than 100,000 people in the U.S. are on a waiting list for a kidney transplant, but each year fewer than 20,000 receive them. Every day, 13 Americans die while waiting for a donor's kidney.

For the past decade, Dr. William Fissell, a kidney specialist at Vanderbilt University, has been working to create an implantable part-biological and part-artificial kidney. Using microchips like those used in computers, he has produced an artificial kidney small enough to implant in the patient's body in place of the failed kidney. According to Dr. Fissell, the artificial kidney is "... a bio-hybrid device that can mimic a kidney to remove enough waste products, salt, and water to keep a patient off [hemo]dialysis."

The filtration system in the artificial kidney consists of a stack of 15 microchips. Tiny pores in the microchips act as a scaffold for the growth of living kidney cells that can mimic the natural functions of the kidney. The living cells form a membrane to filter the patient's blood as a biological kidney would, but with less risk of rejection by the patient's immune system because they are embedded within the device. The new kidney doesn't need a power source because it uses the natural pressure of blood flowing through arteries to push the blood through the filtration system. A major part of the design of the artificial organ was devoted to fine-tuning the fluid dynamics so blood flows through the device without clotting.

The implantable kidney was given fast-track approval for testing in people by the U.S. Food and Drug Administration because of the potentially life-saving benefits of the device. The artificial kidney is expected to be tested in pilot trials by 2018. Dr. Fissell says he has a long list of patients eager to volunteer for the trials.

## REVIEW

1. Where are the kidneys located?
2. Contrast the renal artery and renal vein.
3. Describe the structure of the kidney.
4. Identify the functions of a nephron.
5. Describe in detail what happens to fluids (blood, filtrate, and urine) as they pass through the parts of a nephron.
6. Use the example of the renin-angiotensin-aldosterone system to illustrate how the kidneys control homeostasis with the help of endocrine hormones.
7. Identify two endocrine hormones secreted by the kidneys and the functions they control.
8. Put the following structures in order of how urine flows out of the kidney, from the earliest to the latest:

   collecting ducts; renal tubule; renal pelvis; renal calyces
9. Name two regions in the kidney where water is reabsorbed.
10. *True or False.* Once the filtrate enters the renal tubule, no substances are added to it.
11. *True or False.* Some substances are reabsorbed in the distal end of the renal tubule.
12. Is the blood in the glomerular capillaries more or less filtered than the blood in the peritubular capillaries? Explain your answer.
13. How many nephrons are there per kidney?

    A. One

    B. Thirteen

    C. At least one thousand

    D. At least one million
14. If blood flow to the kidneys is blocked, what do you think would happen?
15. The loop of Henle is part of the:

    A. glomerulus

    B. renal tubule

    C. collecting duct

    D. ureter

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# 14.4: URETERS, URINARY BLADDER, AND URETHRA

## COMMUNICATING WITH URINE

Why do dogs urinate on fire hydrants? Besides "having to go," they are marking their territory with chemicals called pheromones in their urine. It's a form of communication, in which they are "saying" with odors that the yard is theirs and other dogs should stay away. Dogs may urinate on fence posts, trees, car tires, and many other objects in addition to fire hydrants. Urination in dogs, as in people, is usually a voluntary process controlled by the brain. The process of forming urine, which occurs in the kidneys, occurs constantly and is not under voluntary control. What happens to all the urine that forms in the kidneys? It passes from the kidneys through the other organs of the urinary system, starting with the ureters.



Figure **14.4.1**: Dog urinating on hydrant

## URETERS

As shown in Figure **14.4.2**, ureters are tube-like structures that connect the kidneys with the urinary bladder. They are paired structures, with one ureter for each kidney. In adults, ureters are between 25 and 30 cm (10 to 12 in.) long and about 3 to 4 mm (about 1/8 in.) in diameter.

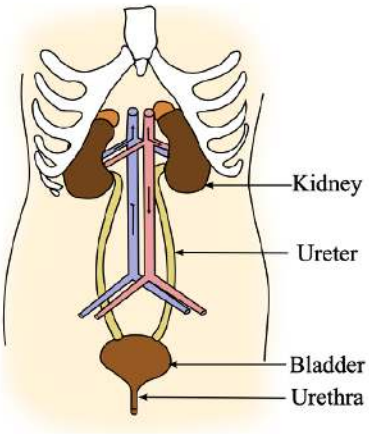



Figure **14.4.2**: Besides the kidneys, the urinary system includes two ureters, the urinary bladder, and the urethra.

Each ureter arises in the pelvis of a kidney (Figure **14.4.3**). It then passes down the side of the kidney and finally enters the back of the bladder.

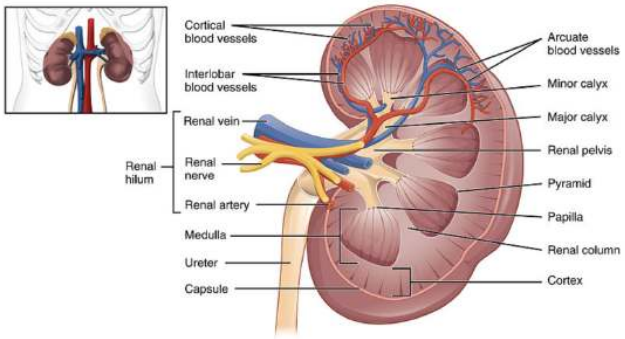



Figure **14.4.3**: Urine collects in the renal pelvis which is continuous with the ureter. The ureter then carries the urine from the kidney to the urinary bladder.

The walls of the ureters are composed of multiple layers of different types of tissues. You can see the layers in Figure **14.4.4**. The innermost layer is a special type of epithelium, called the transitional epithelium. Unlike the epithelium lining most organs, the transitional epithelium is capable of flattening and distending and does not produce mucus. It lines much of the urinary system, including the renal pelvis, bladder, and much of the urethra in addition to the ureters. Transitional epithelium allows these organs to stretch and expand as they fill with urine or allow urine to pass through. The next layer of the ureter walls is made up of loose connective tissue containing elastic fibers, nerves, and blood and lymphatic vessels. After this layer are two layers of smooth muscles, an inner circular layer, and an outer longitudinal layer. The smooth muscle layers can contract in waves of peristalsis to propel urine down the ureters from the kidneys to the urinary bladder. The outermost layer of the ureter walls consists of fibrous tissue.

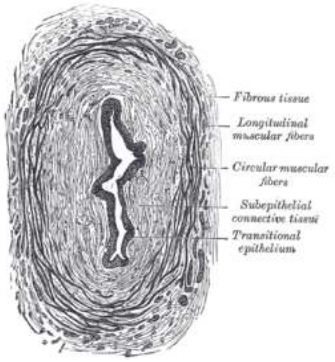



Figure **14.4.4**: This illustration shows a cross-section of a ureter. The white space inside is the lumen through which urine passes. From the lumen outward, the layers of the ureter wall include transitional epithelium, connective tissue, two layers of muscle fibers, and an outer layer of fibrous tissue.

## URINARY BLADDER

The **urinary bladder** is a hollow, muscular, and stretchy organ that rests on the pelvic floor. It collects and stores urine from the kidneys before the urine is eliminated through urination. As shown in Figure **14.4.5**, urine enters the urinary bladder from the ureters through two ureteral openings on either side of the back wall of the bladder.

Urine leaves the bladder through a sphincter called the internal urethral sphincter. When the sphincter relaxes and opens, it allows urine to flow out of the bladder and into the urethra.

Like the ureters, the bladder is lined with transitional epithelium, which can flatten out and stretch as needed as the bladder fills with urine. The next layer (lamina propria) is a layer of loose connective tissue, nerves, and blood and lymphatic vessels. This is followed by a submucosa layer, which connects the lining of the bladder with the detrusor muscle in the walls of the bladder. The outer covering of the bladder is the peritoneum, which is a smooth layer of epithelial cells that lines the abdominal cavity and covers most abdominal organs.

The detrusor muscle in the wall of the bladder is made of smooth muscle fibers that are controlled by both the autonomic and somatic nervous systems. As the bladder fills, the detrusor muscle automatically relaxes to allow it to hold more urine. When the bladder is about half full, the stretching of the walls triggers the sensation of needing to urinate. When the individual is ready to void, conscious nervous signals cause the detrusor muscle to contract and the internal urethral sphincter to relax and open. As a result, urine is forcefully expelled out of the bladder and into the urethra.

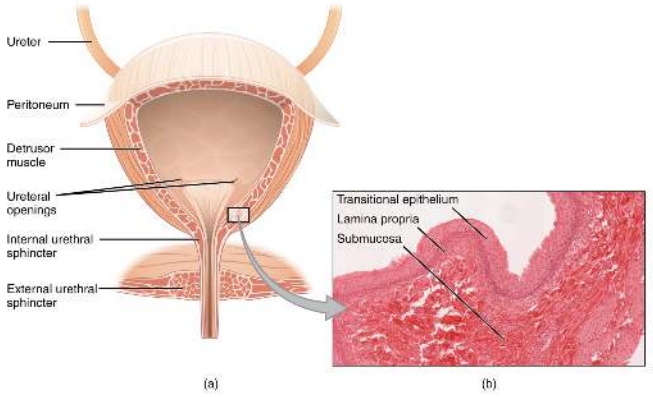



Figure **14.4.5**: This diagram of the urinary bladder shows (a) a cross-sectional drawing of the entire bladder and (b) a microscopic cross-section of the tissues in the wall of the bladder.

## URETHRA

The **urethra** is a tube that connects the urinary bladder to the external urethral orifice, which is the opening of the urethra on the surface of the body. As shown in Figure **14.4.6**, the urethra in a person with XY chromosomes (anatomically male) travels through the penis, so it is much longer than the urethra in a person with XX chromosomes (anatomically female). In a genetically male person, the urethra averages about 20 cm (8 in.) long, whereas, in a genetically female individual, it averages only about 4.8 cm (1.9 in.) long. In an XY individual, the urethra carries semen as well as urine, but in the XX individual, it carries only urine.

Like the ureters and bladder, the proximal (closer to the bladder) two-thirds of the urethra are lined with transitional epithelium. The distal (farther from the bladder) third of the urethra is lined with mucus-secreting epithelium. The mucus helps protect the epithelium from urine, which is corrosive. Below the epithelium is loose connective tissue, and below that are layers of smooth muscle that are continuous with the muscle layers of the urinary bladder. When the bladder contracts to forcefully expel urine, the smooth muscle of the urethra relaxes to allow the urine to pass through.

In order for urine to leave the body through the external urethral orifice, the external urethral sphincter must relax and open. This sphincter is a striated muscle that is controlled by the somatic nervous system, so it is under conscious, voluntary control in most people (exceptions are infants, some elderly people, and patients with certain injuries or disorders). The muscle can be held in a contracted state and hold in the urine until the person is ready to urinate. Following urination, the smooth muscle lining the urethra automatically contracts to re-establish muscle tone, and the individual consciously contracts the external urethral sphincter to close the external urethral opening.

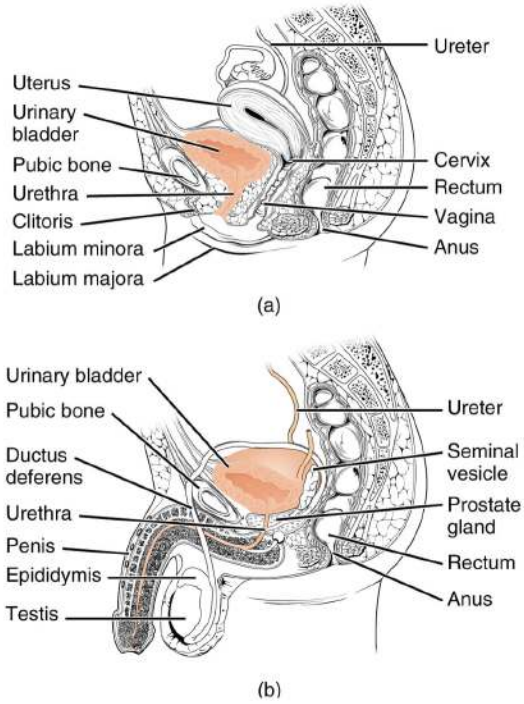



Figure **14.4.6**: The urinary bladder and urethra are colored brown to illustrate them in (a) female anatomy and (b) male anatomy. Notice how much longer the male urethra is because it travels through the length of the penis to reach the external urethral orifice.

## REVIEW

1. What are ureters?
2. Describe the location of the ureters relative to other urinary tract organs.
3. Identify layers in the walls of a ureter and how they contribute to the ureter's function.
4. Describe the urinary bladder.
5. What is the function of the urinary bladder?
6. How does the nervous system control the urinary bladder?
7. What is the urethra?
8. How does the nervous system control urination?

9. Identify the sphincters that are located along the pathway from the ureters to the external urethral orifice.
10. What are two differences between the male and female urethra?
11. *True or False.* Urine travels through the urinary system due solely to the force of gravity.
12. *True or False.* Urination refers to the process that occurs from the formation of urine in the kidneys to the elimination of urine from the body.
13. When the bladder muscle contracts, the smooth muscle in the walls of the urethra _____ .
14. Transitional epithelium lines the:

    A. bladder

    B. ureters

    C. renal pelvis

    D. All of the above

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# 14.5: DISORDERS OF THE URINARY SYSTEM

## AWARENESS RIBBON

Awareness ribbons are symbols meant to show support or raise consciousness for a cause. Different colors are associated with different issues, often relating to health problems. The first ribbon to gain familiarity for a health issue was the red ribbon for HIV/AIDS, created in 1991. The pink ribbon for breast cancer awareness is probably the best known today. Do you know what a green ribbon like the one pictured in Figure **14.5.1** represents? Among several other health problems, a green ribbon is meant to show support or raise awareness for kidney disorders.



Figure **14.5.1**: Kidney disorder awareness ribbon

The kidneys play such vital roles in eliminating wastes and toxins and maintaining body-wide homeostasis that disorders of the kidneys may be life-threatening. The gradual loss of normal kidney function commonly occurs with a number of disorders, including diabetes mellitus and high blood pressure. Other disorders of the kidneys are caused by faulty genes that are inherited. Loss of kidney function may eventually progress to kidney failure.

### DIABETIC NEPHROPATHY

**Diabetic nephropathy** is a progressive kidney disease caused by damage to the capillaries in the glomeruli of the kidneys due to long-standing diabetes mellitus (see Figure **14.5.2**). It is not fully understood how diabetes leads to damage of glomerular capillaries, but it is thought that high levels of glucose in the blood are involved. In people with diabetes, nephropathy is more likely if their blood glucose is poorly controlled. Having high blood pressure, a history of cigarette smoking and a family history of kidney problems are additional risk factors. Diabetic nephropathy often has no symptoms at first. In fact, it may take up to a decade after kidney damage begins for symptoms to appear. When they do appear, they typically include severe tiredness, headaches, nausea, frequent urination, and itchy skin.

Proteins are large molecules that usually are not filtered out of blood in the glomeruli. When the glomerular capillaries are damaged, it allows proteins such as albumin to leak into the filtrate from the blood. As a result, albumin ends up being excreted in the urine. Finding a high level of albumin in the urine is one indicator of diabetic nephropathy and helps to diagnose the disorder. Drugs may be prescribed to reduce protein levels in the urine. Controlling high blood sugar levels and hypertension (high blood pressure) is also important to help slow kidney damage, as is a reduction of sodium intake.

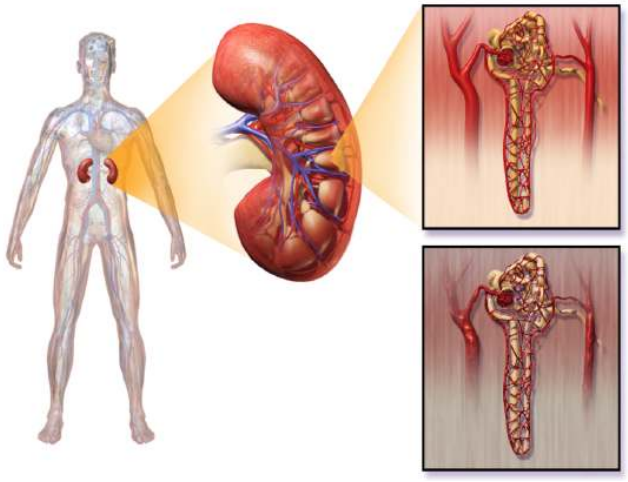


Figure **14.5.2**: Diabetic nephropathy is characterized by damage to the capillaries in the glomeruli of the kidneys, represented by the lower of the two inset diagrams.

### POLYCYSTIC KIDNEY DISEASE

**Polycystic kidney disease (PKD)** is a genetic disorder in which multiple abnormal cysts develop and grow in the kidneys. Figure **14.5.3** shows a pair of kidneys that are riddled with cysts from PKD. In people who inherit PKD, the cysts may start to form at any point in life from infancy through adulthood. Typically, both kidneys are affected. Symptoms of the disorder may include high blood pressure, headaches, abdominal pain, blood in the urine, and excessive urination.



Figure **14.5.3**: In polycystic kidney disease, the kidneys are injured by the formation of multiple cysts, which may grow to be quite large.

There are two types of PKD. The more common type is caused by an autosomal dominant allele, and the less common type is caused by an autosomal recessive allele. Both types collectively make PKD one of the most common hereditary diseases in the United States, affecting more than half a million people. There is little or no difference in the rate of occurrence of PKD between genders or ethnic groups. There is no known cure for this disease other than a kidney transplant.

## KIDNEY FAILURE

Both diabetic nephropathy and PKD may lead to **kidney** (or renal) **failure** (classified as end-stage kidney disease), in which the kidneys are no longer able to adequately filter metabolic wastes from the blood. Long-term, uncontrolled high blood pressure is another common cause of kidney failure. Symptoms of kidney failure may include nausea, more or less frequent urination, blood in the urine, muscle cramps, anemia, swelling of the extremities, and shortness of breath due to the accumulation of fluid in the lungs. If kidney function drops below the level needed to sustain life, then the only treatment option is kidney transplantation or some means of artificial filtration of the blood, such as by hemodialysis.

**Hemodialysis** is a medical procedure in which blood is filtered externally through a machine. You can see how it works in the simplified diagram in Figure **14.5.4**. During dialysis, waste products such as urea as well as excess water are removed from the patient's blood before the blood is returned to the patient. Hemodialysis is typically done on an outpatient basis in a hospital or special dialysis clinic. Less frequently, it is done in the patient's home. Depending on the patient's size, among other factors, the blood is filtered for 3 to 4 hours about 3 times a week. Because the treatment is needed so frequently, hemodialysis is one of the most common procedures performed in U.S. hospitals.

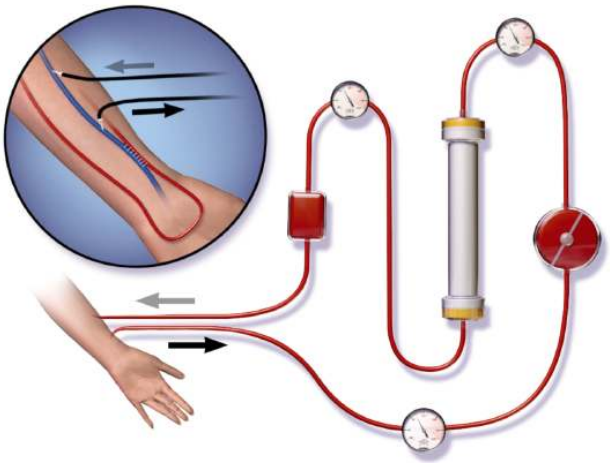


Figure **14.5.4**: This simple diagram shows the general process by which blood is filtered externally in the process of hemodialysis. Blood is taken from a patient, run through a filtration machine, and then returned.

## KIDNEY STONES

A **kidney stone**, also known as a renal calculus, is a solid crystal that forms in a kidney from minerals in urine (see Figure **14.5.5**). The majority of kidney stones consist of crystals of calcium salts. Kidney stones typically leave the body in the urine stream. A small stone may pass through the ureters and other urinary tract organs without causing symptoms and go undetected. A larger stone may cause pain when it passes through the urinary tract. If a kidney stone grows large enough, it may block the ureter. Blockage of a ureter may cause a decrease in kidney function and damage to the kidney.

A kidney stone that causes pain is generally treated with pain medication until it passes through the urinary tract. A stone that causes a blockage may be treated with lithotripsy. This is a medical procedure in which high-intensity ultrasound pulses are applied externally to cause fragmentation of the stone into pieces small enough to pass easily through the urinary tract. Although lithotripsy is noninvasive, it can cause damage to the kidneys. An alternative treatment for a stone that blocks urine flow is to insert a stent into the ureter to expand it and allow both urine and the stone to pass. In some cases, surgery may be required to physically remove a large stone from the ureter.

A combination of lifestyle and genetic factors seem to predispose certain people to develop kidney stones. Risk factors include high consumption of cola soft drinks, eating a diet high in animal protein, being overweight, and not drinking enough fluids. Preventive measures are obvious. They include limiting cola consumption, eating less animal protein, losing weight, and increasing fluid intake.

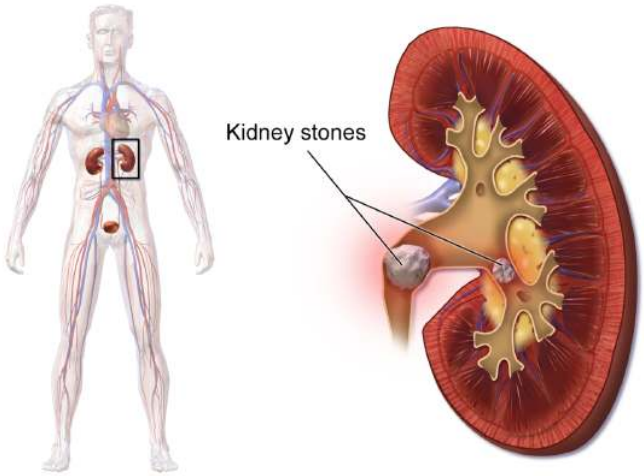



Figure **14.5.5**: Kidney stones form in the kidney and may grow large enough to block the major calyx or ureter.

## OTHER URINARY SYSTEM DISORDERS

Although disorders of the kidneys are generally the most serious urinary system disorders, problems that affect other organs of the urinary tract are generally more common. They include bladder infections and urinary incontinence.

## BLADDER INFECTION

A **bladder infection**, also called cystitis, is a very common type of urinary tract infection in which the urinary bladder becomes infected by bacteria (typically *Escherichia coli*), rarely by fungi. Symptoms of bladder infections may include pain with urination, frequent urination, and feeling the need to urinate despite having an empty bladder. In some cases, there may be blood in the urine. A much less common type of urinary tract infection is pyelonephritis, in which the kidney becomes infected. If a kidney infection occurs, it is generally because of an untreated bladder infection. Bladder infections are treated mainly with antibiotics.




Figure **14.5.6**: Using a diaphragm like this one as a barrier method of birth control may increase the risk of a woman developing a bladder infection following sexual intercourse

Risk factors for urinary bladder infections include sexual intercourse (especially when spermicide or a diaphragm, as shown in Figure **14.5.6**, is used for contraception), diabetes, obesity, and most importantly, female sex. Bladder infections are four times more common in women than in men. In fact, in women, they are the most common type of bacterial infection, and as many as 1 in 10 women has a bladder infection in any given year. Female anatomy explains the sex difference in the incidence of bladder infections. The urethra is much shorter and closer to the anus in females than in males, so contamination of the urethra and then the bladder with GI tract bacteria is more likely in females than in males. Once the bacteria reach the bladder, they can attach to the bladder wall and form a biofilm that resists the body's immune response.

## URINARY INCONTINENCE

**Urinary incontinence** is a chronic problem of uncontrolled leakage of urine. It is very common, especially at older ages and especially in women. Sometimes urinary incontinence is a sign of another health problem, such as diabetes or obesity. Regardless of the underlying cause, the symptoms of urinary incontinence alone may have a large impact on the quality of life, frequently causing inconvenience, embarrassment, and distress.

In a person with male anatomy, urinary incontinence is most commonly caused by an enlarged prostate gland or treatment for prostate cancer. In genetically female individuals, there are two common types of urinary incontinence with different causes: stress incontinence and urge incontinence.

- Stress urinary incontinence is caused by loss of support of the urethra, usually due to stretching of pelvic floor muscles during childbirth. It is characterized by leakage of small amounts of urine with activities that increase abdominal pressure, such as coughing, sneezing, or lifting. Treatment of stress urinary incontinence may include Kegel exercises to strengthen the pelvic muscles (see Explore More below). More serious cases may call for surgery to improve support for the bladder.
- Urge urinary incontinence (commonly called "overactive bladder") is caused by uncontrolled contractions of the detrusor muscle in the wall of the bladder. This causes the bladder to empty unexpectedly. Urge incontinence is characterized by leakage of large amounts of urine in association with an insufficient warning to get to the bathroom in time. Treatment of urge incontinence may include taking medication to relax the detrusor muscle.

### FEATURE: MY HUMAN BODY

You probably have had to "donate" a urine specimen for analysis in conjunction with a medical visit. A thorough medical exam often includes clinical tests for urine. Understanding what your urine may reveal about your health may help you appreciate the need for such tests.

The most common urine test is called a urinalysis. In a routine urinalysis, a urine sample may be analyzed by sight and smell and with simple urine test strips. If a particular disorder is suspected, urinalysis may be more extensive. For example, the urine may be analyzed with specific tests or viewed under a microscope to identify abnormal substances in the urine. If a bacterial infection is suspected, a sample of urine may be cultured in the lab to see if it grows bacteria and which type of bacteria grow. Knowing the type of bacteria is important for deciding which class of antibiotics is likely to be most effective in treating the infection.

The color and clarity of urine may be obvious first indicators of disorders or other abnormalities. Normal urine is yellow to amber in color and looks clear. If urine is nearly colorless, it could be a sign of excessive fluid intake, or it might be a sign of diabetes. Very dark urine may indicate dehydration, but it could also be caused by taking certain medications or ingesting some other substances. If the urine has a reddish tinge, it is often a sign of blood in the urine, which could be due to a urinary tract infection, kidney stone, or even cancer. If the urine appears cloudy instead of clear, it could be due to white blood cells in the urine, which may be another sign of a urinary tract infection.

Normal urine may have virtually no odor if it is very dilute. It will have a stronger odor if it is concentrated. Brief changes in the normal odor of urine often occur due to the ingestion of certain foods or medications. For example, after eating asparagus, urine may have a peculiar and distinctive odor for several hours. More significant is urine that has a sweet smell, because this may indicate sugar in the urine, which is a sign of diabetes.

Urine test strips, much like the familiar litmus test strips used to detect acids and bases in a chemistry lab, are used to identify abnormal levels of certain components in the urine. For example, urine test strips can detect and quantify the presence of nitrites in urine, which is usually a sign of infection with certain types of bacteria. Urine test strips can also be used to identify proteins such as albumin in urine, which may be a sign of a kidney infection or of kidney failure. Levels of sodium in urine can also be measured with test strips, and higher-than-normal levels may be another indication of kidney failure. In

addition, test strips can identify and quantify the presence of white blood cells and blood in a urine specimen, both of which are likely to be a sign of a urinary tract infection or some other urinary system disorder.

Besides the use of urine test strips, other simple urine tests that are often performed include Benedict's test, which is a test for the presence and quantity of glucose in urine. If the level is high, it is likely to indicate diabetes. The test is so simple that it may even be done in the home by the patient to monitor how well sugar levels are being controlled. Testing for some other substances in urine requires the patient to collect urine over a 24-hour period. This is the case, for example, when testing for the adrenal hormone cortisol in urine. When urine cortisol levels are higher than normal it may indicate Cushing's syndrome, and when the levels are lower than normal it may indicate Addison's disease.

## REVIEW

1. What is diabetic nephropathy and what causes it?
2. Describe polycystic kidney disease (PKD).
3. Define kidney failure.
4. What are potential treatments for kidney failure when kidney function drops below the level needed to sustain life?
5. Describe hemodialysis.
6. What are kidney stones?
7. How may a large kidney stone be removed from the body?
8. How are bladder infections usually treated?
9. Why are bladder infections much more common in females than in males?
10. Define urinary incontinence.
11. Compare and contrast stress incontinence and urge incontinence.
12. Why is the presence of a protein such as albumin in the urine a cause for concern?
13. Patients undergoing hemodialysis usually have to do this procedure a few times a week. Why does it have to be done so frequently?
14. Which of the following is considered a genetic disorder?
    A. Polycystic kidney disease
    B. Diabetic nephropathy
    C. Kidney failure
    D. Urinary incontinence
15. What is the most common cause of a kidney infection?

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5. Kidney Stones by Blausen.com staff (2014). "Medical gallery of Blausen Medical 2014". *WikiJournal of Medicine* **1** (2). DOI:10.15347/wjm/2014.010. ISSN 2002-4436. CC BY 3.0 via Wikimedia Commons
6. 'Durex' diaphragm by Wellcome Collection gallery (2018-03-21) CC-BY-4.0 ia Wikimedia Commons
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# 14.6: CASE STUDY CONCLUSION- ALCOHOL AND CHAPTER SUMMARY

## CASE STUDY CONCLUSION: DRINK AND FLUSH

You are probably aware that drinking alcohol can cause visual disturbances, slurred speech, drowsiness, impaired judgment, and loss of coordination because of its effects on the brain. Although it may be less obvious, alcohol also can have serious effects on the functioning of the excretory system.



Figure **14.6.1**: Alcohol bottles

As you learned in the beginning of the chapter from the conversation between Maeva and Bintou, who were in line for the restroom, consumption of alcohol inhibits a hormone that causes our bodies to retain water. The result is that more water is released in urine, increasing the frequency of restroom trips as well as the risk of dehydration.

Which hormone discussed in this chapter does this? If you answered antidiuretic hormone (ADH; also called vasopressin)—you are correct! ADH is secreted by the hypothalamus of the brain and acts on the kidneys. As you have learned, the kidneys filter the blood, reabsorb needed substances, and produce urine. ADH helps the body conserve water by influencing this process. ADH makes the collecting ducts in the kidneys permeable to water, allowing water molecules to be reabsorbed from the urine back into the blood through osmosis into capillaries.

Alcohol is thought to produce more dilute urine by inhibiting the release of ADH. This causes the collecting ducts to be more impermeable to water, so less water can be reabsorbed and more is excreted in the urine. Because the volume of urine is increased, the bladder fills up more quickly, and the urge to urinate occurs more frequently. This is part of the reason why you often see a long line for the restroom in situations where many people are drinking alcohol. In addition to producing more dilute urine, simply consuming many beverages can also increase urine output.

In most cases, moderate drinking causes only a minor and temporary effect on kidney function. However, when people consume a large quantity of alcohol in a short period of time or abuse alcohol over long time periods, there can be serious effects on the kidney. For example, binge drinking (i.e. consuming about four to five drinks in two hours), can cause a condition called “acute kidney injury,” serious and sudden impairment of kidney function that requires immediate medical attention. As with other cases of kidney failure that you learned about in this chapter, the treatment is to artificially filter the blood using hemodialysis. While normal kidney function may eventually return, acute kidney injury can sometimes cause long-term damage to the kidneys.

In cases where people abuse alcohol, particularly for an extended period of time, there can be many serious effects on the kidneys and other parts of the excretory system. The dehydrating effect of alcohol on the body can impair the function of many organs, including the kidneys themselves. Additionally, because of alcohol’s effect on kidney function and water and ion balance, chronic alcohol consumption can cause abnormalities in blood ion concentration and acid-base balance, which can be very dangerous.

Additionally, drinking more than two alcoholic beverages a day can increase your risk of high blood pressure. As you have learned, high blood pressure is a risk factor for some kidney disorders and a common cause of kidney failure. Therefore, drinking too much alcohol can damage the kidneys by raising blood pressure.

Finally, chronic excessive consumption of alcohol can cause liver disease. As you know, the liver is an important organ of the excretory system that breaks down toxic substances in the blood. The liver and kidneys work together to remove wastes from the bloodstream. For example, as you have learned, the liver transforms ammonia into urea, which is then filtered and excreted by the kidneys. When the liver is not functioning normally, it puts added strain on the kidneys, which can result in kidney dysfunction. This association between alcohol, liver disease, and kidney dysfunction is so strong that most of the patients in the United States with both liver disease and related kidney dysfunction are alcoholics.

As you have learned, the excretory system is essential to remove toxic wastes from the body and regulate homeostasis. Having an occasional drink can temporarily alter these functions, but excessive alcohol exposure can seriously and permanently damage this system in many ways. Limiting alcohol consumption can help preserve the normal functioning of the excretory system so that it can protect your health.

## CHAPTER SUMMARY

In this chapter, you learned about the excretory system. Specifically, you learned that:

- Excretion is the process of removing wastes and excess water from the body. It is an essential process in all living things and a major way the human body maintains homeostasis.
- Organs of the excretory system include the skin, liver, large intestine, lungs, and kidneys.
- The skin plays a role in excretion through the production of sweat by sweat glands. Sweating eliminates excess water and

salts and also a small amount of urea, a byproduct of protein catabolism.

- The liver is a very important organ of excretion. The liver breaks down many substances in the blood, including toxins. The liver also excretes bilirubin, a waste product of hemoglobin catabolism, in bile. Bile then travels to the small intestine and is eventually excreted in feces by the large intestine.
- The main excretory function of the large intestine is to eliminate solid waste that remains after food is digested and water is extracted from the indigestible matter. The large intestine also collects and excretes wastes from throughout the body.
- The lungs are responsible for the excretion of gaseous wastes, primarily carbon dioxide from cellular respiration in cells throughout the body. Exhaled air also contains water vapor and trace levels of some other waste gases.
- The paired kidneys are often considered to be the main organs of excretion. Their primary function is the elimination of excess water and wastes from the bloodstream by the production of urine. The kidneys filter many substances out of blood, allow the blood to reabsorb needed materials, and use the remaining materials to form urine.
- The two bean-shaped kidneys are located high in the back of the abdominal cavity on either side of the spine. A renal artery connects each kidney with the aorta and transports unfiltered blood to the kidney. A renal vein connects each kidney with the inferior vena cava and transports filtered blood back to the circulation.
- The kidney has two main layers involved in the filtration of blood and formation of urine: the outer cortex and inner medulla. At least a million nephrons, which are the tiny functional units of the kidney, span the cortex and medulla. The entire kidney is surrounded by a fibrous capsule and protective fat layers.
- As blood flows through a nephron, many materials are filtered out of the blood, needed materials are returned to the blood, and the remaining materials are used to form urine.
    - In each nephron, the glomerulus and the surrounding Bowman's capsule form the unit that filters blood. From Bowman's capsule, the material filtered from the blood, called filtrate, passes through the long renal tubule. As it does, some substances are reabsorbed into the blood and other substances are secreted from the blood into the filtrate, finally forming urine. The urine empties into collecting ducts, where more water may be reabsorbed.
- The kidneys are part of the urinary system, which also includes the ureters, urinary bladder, and urethra. The main function of the urinary system is to eliminate the waste products of metabolism from the body by forming and excreting urine. After urine forms in the kidneys, it is transported through the ureters to the bladder. The bladder stores the urine until urination, when urine is transported by the urethra to be excreted outside the body.
- Besides the elimination of waste products such as urea, uric acid, excess water, and mineral ions, the urinary system has other vital functions. These include maintaining homeostasis of mineral ions in extracellular fluid, regulating acid-base balance in the blood, regulating the volume of extracellular fluids, and controlling blood pressure.
- The formation of urine must be closely regulated to maintain body-wide homeostasis. Several endocrine hormones help control this function of the urinary system, including antidiuretic hormone from the hypothalamus, parathyroid hormone from the parathyroid glands, and aldosterone from the adrenal glands. For example, the kidneys are part of the renin-angiotensin-aldosterone system that regulates the concentration of sodium in the blood to control blood pressure. In this system, the enzyme renin secreted by the kidneys works with hormones from the liver and adrenal gland to stimulate nephrons to reabsorb more sodium and water from urine.
- The kidneys also secrete endocrine hormones, including calcitriol, which helps control the level of calcium in the blood; and erythropoietin, which stimulates the bone marrow to produce red blood cells.
- The process of urination is controlled by both the autonomic and the somatic nervous systems. The autonomic system causes the detrusor muscle in the bladder wall to relax as the bladder fills with urine, but the conscious contraction of the detrusor muscle expels urine from the bladder during urination.
- Ureters are tube-like structures that connect the kidneys with the urinary bladder. Each ureter arises at the renal pelvis of a kidney and travels down through the abdomen to the urinary bladder. The walls of the ureter contain smooth muscle that can contract to push urine through the ureter by peristalsis. The walls are lined with transitional epithelium that can expand and stretch.
- The urinary bladder is a hollow, muscular organ that rests on the pelvic floor. It is also lined with transitional epithelium. The function of the bladder is to collect and store urine from the kidneys before the urine is eliminated through urination. Filling of the bladder triggers the autonomic nervous system to stimulate the detrusor muscle in the bladder wall to contract. This forces urine out of the bladder and into the urethra.
- The urethra is a tube that connects the urinary bladder to the external urethral orifice. Somatic nerves control the sphincter at the distal end of the urethra. This allows the opening of the sphincter for urination to be under voluntary control.
- Diabetic nephropathy is a progressive kidney disease caused by damage to the capillaries in the glomeruli of the kidneys due to long-standing diabetes mellitus. Years of capillary damage may occur before symptoms first appear.
- Polycystic kidney disease (PKD) is a genetic disorder (autosomal dominant or recessive) in which multiple abnormal cysts grow in the kidneys.
- Diabetic nephropathy, PKD, or chronic hypertension may lead to kidney failure, in which the kidneys are no longer able to adequately filter metabolic wastes from the blood. Kidneys may fail to such a degree that kidney transplantation or repeated, frequent hemodialysis is needed to support life. In hemodialysis,

the patient's blood is filtered artificially through a machine and then returned to the patient's circulation.

- A kidney stone is a solid crystal that forms in a kidney from minerals in the urine. A small stone may pass undetected through the ureters and the rest of the urinary tract. A larger stone may cause pain when it passes or be too large to pass so it blocks a ureter. Large kidney stones may be shattered with high-intensity ultrasound into pieces small enough to pass through the urinary tract, or they may be removed surgically.
- A bladder infection is generally caused by bacteria that reach the bladder from the GI tract and multiply. Bladder infections are much more common in females than males because the female urethra is much shorter and closer to the anus. Treatment generally includes antibiotic drugs.
- Urinary incontinence is a chronic problem of uncontrolled leakage of urine. It is very common, especially at older ages and in women. In men, urinary incontinence is usually caused by an enlarged prostate gland. In women, it is usually caused by stretching of pelvic floor muscles during childbirth (stress incontinence) or by an "overactive bladder" that empties without warning (urge incontinence).

You have learned that the excretory system protects your body through the removal of toxic wastes and the maintenance of homeostasis. But how does your body protect itself against pathogens and other threats? Read the next chapter on the immune system to find out.

## CHAPTER SUMMARY REVIEW

1. Match each organ of the excretory system with the description that best fits it. Each organ is used only once. Organs: lungs, skin, kidneys, liver, large intestine
   A. Excretes solid wastes from food
   B. Cools the body while it eliminates water and other wastes
   C. Part of the urinary system
   D. Produces bile and breaks down toxins in the blood
   E. Eliminates waste gases
2. In what ways can the alveoli of the lungs be considered analogous to the nephrons of the kidney?
3. What is urea? Where is urea produced and what is it produced from? How is urea excreted from the body?
4. *True or False.* The lungs help excrete excess water, in addition to carbon dioxide.
5. *True or False.* There are two kidneys in the human body, and both are the same size and shape.
6. *True or False.* The renal pelvis is a bone that surrounds the kidneys.
7. If a person has a large kidney stone that prevents urine that has left the kidney from reaching the bladder, where do you think this kidney stone is located? Explain your answer.
8. Match each of the following structures with the description that best fits it. Each structure is used only once. Structures: urethra; nephron; ureters; urinary bladder
   A. Produces urine
   B. Stores relatively large quantities of urine
   C. Releases urine to the outside of the body
   D. Transports urine between where it is produced and where it is stored
9. Explain what is meant by "Excretion = Filtration – Reabsorption + Secretion" regarding the production of urine.
10. Which disease discussed in the chapter specifically affects the glomerular capillaries of the kidneys? Where are the glomerular capillaries located within the kidneys, and what is their function?
11. Describe one way in which the excretory system helps maintain homeostasis in the body.
12. Secretion in a nephron occurs:
    A. before filtration, and goes from the filtrate into the blood
    B. after filtration, and goes from the filtrate into the blood
    C. before filtration, and goes from the blood into the filtrate
    D. after filtration, and goes from the blood into the filtrate
13. High blood pressure can both contribute to the development of kidney disorders and be a symptom of kidney disorders. What is a kidney disorder that can be caused by high blood pressure? What is a kidney disorder that has high blood pressure as a symptom? How does blood pressure generally relate to the function of the kidney?
14. If the body is dehydrated, what do the kidneys do? What does this do to the appearance of the urine produced?
15. Which of the following contain filtered blood in the kidney?
    A. Arteries
    B. Venules
    C. Veins
    D. B and C
16. *True or False.* Hormones influence the functions of the kidney, but the kidney itself does not produce hormones.
17. *True or False.* Both the lungs and the kidneys help maintain the pH of the blood.
18. Identify three risk factors for the development of kidney stones.

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# CHAPTER OVERVIEW

## 15: THE REPRODUCTIVE SYSTEM

Please note there are not only two genders in the human population. When male or female is mentioned in this chapter, it only refers to the biological male and female sexes. This chapter outlines the structures and functions of the male and female reproductive systems, explains how fertilization occurs, and discusses the menstrual cycle's role. The chapter describes the causes of and treatments for male and female reproductive system disorders, infertility, and contraception methods.


15.1: Case Study- Making Babies
15.2: Introduction to the Reproductive System
15.3: Structures of the Male Reproductive System
15.4: Functions of the Male Reproductive System
15.5: Disorders of the Male Reproductive System
15.6: Structures of the Female Reproductive System
15.7: Menstrual Cycle
15.8: Functions of the Female Reproductive System
15.9: Disorders of the Female Reproductive System
15.10: Infertility
15.11: Contraception
15.12: Case Study Conclusion- Trying to Conceive and Chapter Summary



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# 15.1: CASE STUDY- MAKING BABIES

## CASE STUDY: TRYING TO CONCEIVE

Isabella, 28, and Omar, 30, have been together for three years. A year ago, they decided they wanted to have a baby, and they stopped using birth control. At first, they did not pay attention to the timing of their sexual activity in relation to Isabella's menstrual cycle, but after six months passed without Isabella becoming pregnant, they decided to try to maximize their efforts.



Figure **15.1.1**: Couples holding hands

They knew that in order for a woman to become pregnant, the man's sperm must encounter the woman's egg, which is typically released once a month through a process called ovulation. They had also heard that for the average woman, ovulation occurs around day 14 of the menstrual cycle. To maximize their chances of conception, they tried to have sexual intercourse on day 14 of Isabella's menstrual cycle each month.



Figure **15.1.2**: Monitoring body temperature before getting out of bed in the morning can often help tell if and when a woman is ovulating. Usually, a special, highly sensitive thermometer is used.

After several months of trying this method, Isabella is still not pregnant. She is concerned that she may not be ovulating on a regular basis because her menstrual cycles are irregular and often longer than the average 28 days. Omar is also concerned about his own fertility. He had some injuries to his testicles (testes) when he was younger, and wonders if that may have caused a problem with his sperm.

Isabella calls her doctor for advice. Dr. Bashir recommends that she try taking her temperature each morning before she gets out of bed. This temperature is called basal body temperature (BBT), and recording BBT throughout a woman's menstrual cycle can sometimes help identify if and when they ovulate. Additionally, Dr. Bashir recommends she try using a home ovulation predictor kit, which predicts ovulation by measuring the level of **luteinizing hormone (LH)** in the urine. In the meantime, Dr. Bashir sets up an appointment for Omar to give a semen sample, so that his sperm may be examined with a microscope.

As you read this chapter, you will learn about the male and female reproductive systems, how sperm and eggs are produced, and how they meet each other to ultimately produce a baby. You will learn how these complex processes are regulated, and how they can be susceptible to problems along the way. Problems in either the male or female reproductive systems can result in infertility, or difficulty in achieving a successful pregnancy. As you read the chapter, you will understand exactly how BBT and LH relate to ovulation, why Dr. Bashir recommended that Isabella monitor these variables, and the types of problems she will look for in Omar's semen. At the end of the chapter, you will find out the results of Isabella and Omar's fertility assessments, steps they can take to increase their chances of conception, and whether they are ultimately able to get pregnant.

### LGBTQ +

Most of the information in this chapter is in terms of cis-gendered individuals because there is a lack of data on lesbian, gay, bisexual, transgender, and queer (LGBTQ) individuals. About 3.5% of Americans identify themselves as lesbian, gay, or bisexual, and 0.3% identify themselves as transgender. The acronym LGBTQIA+ is an umbrella term that includes a number of groups: lesbian (homosexual woman), gay (homosexual man or woman), bisexual (person who is attracted to both genders), transgender (person who identifies their gender as different from their biological one), queer (a synonym for gay; some people prefer to identify themselves as queer to empower themselves and take their identity "back from the bullies"), questioning (people who are unsure about their gender identity/sexuality), intersex (people with two sets of genitalia), asexual (people who are not sexually attracted to anyone and who don't identify with any orientation), allies (the loving supporters of the community, though not necessarily part of it), two spirits (a tradition in many First Nations that considers sexual minorities to have both male and female spirits), and pansexual (person sexually attracted to others of any sex or gender).

## CHAPTER OVERVIEW: REPRODUCTIVE SYSTEM

In this chapter, you will learn about the male and female reproductive systems. Specifically, you will learn about:

- The functions of the reproductive system, which include the production and fertilization of gametes (eggs and sperm), the production of sex hormones by the gonads (testes and ovaries), and, in females, the carrying of a fetus
- How the male and female reproductive systems differentiate in the embryo and fetus, and how they mature during puberty
- The structures of the male reproductive system, including the testes, epididymis, vas deferens, ejaculatory ducts, seminal

vesicles, prostate gland, bulbourethral glands, and the penis
- How sperm are produced, matured, stored, and deposited into the female
- The fluids in semen that protect and nourish sperm, and where those fluids are produced
- Disorders of the male reproductive system, including erectile dysfunction, epididymitis, prostate cancer, and testicular cancer —some of which predominantly affect younger men
- The structures of the female reproductive system, including the ovaries, fallopian tubes, uterus, cervix, vagina, and external structures of the vulva
- How eggs are produced in the female fetus, and how they then mature after puberty through the process of ovulation
- The menstrual cycle, its purpose, and the hormones that control it
- How fertilization and implantation occur, the stages of pregnancy and childbirth, and how the mother's body produces milk to feed the baby
- Disorders of the female reproductive system, including cervical cancer, endometriosis, and vaginitis (which includes yeast infections)
- Some causes and treatments of male and female infertility
- Forms of contraception (birth control), including barrier methods (such as condoms), hormonal methods (such as the birth control pill), behavioral methods, intrauterine devices, and sterilization

As you read the chapter, think about the following questions:

1. Why might sexual intercourse on day 14 of Isabella's menstrual cycle not necessarily be optimal timing to achieve a pregnancy?
2. Why is Isabella concerned about her irregular and long menstrual cycles? How could tracking her BBT and LH level help identify if she is ovulating and when?
3. Why do you think Omar is concerned about past injuries to his testes? How might an analysis of his semen help assess whether he has a fertility issue—and, if so, the type of issue?

## ATTRIBUTIONS


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# 15.2: INTRODUCTION TO THE REPRODUCTIVE SYSTEM

## IT'S ALL ABOUT SEX

A tiny sperm breaks through the surface of a huge egg. Voilà! In nine months, a new baby will be born. Like most other multicellular organisms, human beings reproduce sexually. In human sexual reproduction, individuals with testes produce sperm, and individuals with ovaries produce eggs, and a new offspring forms when a sperm unites with an egg. How do sperm and eggs form? And how do they arrive together at the right place and time so they can unite to form a new offspring? These are functions of the reproductive system.

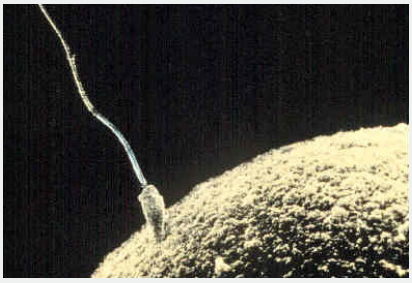


Figure **15.2.1**: A sperm cell fertilizing an egg cell

## WHAT IS THE REPRODUCTIVE SYSTEM?

The **reproductive system** is the human organ system responsible for the production and fertilization of gametes (sperm or eggs) and carrying of a fetus. Both both sexes **gonads** produce gametes. A **gamete** is a haploid cell that combines with another haploid gamete during fertilization, forming a single diploid cell called a zygote. Besides producing gametes, the gonads also produce sex hormones. **Sex hormones** are endocrine hormones that control the development of sex organs before birth, sexual maturation at puberty, and reproduction once sexual maturation has occurred. Other reproductive system organs have various functions, such as maturing gametes, delivering gametes to the site of fertilization, and providing an environment for the development and growth of offspring.

## SEX DIFFERENCES IN THE REPRODUCTIVE SYSTEM

The reproductive system is the only human organ system that is significantly different between males and females. Embryonic structures that will develop into the reproductive system start out the same in males and females, but by birth, the reproductive systems have differentiated. How does this happen?

### SEX DIFFERENTIATION

Starting around the seventh week after conception in genetically male (XY) embryos, a gene called SRY on the Y chromosome (Figure **15.2.2**) initiates the production of multiple proteins. These proteins cause undifferentiated gonadal tissue to develop into testes. Testes secrete hormones — including testosterone — that trigger other changes in the developing offspring (now called a fetus), causing it to develop a complete male reproductive system. Without a Y chromosome, an embryo will develop ovaries, that will produce estrogen. Estrogen, in turn, will lead to the formation of the other organs of a female reproductive system.

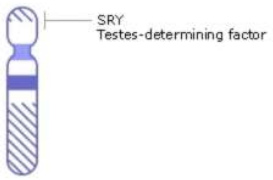



Figure **15.2.2**: The SRY gene on the short arm of the Y chromosome causes the undifferentiated gonads of an embryo to develop into testes. Otherwise, the gonads develop into ovaries.

### HOMOLOGOUS STRUCTURES

Undifferentiated embryonic tissues develop into different structures in male and female fetuses. Structures that arise from the same tissues in males and females are called **homologous structures**. The testes and ovaries, for example, are homologous structures that develop from the undifferentiated gonads of the embryo. Likewise, the penis and clitoris are homologous structures that develop from the same embryonic tissues.

### SEX HORMONES AND MATURATION

Male and female reproductive systems are different at birth, but they are immature and incapable of producing gametes or sex hormones. Maturation of the reproductive system occurs during puberty when hormones from the hypothalamus and pituitary gland stimulate the testes or ovaries to start producing sex hormones again. The main sex hormones are **testosterone** and **estrogen**. Sex hormones, in turn, lead to the growth and maturation of the reproductive organs, rapid body growth, and the development of **secondary sex characteristics**, such as body and facial hair and breasts.

### ROLE OF SEX HORMONES IN TRANSGENDER TREATMENT

Feminizing or masculinizing hormone therapy is the administration of exogenous endocrine agents to induce changes in physical appearance. Since hormone therapy is inexpensive relative to surgery and highly effective in the development of secondary sex characteristics (e.g., facial and body hair in female-to-male [FTM] individuals or breast tissue in male-to-females [MTFs]), hormone therapy is often the first, and sometimes only, medical gender affirmation intervention accessed by transgender individuals looking to develop masculine or feminine characteristics consistent with their gender identity. In some cases, hormone therapy may be required before surgical interventions can be conducted. Trans-females are prescribed estrogen and anti-testosterone medication, such as cyproterone acetate and spironolactone. Trans-men are prescribed testosterone.

## MALE REPRODUCTIVE SYSTEM

The main structures of the male reproductive system are external to the body and illustrated in Figure **15.2.3**. The two testes (singular, testis) hang between the thighs in a sac of skin called the scrotum. The testes produce both sperm and testosterone. Resting atop each testis is a coiled structure called the epididymis (plural, epididymes). The function of the epididymes is to mature and store sperm. The penis is a tubular organ that contains the urethra and has the ability to stiffen during sexual arousal. Sperm passes out of the body through the urethra during a sexual climax (orgasm). This release of sperm is called ejaculation.

In addition to these organs, there are several ducts and glands that are internal to the body. The ducts, which include the vas deferens (also called the ductus deferens), transport sperm from the epididymis to the urethra. The glands, which include the prostate gland and seminal vesicles, produce fluids that become part of semen. Semen is the fluid that carries sperm through the urethra and out of the body. It contains substances that control pH and provide sperm with nutrients for energy.

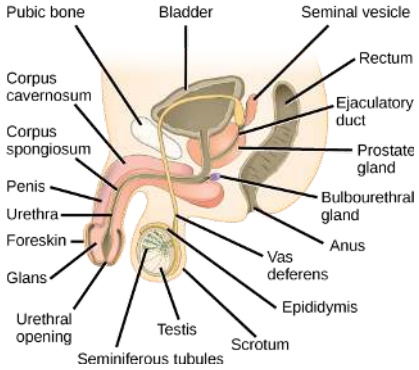
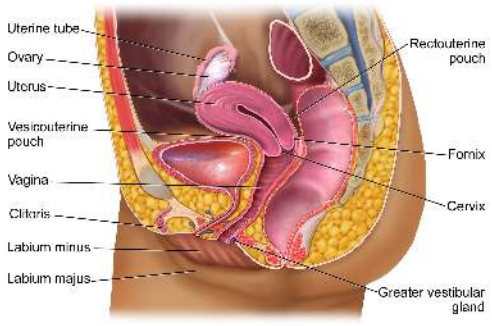



Figure **15.2.3**: The main organs of the male reproductive system. Focus on the seminiferous tubules, testis, scrotum, epididymis, vas deferens, urethra, penis, and the glands that produce semen.

## FEMALE REPRODUCTIVE SYSTEM




**The Female Reproductive System**

Figure **15.2.4**: The main organs of the female reproductive system lie within the abdominal cavity. Pay attention to ovaries, uterine tube, uterus, cervix, and vagina.

The main structures of the female reproductive system are internal to the body and shown in Figure **15.2.4**. They include the paired ovaries, which are small, oval structures that produce eggs and secrete estrogen. The two Fallopian tubes (aka uterine tubes) start near the ovaries and end at the uterus. Their function is to transport eggs from the ovaries to the uterus. If an egg is fertilized, it usually occurs while it is traveling through a Fallopian tube. The uterus is a pear-shaped muscular organ that functions to carry a fetus until birth. It can expand greatly to accommodate a growing fetus, and its muscular walls can contract forcefully during labor to push the baby into the vagina. The vagina is a tubular tract connecting the uterus to the outside of the body. The vagina is where sperm are usually deposited during sexual intercourse and ejaculation. The vagina is also called the birth canal because a baby travels through the vagina to leave the body during birth.

The external structures of the female reproductive system are referred to collectively as the vulva. They include the clitoris, which is homologous to the male penis. They also include two pairs of labia (singular, labium), which surround and protect the openings of the urethra and vagina.

## REVIEW

1. What is the reproductive system?
2. Define gonad.
3. What are sex hormones? What are their general functions?
4. Distinguish between male and female sex hormones.
5. How does the differentiation of the reproductive system occur in males and females?
6. In the context of the human male and female reproductive systems, what are homologous structures?
7. When and how does the human reproductive system mature?
8. List the organs of the male reproductive system.
9. List the organs of the female reproductive system.
10. What are female gametes called? What are male gametes called?
11. *True or False:* The vagina is the homologous structure to the penis.
12. *rue or False:* In the absence of a Y chromosome in humans, ovaries will develop.
13. Which are secondary sex characteristics?
    A. Fallopian tubes
    B. ovaries
    C. breasts
    D. all of the above
14. Fertilization usually occurs in which of these structures?
    A. ovary
    B. Fallopian tube
    C. uterus
    D. vagina
15. Explain the difference between the vulva and the vagina.

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# 15.3: STRUCTURES OF THE MALE REPRODUCTIVE SYSTEM

## ROCKY MOUNTAIN OYSTERS

First, they are peeled and pounded flat. Then, they are coated in flour, seasoned with salt and pepper, and deep-fried. What are they? They are often called Rocky Mountain oysters, but they don't come from the sea. They may also be known as Montana tendergroin, cowboy caviar, or swinging beef — all names that hint at their origins. Here's another hint: they are harvested only from male animals, such as bulls or sheep. What are they? In a word: testes.



Figure **15.3.1**: Lamb fries are fried lamb testicles

## TESTES AND SCROTUM

The two **testes** (singular, testis) are sperm- and testosterone-producing gonads in male mammals, including male humans. These and other organs of the human male reproductive system are shown in Figure **15.3.2**. The testes are contained within the **scrotum,** a pouch made of skin and smooth muscle that hangs down behind the penis.

### TESTES STRUCTURE

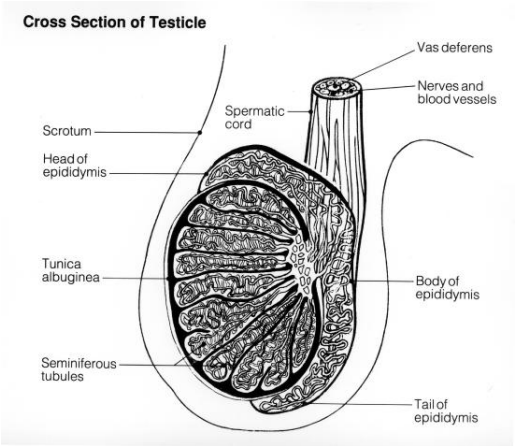



Figure **15.3.2**: This drawing includes a testis, epididymis, and vas (or ductus) deference. The three structures are connected to create a tract through which sperm can travel. Testes are composed of microscopic tubes called Seminiferous tubues where spersm are produced. Sperm is stored in epididymis after maturation until it is ejeculated via vas derernes.

The testes are filled with hundreds of tiny tubes, called **seminiferous tubules**, which are the functional units of the testes. The seminiferous tubules are coiled and tightly packed within divisions of the testis called lobules. Lobules are separated from one another by internal walls (or septa).

One or more seminiferous tubules are tightly coiled within each of the hundreds of lobules in the testis. A single testis normally contains a total of about 30 m (90 ft) of these tightly packed tubules! As shown in the cross-sectional drawing of a seminiferous tubule in Figure **15.3.2**, the tubule contains sperm in several different stages of development

### OTHER SCROTAL STRUCTURES

Besides the two testes, the scrotum also contains a pair of organs called epididymes (singular, epididymis) and part of each of the paired vas deferens (or ducti deferens). Both structures play important functions in the production or transport of sperm.

#### *EPIDIDYMIS*

The seminiferous tubules within each testis join together to form ducts (called efferent ducts) that transport immature sperm to the epididymis associated with that testis. Each **epididymis** (plural, epididymes) consists of a tightly coiled tubule with a total length of about 6 m (20 ft). As shown in Figure **15.3.2** the epididymis is generally divided into three parts: the head (which rests on top of the testis), the body (which drapes down the side of the testis), and the tail (which joins with the vas deferens near the bottom of the testis). The functions of the two epididymes are to mature sperm, and then to store that mature sperm until they leave the body during an ejaculation when they pass the sperm on to the vas deferens.

#### *VAS DEFERENS*

The **vas deferens,** also known as sperm ducts, are a pair of thin tubes, each about 30 cm (1 ft) long, which begin at the epididymis in the scrotum and continue up into the pelvic cavity. They are composed of ciliated epithelium and smooth muscle. These structures help the vas deferens fulfill their function of transporting sperm from the epididymes to the ejaculatory ducts, which are accessory structures of the male reproductive system.

## ACCESSORY STRUCTURES

In addition to the structures within the scrotum, the male reproductive system includes several internal accessory structures. They include the ejaculatory ducts, seminal vesicles, and the prostate and bulbourethral (Cowper's) glands. See Figure **15.3.3**. The major reproductive structures represented in this figure are explained below.

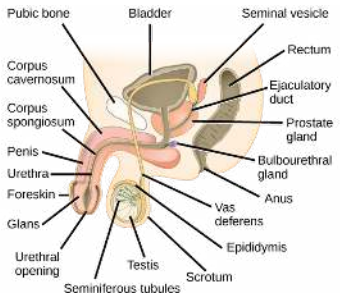



Figure **15.3.3**: The figure shows the ejaculatory duct, seminal vesicles, and the bulbourethral gland that produce semen. The figure also shows the other major structures of the male reproductive system.

## SEMINAL VESICLES

The **seminal vesicles** are a pair of glands that each consist of a single tube, which is folded and coiled upon itself. Each vesicle is about 5 cm (2 in.) long and has an excretory duct that merges with the vas deferens to form one of the two ejaculatory ducts. Fluid secreted by the seminal vesicles into the ducts makes up about 70 percent of the total volume of **semen,** which is the sperm-containing fluid that leaves the penis during an ejaculation. The fluid from the seminal vesicles is alkaline, so it gives semen a basic pH that helps prolong the lifespan of sperm after it enters the acidic secretions inside the female vagina. Fluid from the seminal vesicles also contains proteins, fructose (a simple sugar), and other substances that help nourish sperm.

## EJACULATORY DUCTS

The **ejaculatory ducts** form where the vas deferens join with the ducts of the seminal vesicles in the prostate gland. They connect the vas deferens with the urethra. The ejaculatory ducts carry sperm from the vas deferens, as well as secretions from the seminal vesicles and the prostate gland that together form semen. The substances secreted into semen by the glands as it passes through the ejaculatory ducts control its pH and provide nutrients to sperm, among other functions. The fluid itself provides sperm with a medium in which to “swim.”

## PROSTATE GLAND

The **prostate gland** is located just below the seminal vesicles. It is a walnut-sized organ that surrounds the urethra and its junction with the two ejaculatory ducts. The function of the prostate gland is to secrete a slightly alkaline fluid that constitutes close to 30 percent of the total volume of semen. The prostate fluid contains small quantities of proteins, such as enzymes. In addition, it has a very high concentration of zinc, which is an important nutrient for maintaining sperm quality and motility.

## BULBOURETHRAL GLANDS

Also called Cowper’s glands, the two **bulbourethral glands** are each about the size of a pea and located just below the prostate gland. The bulbourethral glands secrete a clear, alkaline fluid that is rich in proteins. Each of the glands has a short duct that carries the secretions into the urethra, where they make up a tiny percentage of the total volume of semen. The function of the bulbourethral secretions is to help lubricate the urethra and neutralize any urine (which is acidic) that may remain in the urethra.

# PENIS

The **penis** is the external male organ that has the reproductive function of delivering sperm to the female reproductive tract. This function is called intromission. The penis also serves as the organ that excretes urine.

## STRUCTURE OF THE PENIS

The structure of the penis and its location relative to other reproductive organs are shown in Figure **15.3.4**. The part of the penis that is located inside the body and out of sight is called the root of the penis. The shaft of the penis is the part of the penis that is outside the body. The enlarged, bulbous end of the shaft is called the glans penis.

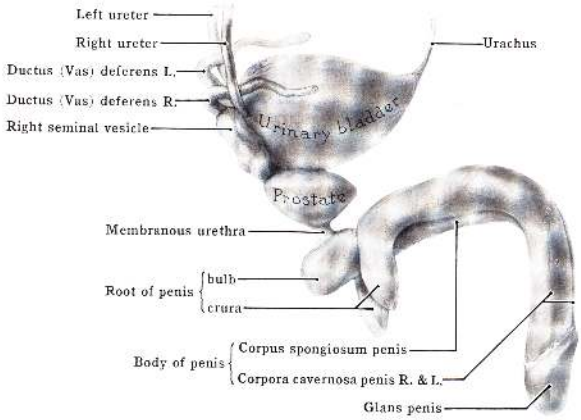



Figure **15.3.4**: This section shows the internal anatomy of the penis and related structures. The penis is composed of glans pernis, shaft, root of pernis. The corpus spongiosum is the column of erectile tissue that contains the urethra. The corpora cavernosa are the other two columns that erect the penis.

## URETHRA

The urethra passes through the penis to carry urine from the bladder — or semen from the ejaculatory ducts — through the penis and out of the body. After leaving the urinary bladder, the urethra passes through the prostate gland, where the urethra is joined by the ejaculatory ducts. From there, the urethra passes through the penis to its external opening at the tip of the glans penis. Called the external urethral orifice, this opening provides a way for urine or semen to leave the body.

## TISSUES OF THE PENIS

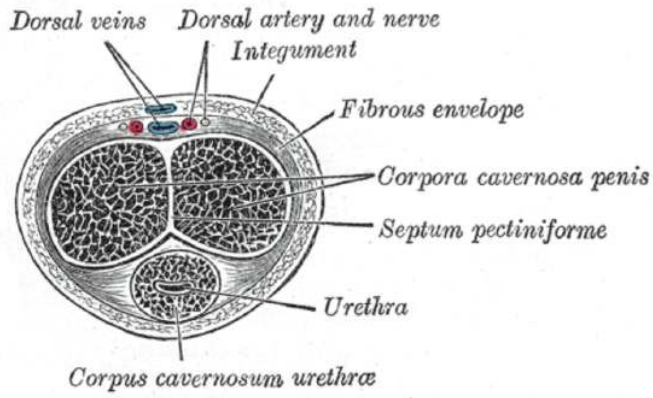



Figure 15.3.5: Cross-section of the penis: The penis consists mostly of spongy tissues that can fill with blood, stiffening the organ. The corpus cavernosum urethrae are now called corpus spongiosum. You can see the urethra in the center of the corpus spongiosum.

The penis is covered with skin (epithelium) that is unattached and free to move over the body of the penis. In an uncircumcised male, the glans penis is also mainly covered by epithelium, which (in this location) is called the foreskin, and below which is a layer of the mucous membrane. The foreskin is attached to the penis at an area on the underside of the penis called the frenulum.

As shown in Figure 15.3.5, the interior of the penis consists of three columns of spongy tissue that can fill with blood and swell in size, allowing the penis to become erect. This spongy tissue is called corpus cavernosum (plural, corpora cavernosa). Two columns of this tissue run side by side along the top of the shaft, and one column runs along the bottom of the shaft. The urethra runs through this bottom column of spongy tissue, which is sometimes called corpus spongiosum. The glans penis also consists mostly of spongy erectile tissue. Veins and arteries run along the top of the penis, allowing blood circulation through the spongy tissues.

### FEATURE: HUMAN BIOLOGY IN THE NEWS

Lung, heart, kidney, and other organ transplants have become relatively commonplace, so when they occur, they are unlikely to make the news. However, when the nation's first penis transplant took place, it was considered very newsworthy.

In 2016, Massachusetts General Hospital in Boston announced that a team of its surgeons had performed the first penis transplant in the United States. The patient who received the donated penis was a 64-year-old cancer patient. During the 15-hour procedure, the intricate network of nerves and blood vessels of the donor penis were connected with those of the penis recipient. The surgery went well, but doctors reported it would be a few weeks until they would know if normal urination would be possible, and even longer before they would know if sexual functioning would be possible. At the time that news of the surgery was reported in the media, the patient had not shown any signs of rejecting the donated organ. The surgeons also reported they were hopeful that such transplants would become relatively common, and that patient populations would expand to include wounded warriors and transgender males seeking to transition.

The 2016 Massachusetts operation was not the first penis transplant ever undertaken. The world's first successful penis transplant was actually performed in 2014 in Cape Town, South Africa. A young man who had lost his penis from complications of a botched circumcision at age 18 was given a donor penis three years later. That surgery lasted nine hours and was highly successful. The young man made a full recovery and regained both urinary and sexual functions in the transplanted organ.

In 2005, a man in China also received a donated penis in a technically successful operation. However, the patient asked doctors to reverse the procedure just two weeks later, because of psychological problems associated with the transplanted organ for both himself and his wife.

## REVIEW

1. What are the testes? Where are they located?
2. Describe the structure of a testis.
3. Identify the epididymis and its functions.
4. What are the vas deferens? What do they do?
5. Where are the seminal vesicles located? What is their reproductive role?
6. Which parts of the male reproductive system are connected by the ejaculatory ducts? What fluids enter and leave the ejaculatory ducts?
7. Identify the location of the prostate gland relative to other male reproductive organs. What is the prostate's function?
8. Where are the bulbourethral glands? What is their function?
9. Relate the structure of the penis to its two basic functions.
10. For each of the descriptions below, match the part of the male reproductive system from the list that best fits it. Each part is used only once. Parts of the male reproductive system: *urethra*, *seminal vesicle*, *epididymis*, *testes*
    A. Sperm are produced here.
    B. Sperm mature here.
    C. Sperm are transported through the penis in this structure.
    D. This is a gland that produces fluid that is a major component of semen.
11. A vasectomy is a form of birth control for men that is performed by surgically cutting or blocking the vas deferens so that sperm cannot be ejaculated out of the body. Do you think men who have a vasectomy emit semen when they ejaculate? Why or why not?
12. Which of the following structures are located internally within the body? Choose all that apply.
    A. testes
    B. seminal vesicles
    C. epididymis
    D. prostate
    E. glans penis

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# 15.4: FUNCTIONS OF THE MALE REPRODUCTIVE SYSTEM

## COLORFUL SPERM

The false-color image in Figure **15.4.1** shows real human sperm. The tiny gametes are obviously greatly magnified in the picture because they are actually the smallest of all human cells. In fact, human sperm cells are small, even when compared with sperm cells of other animals. Mice sperm are about *twice* the length of human sperm! Human sperm may be small in size, but in a normal, healthy man, huge numbers of them are usually released during each ejaculation. There may be hundreds of millions of sperm cells in a single teaspoon of semen. Producing sperm is one of the major functions of the male reproductive system.

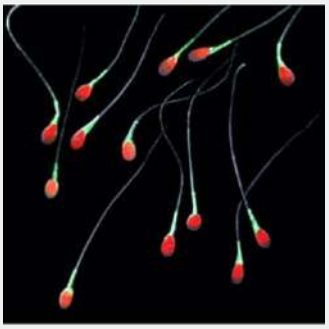


Figure **15.4.1**: Human spermatozoa (sperm cells)

## SPERM ANATOMY

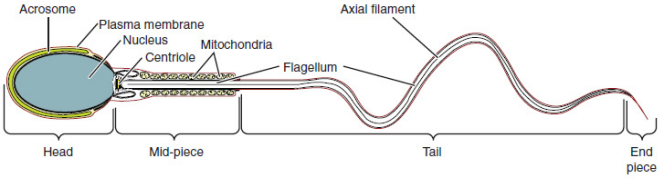



Figure **15.4.2**: Each normal mature sperm cell has the structures labeled in this image. The acrosome is at the front end, just behind the nucleus. The midpiece connects the nucleus to the tail.

A mature sperm cell has several structures that help it reach and penetrate an egg. These are labeled in the drawing of a sperm shown in Figure **15.4.2**.

- The **head** is the part of the sperm that contains the nucleus — and not much else. The nucleus, in turn, contains tightly coiled DNA that is the male parent's contribution to the genetic makeup of a zygote (if one forms). Each sperm is a haploid cell, containing half the chromosomal complement of a normal, diploid body cell.
- The front of the head is an area called the **acrosome**. The acrosome contains enzymes that help the sperm penetrate an egg (if it reaches one).
- The **midpiece** is the part of the sperm between the head and the flagellum tail. The midpiece is packed with mitochondria that produce the energy needed to move the flagellum.
- The **flagellum** (also called the tail) can rotate like a propeller, allowing the sperm to "swim" through the female reproductive tract to reach an egg if one is present.

## SPERMATOGENESIS

The process of producing sperm is known as **spermatogenesis.** Spermatogenesis normally starts when a boy reaches puberty, and it usually continues uninterrupted until death, although a decrease in sperm production generally occurs at older ages. A young, healthy male may produce hundreds of millions of sperm a day! Only about half of these, however, are likely to become viable, mature sperm.

### WHERE SPERM ARE PRODUCED

Spermatogenesis occurs in the seminiferous tubules in the testes. Spermatogenesis requires high concentrations of testosterone. Testosterone is secreted by Leydig cells, which are adjacent to the seminiferous tubules in the testes.

Sperm production in the seminiferous tubules is very sensitive to temperature. This may be the most important reason the testes are located outside the body in the scrotum. The temperature inside the scrotum is generally about 2 degrees Celsius (almost 4 degrees Fahrenheit) cooler than core body temperature. This lower temperature is optimal for spermatogenesis. The scrotum regulates its internal temperature as needed by contractions of the smooth muscles lining the scrotum. When the temperature inside the scrotum becomes too low, the scrotal muscles contract. The contraction of the muscles pulls the scrotum higher against the body, where the temperature is warmer. The opposite occurs when the temperature inside the scrotum becomes too high.

### EVENTS OF SPERMATOGENESIS

Figure **15.4.3** summarizes of the main cellular events that occur in the process of spermatogenesis. The process begins with a diploid stem cell called a **spermatogonium** (plural, spermatogonia), and involves several cell divisions. The entire process takes at least ten weeks to complete, including maturation in the epididymis.

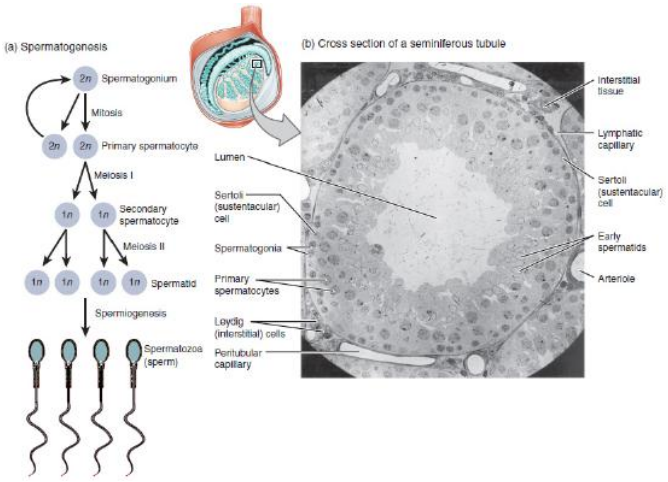



Figure **15.4.3**: Spermatogenesis includes one mitotic division and two meiotic divisions. Also on the right, the cross-section of the seminiferous tubule shows the locations of the lumen, cells of spermatogenesis, Sertoli, and Leydig cells in the tube.

1. A spermatogonium undergoes mitosis to produce two diploid cells called primary spermatocytes. One of the primary spermatocytes goes on to produce sperm. The other replenishes the reserve of spermatogonia.
2. The primary spermatocyte undergoes meiosis I to produce two haploid daughter cells called secondary spermatocytes.
3. The secondary spermatocytes rapidly undergo meiosis II to produce a total of four haploid daughter cells called spermatids.
4. The spermatids begin to form a tail, and their DNA becomes highly condensed. Unnecessary cytoplasm and organelles are removed from the cells, and they form a head, midpiece, and flagellum. The resulting cells are sperm (spermatozoa).

As shown in Figure **15.4.3**, the events of spermatogenesis begin near the wall of the seminiferous tubule — where spermatogonia are located — and continue inward toward the lumen of the tubule. Sertoli cells extend from the wall of the seminiferous tubule inward toward the lumen, so they are in contact with developing sperm at all stages of spermatogenesis. Sertoli cells play several roles in spermatogenesis:

- They secrete endocrine hormones that help regulate spermatogenesis.
- They secrete substances that initiate meiosis.
- They concentrate testosterone (from Leydig cells), which is needed at high levels to maintain spermatogenesis.
- They phagocytize the extra cytoplasm that is shed from developing sperm cells.
- They secrete a testicular fluid that helps carry sperm into the epididymis.
- They maintain a blood-testis barrier, so immune system cells cannot reach and attack the sperm

### MATURATION IN THE EPIDIDYMIS

Although the sperm produced in the testes have tails, they are not yet motile (able to “swim”). The non-motile sperms are transported to the epididymis in the testicular fluid that is secreted by Sertoli cells with the help of peristaltic contractions. In the epididymis, the sperms gain motility, so they are capable of swimming up the female genital tract and reaching an egg. The mature sperms are stored in the epididymis until ejaculation occurs.

## EJACULATION

Sperms are released from the body during **ejaculation,** which typically occurs during orgasm. Hundreds of millions of mature sperm — contained within a small amount of thick, whitish fluid called semen — are propelled from the penis during a normal ejaculation.

### HOW EJACULATION OCCURS

Ejaculation occurs when peristalsis of the muscle layers of the vas deferens and other accessory structures propel sperm from the epididymes, where mature sperm are stored. The muscle contractions force the sperm through the vas deferens and the ejaculatory ducts, and then out of the penis through the urethra. Due to the peristaltic action of the muscles, the ejaculation occurs in a series of spurts.

### THE ROLE OF SEMEN

As sperms travel through the ejaculatory ducts during ejaculation, they mix with secretions from the seminal vesicles, prostate gland, and bulbourethral glands to form semen (Figure **15.4.4**). The average amount of semen per ejaculate is about 3.7 mL, which is a little less than a teaspoonful. Most of this volume of semen consists of glandular secretions, with the hundreds of millions of sperm cells actually contributing relatively little to the total volume.



Figure **15.4.4**: This petri dish shows normal human semen in a typical ejaculate.

The secretions in semen are important for the survival and motility of sperm. They provide a medium through which sperm can swim. They also include sperm-sustaining substances, such as high concentrations of the sugar fructose, which is the main source of energy for sperm. In addition, semen contains many alkaline substances that help neutralize the acidic environment in the female vagina. This protects the DNA in sperm from being denatured by the acid and prolongs the life of sperm in the female reproductive tract.

## ERECTION

Besides providing a way for sperm to leave the body, the main role of the penis in reproduction is **intromission** or depositing sperm in the vagina of the female reproductive tract. Intromission depends on the ability of the penis to become stiff and erect, a state referred to as an **erection.** The human penis, unlike that of most other mammals, contains no erectile bone. Instead, in order to reach its erect state, it relies entirely on engorgement with the blood of its columns of spongy tissue. During sexual arousal, the arteries that supply blood

to the penis dilate, allowing more blood to fill the spongy tissue. The now-engorged spongy tissue presses against and constricts the veins that carry blood away from the penis. As a result, more blood enters than leaves the penis, until a constant erectile size is achieved.

In addition to sperm, the penis also transports urine out of the body. These two functions cannot occur simultaneously. During an erection, the sphincters that prevent urine from leaving the bladder are controlled by centers in the brain so they cannot relax and allow urine to enter the urethra.

## TESTOSTERONE PRODUCTION

The final major function of the male reproductive system is the production of the male sex hormone testosterone. In mature males, this occurs mainly in the testes. Testosterone production is under the control of luteinizing hormone (LH) from the pituitary gland. LH stimulates Leydig cells in the testes to secrete testosterone.

Testosterone is important for male sexual development at puberty. It stimulates maturation of the male reproductive organs, as well as the development of secondary male sex characteristics (such as facial hair). Testosterone is also needed in mature males for normal spermatogenesis to be maintained in the testes. Follicle stimulating hormone (FSH) from the pituitary gland is also needed for spermatogenesis to occur, in part because it helps Sertoli cells in the testes concentrate testosterone to high enough levels to maintain sperm production. Testosterone is also needed for the proper functioning of the prostate gland. In addition, testosterone plays a role in erection, allowing sperm to be deposited within the female reproductive tract.

### FEATURE: MY HUMAN BODY

If you're a man and you use a laptop computer on your lap for long periods of time, you may be decreasing your fertility. The reason? A laptop computer generates considerable heat, and its proximity to the scrotum during typical use results in a significant rise in temperature inside the scrotum. Spermatogenesis is very sensitive to high temperatures, so it may be adversely affected by laptop computer use. If you want to avoid the potentially fertility-depressing effect of laptop computer use, you might want to consider using your laptop computer on a table or other surface rather than on your lap — at least when you log on for long computer sessions. Other activities that raise scrotal temperature and have the potential to reduce spermatogenesis including soaking in hot tubs, wearing tight clothing, and biking. Although the effects of short-term scrotal heating on fertility seem to be temporary, years of such heat exposure may cause irreversible effects on sperm production.



Figure **15.4.5**: A male with a laptop on his lap

## REVIEW

1. List parts of mature sperm.
2. What is spermatogenesis? When does it occur?
3. Where does spermatogenesis take place? State one role of Sertoli cells in spermatogenesis.
4. Summarize the steps of sperm production, naming the cells and processes involved.
5. What must happen to sperm before they are able to "swim"?
6. What is ejaculation?
7. Describe semen and its components.
8. Define intromission. How is it related to erection?
9. Explain how an erection occurs.
10. What cells secrete testosterone? What controls this process?
11. Identify the functions of testosterone in males.
12. Which of the following cells are haploid? Choose all that apply.
    1. spermatids
    2. spermatogonia
    3. primary spermatocytes
    4. secondary spermatocytes
    5. mature sperm
13. Describe one way in which Leydig and Sertoli cells work together to maintain spermatogenesis.
14. *True or False:* When it is cold outside the body, the scrotal muscles relax.
15. *True or False:* During an erection, the arteries and veins of the penis dilate.

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# 15.5: DISORDERS OF THE MALE REPRODUCTIVE SYSTEM

## OFFERING TO THE GODS

The marble penis and scrotum depicted in Figure **15.5.1** comes from ancient Rome, during the period from about 200 BCE to 400 CE. During that time, offerings like this were commonly given to the gods by people with health problems, either in the hopes of a cure or as thanks for receiving one. The offerings were generally made in the shape of the afflicted body part. Scholars think this marble penis and scrotum may have been an offering given in hopes of — or thanks for — a cure for impotence, known medically today as erectile dysfunction.



Figure **15.5.1**: Votive male genitalia, Roman, 200 BCE-400 CE

## ERECTILE DYSFUNCTION

**Erectile dysfunction (ED)** is sexual dysfunction characterized by the regular and repeated inability of a sexually mature individual to obtain or maintain an erection. It is a common disorder that affects about 40 percent of people with penises.

### CAUSES OF ERECTILE DYSFUNCTION

The penis normally stiffens and becomes erect when the columns of spongy tissue within the shaft of the penis (the corpora cavernosa and corpus spongiosum) become engorged with blood. Anything that hampers normal blood flow to the penis may, therefore, interfere with its potential to fill with blood and become erect. The normal nervous control of sexual arousal or penile engorgement may also fail and lead to problems obtaining or maintaining an erection

Specific causes of ED include both physiological and psychological causes. Physiological causes include the use of therapeutic drugs (such as antidepressants), aging, kidney failure, diseases (such as diabetes or multiple sclerosis), tobacco smoking, and treatments for other disorders (such as prostate cancer). Psychological causes are less common but may include stress, performance anxiety, or mental disorders. The risk of ED may also be greater in people with obesity, cardiovascular disease, poor dietary habits, and overall poor physical health. Having an untreated hernia in the groin may also lead to ED.

### TREATMENTS FOR ERECTILE DYSFUNCTION

Treatment of ED depends on its cause or contributing factors. For example, for tobacco smokers, smoking cessation may bring significant improvement in ED. Improving overall physical health by losing weight and exercising regularly may also be beneficial. The most common first-line treatment for ED, however, is the use of oral prescription drugs, known by brand names such as Viagra® and Cialis®. These drugs help ED by increasing blood flow to the penis. Other potential treatments include topical creams applied to the penis, injection of drugs into the penis, or the use of a vacuum pump that helps draw blood into the penis by applying negative pressure. More invasive approaches may be used as a last resort if other treatments fail. These usually involve surgery to implant inflatable tubes or rigid rods into the penis.

Ironically, the world's most venomous spider —the Brazilian wandering spider (Figure **15.5.2**) — may offer a new treatment for ED. The venom of this spider is known to cause priapism in humans. Priapism is a prolonged erection that may damage the reproductive organs and lead to infertility if it continues too long. Researchers are investigating one of the components of the spider's venom as a possible treatment for ED if taken in minute quantities.



Figure **15.5.2**: The venom of a Brazilian wandering spider may be deadly, but one of its components might lead to a new treatment for ED.

## EPIDIDYMITIS

**Epididymitis** is inflammation of the epididymis. The epididymis is one of the paired organs within the scrotum where sperm mature and are stored. Discomfort or pain and swelling in the scrotum are typical symptoms of epididymitis, which is a relatively common condition, especially in young individuals. In the U.S. alone, more than half a million cases of epididymitis are diagnosed annually between the ages of 18 and 35.

### ACUTE VS. CHRONIC EPIDIDYMITIS

Epididymitis may be acute or chronic. Acute diseases are generally short-term conditions, whereas chronic diseases may last years or even a lifetime.

#### *ACUTE EPIDIDYMITIS*

Acute epididymitis generally has a fairly rapid onset and is most often caused by a bacterial infection. Bacteria in the urethra can

backflow through the urinary and reproductive structures to the epididymis. In sexually active individuals, many cases of acute epididymitis are caused by sexually transmitted bacteria. Besides pain and swelling, common symptoms of acute epididymitis include redness, warmth in the scrotum, and a fever. There may also be a urethral discharge.

#### CHRONIC EPIDIDYMITIS

Chronic epididymitis is epididymitis that lasts for more than three months. In some, the condition may last for years. It may occur with or without a bacterial infection being diagnosed. Sometimes, it is associated with lower back pain after an activity that stresses the lower back, such as heavy lifting or a long time spent driving a vehicle.

### TREATMENT OF EPIDIDYMITIS

If a bacterial infection is suspected, acute and chronic epididymitis are generally treated with antibiotics. Antibiotic treatment may be prescribed for chronic epididymitis for four to six weeks to ensure the complete eradication of any possible bacteria. Additional treatments often include anti-inflammatory drugs to reduce inflammation of the tissues and painkillers to control the pain, which may be severe. Physically supporting the scrotum and applying cold compresses may also be recommended to help relieve swelling and pain.

Regardless of symptoms, treatment is important for both acute and chronic epididymitis because major complications may occur otherwise. Untreated acute epididymitis may lead to an abscess—a buildup of pus—or to the infection spreading to other organs. Untreated chronic epididymitis may lead to permanent damage to the epididymis and testis, and it may even cause infertility.

## MALE REPRODUCTIVE CANCERS

Why does the Brazilian hospital pictured in Figure **15.5.3** have a huge blue mustache on its “face”? The mustache is a symbol of “Movember.” This is an international campaign to raise awareness of prostate cancer, as well as money to fund prostate cancer research.




Figure **15.5.3**: The mustache is a symbol for “Movember,” a campaign against prostate cancer.

### PROSTATE CANCER

The prostate gland is an organ located in the male pelvis. The urethra passes through the prostate gland after it leaves the bladder and before it reaches the penis. The function of the prostate is to secrete zinc and other substances into semen during ejaculation. In the United States, **prostate cancer** is the most common type of cancer and the second leading cause of cancer death in people carrying prostate gland. About 80 percent of American individuals with the prostate will have cancerous cells in their prostate gland by the age of 80.

#### HOW PROSTATE CANCER OCCURS

Prostate cancer occurs when glandular cells of the prostate mutate into tumor cells. Eventually, the tumor, if undetected, may invade nearby structures, such as the seminal vesicles. Tumor cells may also metastasize and travel in the bloodstream or lymphatic system to organs elsewhere in the body. Prostate cancer most commonly metastasizes to the bones, lymph nodes, rectum, or lower urinary tract organs.

#### SYMPTOMS OF PROSTATE CANCER

Early in the course of prostate cancer, there may be no symptoms. When symptoms *do* occur, they mainly involve urination, because the urethra passes through the prostate gland. The symptoms typically include frequent urination, difficulty starting and maintaining a steady stream of urine, blood in the urine, and painful urination. Prostate cancer may also cause problems with sexual function, such as difficulty achieving an erection or painful ejaculation.

#### RISK FACTORS FOR PROSTATE CANCER

Some factors that increase the risk of prostate cancer can be changed, and others cannot.

- Risk factors that *can* be changed include a diet high in meat, a sedentary lifestyle, obesity, and high blood pressure.
- Older age, a family history of prostate cancer, and African ancestry are risk factors that cannot be changed. Family history is an important risk factor, so genes are involved. Many different genes have been implicated.

#### DIAGNOSING PROSTATE CANCER

The only definitive test to confirm a diagnosis of prostate cancer is a biopsy. In this procedure, a small piece of the prostate gland is surgically removed and then examined microscopically. A biopsy is done only after less invasive tests have found evidence that a patient may have prostate cancer.

A routine exam by a doctor may find a lump on the prostate, which might be followed by a blood test that detects an elevated level of prostate-specific antigen (PSA). PSA is a protein secreted by the prostate that normally circulates in the blood. Higher-than-normal levels of PSA can be caused by prostate cancer, but they may also have other causes. Ultrasound or magnetic resonance imaging (MRI) might also be undertaken to provide images of the prostate gland and additional cancer information.

#### TREATMENT OF PROSTATE CANCER

The average age at which men are diagnosed with prostate cancer is 70. Prostate cancer is typically such a slow-growing cancer that elderly patients may not require treatment. Instead, the patients are

watched carefully over the subsequent years to make sure the cancer isn't growing and posing an immediate threat — an approach that is called active surveillance. It is used for at least 50 percent of patients who are expected to die from other causes before their prostate cancer causes symptoms.

Treatment of younger patients — or those with more aggressively growing tumors — may include surgery to remove the prostate, chemotherapy, and/or radiation therapy (such as brachytherapy, see Figure **15.5.4**). All of these treatment options can have significant side effects, such as erectile dysfunction or urinary incontinence. Patients should learn the risks and benefits of the different treatments, and discuss them with their healthcare provider to decide on the best treatment options for their particular case.

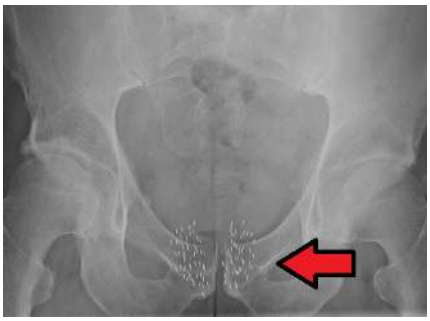


Figure **15.5.4**: Brachytherapy is a form of radiation therapy for prostate cancer. Radioactive "seeds" like the ones shown here are inserted into the prostate gland. The seeds give off radiation that kills cancer cells.

## TESTICULAR CANCER

Reproductive cancer, which is rare and most commonly affects young individuals, is **testicular cancer**. The testes are the paired reproductive organs in the scrotum that produce sperm and secrete testosterone. The risk of testicular cancer is about four to five times greater in individuals of European than African ancestry. The cause of this difference is unknown.

### *SIGNS AND SYMPTOMS OF TESTICULAR CANCER*

One of the first signs of testicular cancer is often a lump or swelling in one of the two testes. The lump may or may not be painful. If pain is present, it may occur as a sharp pain or a dull ache in the lower abdomen or scrotum. Some people with testicular cancer report a feeling of heaviness in the scrotum. Testicular cancer does not commonly spread beyond the testis, but if it does, it most often spreads to the lungs, where it may cause shortness of breath or a cough.

### *DIAGNOSIS OF TESTICULAR CANCER*

The main way testicular cancer is diagnosed is by detecting a lump in the testis. Further diagnostic tests will likely follow this. An ultrasound may be done to determine the exact location, size, and characteristics of the lump. Blood tests may be done to identify and measure tumor-marker proteins in the blood that are specific to testicular cancer. CT scans may also be done to determine whether the disease has spread beyond the testis. However, unlike the case with prostate cancer, a biopsy is not recommended because it increases the risk of cancer cells spreading into the scrotum.

### *TREATMENT OF TESTICULAR CANCER*

Testicular cancer has one of the highest cure rates of all cancers. Three basic types of treatment for testicular cancer are surgery, radiation therapy, and/or chemotherapy. Generally, the initial treatment is surgery to remove the affected testis. If the cancer is caught at an early stage, the surgery is likely to cure the cancer and has nearly a 100 percent five-year survival rate. When just one testis is removed, the remaining (if healthy) is adequate to maintain fertility, hormone production, and other normal functions. Radiation therapy and/or chemotherapy may follow surgery to kill any tumor cells that might exist outside the affected testis, even when there is no indication that cancer has spread. In many cases, however, surgery is followed by surveillance instead of additional treatments.

## REVIEW

1. What is erectile dysfunction? When does it occur?
2. Underlying causes of erectile dysfunction may include physiological and/or psychological factors. Identify some of these factors.
3. Discuss types of treatment for erectile dysfunction.
4. Define epididymitis. What is its most common cause?
5. Identify possible treatments for epididymitis. Why is treatment important, even when there are no symptoms?
6. Rank prostate cancer as a cause of cancer and a cause of cancer death in men. What are some of the symptoms of prostate cancer?
7. List the risk factors for prostate cancer.
8. How is prostate cancer detected?
9. In many cases, treatment for prostate cancer is unnecessary. Why? When is treatment necessary, and what are the treatment options?
10. Testicular cancer is generally rare, but it is the most common cancer in one age group. What age group is it?
11. Identify possible signs and symptoms of testicular cancer.
12. How can testicular cancer be diagnosed?
13. Describe how testicular cancer is typically treated.
14. Which of the following is common in younger individuals (i.e., under age 39)?

    A. prostate cancer
    B. testicular cancer
    C. epididymitis
    D. B and C

15. A biopsy is important in cases of suspected:

    A. epididymitis
    B. testicular cancer
    C. prostate cancer
    D. B and C

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# 15.6: STRUCTURES OF THE FEMALE REPRODUCTIVE SYSTEM

## FERTILITY SYMBOL

The geometric design on this ancient stone carving represents a powerful symbol of fertility: the vagina. The symbol is called yoni in Hindu, and it reflects the value placed by Hindu culture on the ability to give birth. The vagina is one of several organs in the female reproductive system.



Figure **15.6.1**: A stone yoni found in Cát Tiên sanctuary, Lam Dong, Vietnam.

## FEMALE REPRODUCTIVE ORGANS

The female reproductive system is made up of internal and external organs that function to produce haploid gametes called eggs (or oocytes), secrete sex hormones (such as estrogen), and carry and give birth to a fetus. As shown in Figure **15.6.2**, the internal reproductive organs include the vagina, uterus, Fallopian (uterine) tubes, and ovaries. The external organs — collectively called the vulva — include the clitoris and labia.

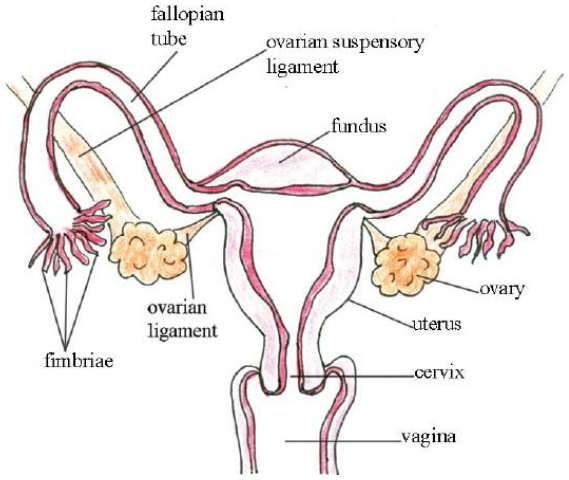



Figure **15.6.2**: Structures of the internal female reproductive organs.

The **vagina** is an elastic, muscular canal leading from its opening in the vulva to the neck of the uterus, called the cervix. It is about 7.5 cm (3.0 in.) long at the front, and about 9 cm (3.5 in.) long at the back. The vagina accommodates the penis and is the site where sperm are usually ejaculated during sexual intercourse. In the context of pregnancy and natural (vaginal) childbirth, the vagina is also referred to as the birth canal. In addition, it channels the flow of menstrual blood from the uterus.

## STRUCTURE OF THE VAGINA

The **vagina**, shown at the bottom of Figure **15.6.2**, is a muscular canal (approximately 10 cm long) that serves as the entrance to the reproductive tract. It also serves as the exit from the uterus during menses and childbirth. The outer walls of the anterior and posterior vagina are formed into longitudinal columns or ridges, and the superior portion of the vagina—called the fornix—meets the protruding uterine cervix. The walls of the vagina are lined with an outer, fibrous adventitia; a middle layer of smooth muscle; and an inner mucous membrane with transverse folds called **rugae**. Together, the middle and inner layers allow the expansion of the vagina to accommodate intercourse and childbirth. The thin, perforated hymen can partially surround the opening to the vaginal orifice. The hymen can be ruptured with strenuous physical exercise, penile-vaginal intercourse, and childbirth. The Bartholin's glands and the lesser vestibular glands (located near the clitoris) secrete mucus, which keeps the vestibular area moist.

The vagina is home to a normal population of microorganisms that help to protect against infection by pathogenic bacteria, yeast, or other organisms that can enter the vagina. In a healthy individual, 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-cleaning organ. However, douching—or washing out the vagina with fluid—can disrupt the normal balance of healthy microorganisms, and actually increase the risk for infections and irritation. Indeed, the American College of Obstetricians and Gynecologists recommend that people do not douche and that they allow the vagina to maintain its normal healthy population of protective microbial flora.

## UTERUS

The **uterus** (commonly called the womb) is a pear-shaped, muscular organ that is about 7.6 cm (3 in.) long. It is located above the vagina and behind the bladder in the center of the pelvis. The position of the uterus in the pelvis is stabilized by several ligaments and bands of supportive tissue. The uterus is where a fetus develops during gestation, and the organ provides mechanical protection and support for the developing offspring. Contractions of the muscular wall of the uterus are responsible for pushing the fetus out of the uterus during childbirth.

### PARTS OF THE UTERUS

As shown in Figure **15.6.3**, the lower end of the uterus forms the **cervix,** which is also called the neck of the uterus. The cervix is about 2.5 cm (1 in.) long and protrudes downward into the vagina. A

small canal runs the length of the cervix, connecting the uterine cavity with the lumen of the vagina. This allows semen deposited in the vagina to enter the uterus, and a baby to pass from the uterus into the vagina during birth. Glands in the cervix secrete mucus that varies in water content and thickness, so it can function either as a barrier to keep microorganisms out of the uterus during pregnancy or as a transport medium to help sperm enter the uterus around the time of ovulation. The rest of the uterus above the cervix is called the body of the uterus. The upper end of the uterus is connected with the two Fallopian tubes.

### TISSUES OF THE UTERUS

As indicated in Figure **15.6.3**, the uterus consists of three tissue layers, called the endometrium, myometrium, and perimetrium.

- The **endometrium** is the innermost tissue layer of the uterus. It consists of epithelial tissue, including mucous membranes. This layer thickens during each menstrual cycle and, unless an egg is fertilized, sloughs off during the following menstrual period. If an egg is fertilized, the thickened endometrium is maintained by hormones and provides nourishment to the embryo. As gestation progresses, the endometrium develops into the maternal portion of the placenta. The **placenta** is a temporary organ that consists of a mass of maternal and fetal blood vessels through which the mother's and fetus's blood exchange substances.
- The **myometrium** is the middle layer of the uterus. It consists mostly of a thick layer of smooth muscle tissue. Powerful contractions of the smooth muscle allow the uterus to contract and expel an infant during childbirth.
- The **perimetrium** is the outermost layer of the uterus. It covers the outer surface of the uterus. This layer actually consists of two layers of epithelium that secrete fluid into the space between them. The fluid allows for small movements of the uterus within the pelvis, without causing it to rub against other organs.

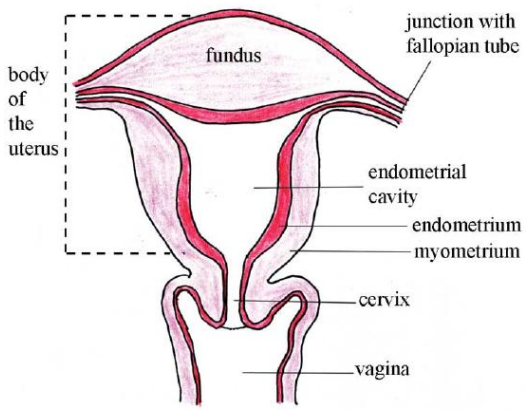



Figure **15.6.3**: The cervix of uterus connects it to vagina. The thick walls of the uterus are composed of layers of tissues known as endometrium, myometrium, and perimetrium.

## FALLOPIAN TUBES

The **Fallopian tubes** (Figure **15.6.2**) are two thin tubes that lie between the ovaries and the uterus. The Fallopian tubes are not attached to the ovaries, but their broad upper ends — called infundibula — lie very close to the ovaries. The infundibula also have fringe-like extensions called fimbriae that move in a waving motion to help guide eggs from the ovaries into the Fallopian tubes. The lower ends of the Fallopian tubes are attached to the upper part of the body of the uterus on either side of the body. They open into the uterus. Egg is fertilized in the fallopian tubes.

## OVARIES

The **ovaries** are the gonads. 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 many ligaments. The ovaries are the ovum-producing organs of the internal reproductive system. The ovary is an ovum-producing reproductive organ, typically found in pairs. Ovaries are analogous to testes in that both are gonads and endocrine glands. Ovaries secrete both estrogen and progesterone. Estrogen is responsible for the appearance of secondary sex characteristics of females at puberty and for the maturation and maintenance of the reproductive organs in their mature functional state. Progesterone functions with estrogen by promoting menstrual cycle changes in the endometrium.

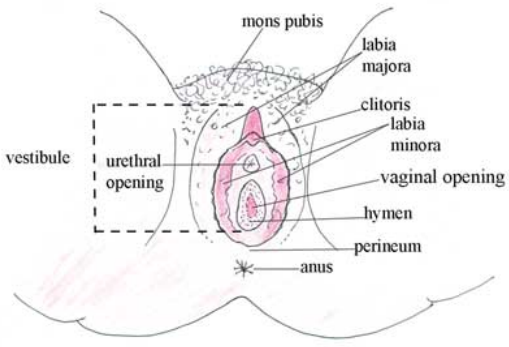



Figure **15.6.4**: External female genitalia (vulva)

## VULVA

The external reproductive structures are referred to collectively as the **vulva** (Figure **15.6.4**). 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 medially to the labia majora. Although they naturally vary in shape and size, the labia minora serve to protect the urethra and the entrance to the 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).

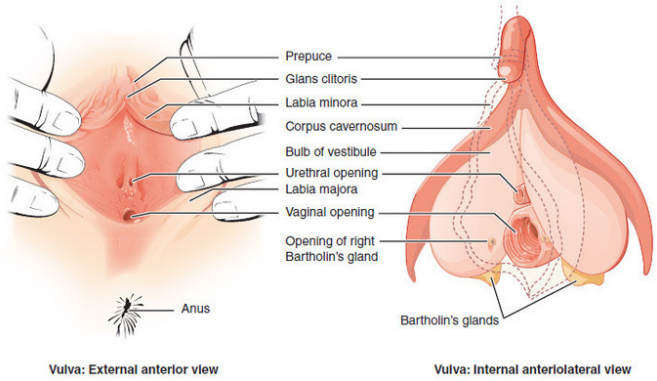



Figure **15.6.5**: External and internal view of a vulva

## BREASTS

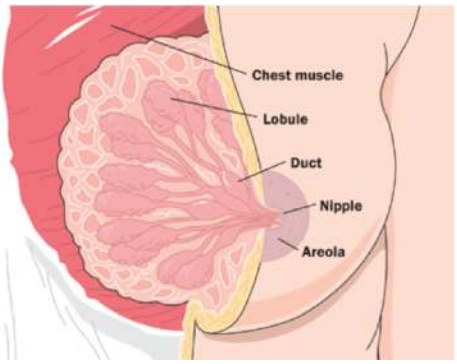



Figure **15.6.6**: The breasts are not really reproductive organs, but they play a reproductive role as mammary glands that can produce milk to feed an infant. Milk is produced in the glands of the lobules. Then the milk is created through ducts when the infant suks on the nipples.

The breasts are not directly involved in reproduction, but because they contain **mammary glands,** they can provide nourishment to an infant after birth. The breasts overlay major muscles in the chest from which they project outward in a conical shape. The two main types of tissues in the breast are adipose (fat) tissue and glandular tissue that produces milk. As shown in Figure **15.6.6**, each mature breast contains many lobules, where milk is produced and stored during pregnancy.

During nursing (or lactation), the milk drains into ducts and sacs, which in turn converge at the nipple. Milk exits the breast through the nipple in response to the suckling action of an infant. The nipple is surrounded by a more darkly pigmented area called the areola. The areola contains glands that secrete an oily fluid, which lubricates and protects the nipple during breastfeeding.

In 2018, during a survey, the respondents mentioned about two protocols of lactation induction in a trans woman, Zil Goldstein and Newman-Goldfarb protocols, which was initially designed for a cis woman to nurse a baby born to a surrogate mother. The Zil Goldstein protocol starts with 10 mg domperidone (a drug) three times daily while the Newman-Goldfarb protocol recommends 10 mg domperidone four times daily. Both regimens subsequently increase the dose to 20 mg four times daily. Since domperidone is not approved by the Food and Drug Administration, the patients obtain the drug elsewhere. Both regimens also utilize estradiol and progesterone sex hormones. Subsequently, the physical stimulation of the nipples is recommended for milk production. Informal reports of trans women who induced lactation have emerged recently. However, there are no data to support any of the other reports. There is a critical gap in evidence-based medicine for this population.

## REVIEW

1. State the general functions of the female reproductive system.
2. Describe the vagina and its reproductive functions.
3. Outline the structure and basic functions of the uterus.
4. What is the endometrium? How does it change during the monthly cycle?
5. Relate features of the Fallopian tubes to the functions of these structures.
6. Define ovary.
7. Identify the functional units of the ovaries.
8. Discuss the timing of egg production and ovulation in the context of a female's lifetime.
9. What is the vulva? What structures does it include?
10. Why are breasts included in discussions of reproduction, if they are not organs of the female reproductive system?
11. What is the function of the folds in the mucous membrane lining of the vagina?
12. What are two ways in which the female reproductive system protects itself from pathogens?
13. *True or False:* The fallopian tube runs through the cervix and allows sperm to enter the uterus.
14. *True or False:* The nipple and the areola are not the same things.
15. Immature eggs are located in _____, which are located within _____ .

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# 15.7: MENSTRUAL CYCLE

## TABOO TOPIC

The banner in Figure **15.7.1** was carried in a 2014 march in Uganda as part of the celebration of Menstrual Hygiene Day. Menstrual Hygiene Day is an awareness day on May 28 of each year that aims to raise awareness worldwide about menstruation and menstrual hygiene. Maintaining good menstrual hygiene is difficult in developing countries like Uganda because of taboos on discussing menstruation and the lack of availability of menstrual hygiene products. Poor menstrual hygiene, in turn, can lead to embarrassment, degradation, and reproductive health problems in females. May 28 was chosen as Menstrual Hygiene Day because of its symbolism. May is the fifth month of the year that symbolizes the five days of bleeding during menstruation each month. The 28$^{th}$ day was chosen because the menstrual cycle averages about 28 days.




Figure **15.7.1**: Water for People Uganda celebration of Menstrual Hygiene Day in 2014

## WHAT IS THE MENSTRUAL CYCLE?

The **menstrual cycle** refers to natural changes that occur in the female reproductive system each month during the reproductive years. The cycle is necessary for the production of eggs and the preparation of the uterus for pregnancy. It involves changes in both the ovaries and the uterus and is controlled by pituitary and ovarian hormones. Day 1 of the cycle is the first day of the menstrual period**,** when bleeding from the uterus begins as the built-up endometrium lining the uterus is shed. The endometrium builds up again during the remainder of the cycle, only to be shed again during the beginning of the next cycle if pregnancy does not occur. In the ovaries, the menstrual cycle includes the development of a follicle, ovulation of a secondary oocyte, and the degeneration of the follicle if pregnancy does not occur. Both uterine and ovarian changes during the menstrual cycle are generally divided into three phases, although the phases are not the same in the two organs.

### MENARCHE AND MENOPAUSE

The female reproductive years are delineated by the start and stop of the menstrual cycle. The first menstrual period usually occurs around 12 or 13 years of age, an event that is known as **menarche.** There is considerable variation among individuals in the age of menarche. It may occasionally occur as early as eight years of age or as late as 16 years of age and still be considered normal. The average age is generally later in the developing world, and earlier in the developed world. This variation is thought to be largely attributable to nutritional differences.

The cessation of menstrual cycles at the end of a woman's reproductive years is termed **menopause.** The average age of menopause is 52 years, but it may occur normally at any age between about 45 and 55 years of age. The age of menopause varies due to a variety of biological and environmental factors. It may occur earlier as a result of certain illnesses or medical treatments.

### VARIATION IN THE MENSTRUAL CYCLE

The length of the menstrual cycle — as well as its phases — may vary considerably, not only among different individuals but also from month to month for a given person. The average length of time between the first day of one menstrual period and the first day of the next menstrual period is 28 days, but it may range from 21 days to 45 days. Cycles are considered regular when a woman's longest and shortest cycles differ by less than eight days. The menstrual period itself is usually about five days long, but it may vary in length from about two days to seven days.

## OVARIAN CYCLE

The events of the menstrual cycle that take place in the ovaries make up the **ovarian cycle.** It consists of changes that occur in the follicles of one of the ovaries. The ovarian cycle is divided into the following three phases: the follicular phase, ovulation, and luteal phase. These phases are illustrated in Figure **15.7.2**.

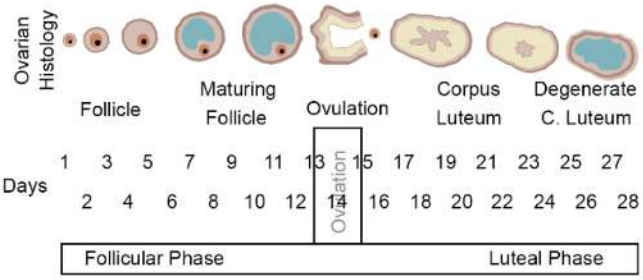



Figure **15.7.2**: The diagram shows the maturation of follicles in the ovary, ovulation, and formation of corpus luteum during follicular and luteal phases of ovaries. The phases and days of the ovarian cycle are shown in this diagram. The ovarian cycle depicted in the diagram represents a cycle in which fertilization does not occur so the corpus luteum degenerates during the luteal phase.

## FOLLICULAR PHASE

The **follicular phase** is the first phase of the ovarian cycle. It generally lasts about 12 to 14 days for a 28-day menstrual cycle. During this phase, several ovarian follicles are stimulated to begin maturing, but usually only one — called the Graafian follicle — matures completely so it is ready to release an egg. The other maturing follicles stop growing and disintegrate. Follicular development occurs because of a rise in the blood level of follicle-stimulating hormone (FSH), which is secreted by the pituitary gland. The maturing follicle releases estrogen, the level of which rises throughout the follicular phase. You can see these and other changes in hormone levels that occur during the menstrual cycle in the chart in Figure 15.7.3.

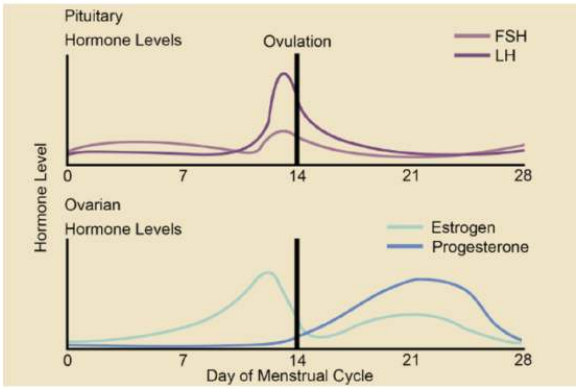



Figure 15.7.3: Pituitary and ovarian hormone levels. FSH in the pituitary and estrogen in the ovaries increase during the first half of the menstrual cycle. LH in the pituitary surges shortly before ovulation occurs due to the rise in estrogen in the ovaries. After ovulation, the level of progesterone and estrogen increases in ovaries due to the formation of the corpus luteum if pregnancy does not occur.

## OVULATION

**Ovulation** is the second phase of the ovarian cycle. It usually occurs around day 14 of a 28-day menstrual cycle. During this phase, the Graafian follicle ruptures and releases its egg. Ovulation is stimulated by a sudden rise in the blood level of luteinizing hormone (LH) from the pituitary gland. This is called the LH surge. You can see the LH surge in the top hormone graph above. The LH surge generally starts around day 12 of the cycle and lasts for a day or two. The surge in LH is triggered by a continued rise in estrogen from the maturing follicle in the ovary. During the follicular phase, the rising estrogen level actually suppresses LH secretion by the pituitary. However, by the time the follicular phase is nearing its end, the level of estrogen reaches a threshold level above which this effect is reversed, and estrogen stimulates the release of a large amount of LH. The surge in LH matures the egg and weakens the wall of the follicle, causing the fully developed follicle to release its secondary oocyte.

## LUTEAL PHASE

The **luteal phase** is the third and final phase of the ovarian cycle. It typically lasts about 14 days in a 28-day menstrual cycle. At the beginning of the luteal phase, FSH and LH cause the Graafian follicle that ovulated the egg to transform into a structure called a corpus luteum. The corpus luteum secretes progesterone, which in turn suppresses FSH and LH production by the pituitary and stimulates the continued buildup of the endometrium in the uterus. How this phase ends depends on whether or not the egg has been fertilized.

- If fertilization has not occurred, the falling levels of FSH and LH during the luteal phase cause the corpus luteum to atrophy, so its production of progesterone declines. Without a high level of progesterone to maintain it, the endometrium starts to break down. By the end of the luteal phase, the endometrium can no longer be maintained, and the next menstrual cycle begins with the shedding of the endometrium (menses).
- If fertilization has occurred so a zygote forms and then divides to become a blastocyst, the outer layer of the blastocyst produces a hormone called human chorionic gonadotropin. This hormone is very similar to LH and preserves the corpus luteum. The corpus luteum can then continue to secrete progesterone to maintain the new pregnancy.

## UTERINE CYCLE

The events of the menstrual cycle that take place in the uterus make up the **uterine cycle**. This cycle consists of changes that occur mainly in the endometrium, which is the layer of tissue that lines the uterus. The uterine cycle is divided into the following three phases: menstruation, proliferative phase, and secretory phase. These phases are illustrated in Figure 15.7.4.

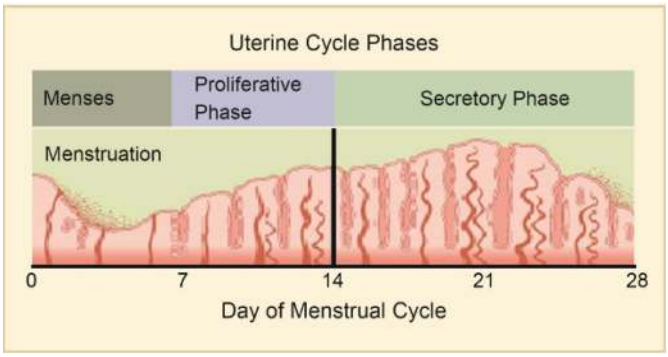



Figure 15.7.4: The uterine cycle begins with menstruation, which starts on day 1 of the cycle. The proliferative phase ranges from day 7 to 14. The secretory phase laster for the second half of the uterine cycle.

## MENSTRUATION

**Menstruation** (also called the menstrual period or menses) is the first phase of the uterine cycle. It occurs if fertilization has not taken place during the preceding menstrual cycle. During menstruation, the endometrium of the uterus, which has built up during the preceding cycle, degenerates and is shed from the uterus. The average loss of blood during menstruation is about 35 mL. The flow of blood is often accompanied by uterine cramps, which may be severe in some people.

## PROLIFERATIVE PHASE

The **proliferative phase** is the second phase of the uterine cycle. During this phase, estrogen secreted by cells of the maturing ovarian follicle causes the lining of the uterus to grow, or proliferate. Estrogen also stimulates the cervix of the uterus to secrete larger amounts of thinner mucus that can help sperm swim through the cervix and into the uterus, making fertilization more likely.

## SECRETORY PHASE

The **secretory phase** is the third and final phase of the uterine cycle. During this phase, progesterone produced by the corpus luteum in the ovary stimulates further changes in the endometrium so it is more receptive to implantation of a blastocyst. For example, progesterone increases blood flow to the uterus and promotes uterine secretions. It also decreases the contractility of smooth muscle tissue in the uterine wall.

### MY BODY: MENSTRUATORS, NOT MENSTRUATING WOMEN

Within the field of critical menstruation studies, we must pay attention to our depictions of menstruation and menstruators, and the knowledge we produce in the pursuit to de-stigmatize menstruation. Not all women menstruate, for example, trans women, postmenopausal women, pregnant women, and those experiencing amenorrhea, and not all who menstruate are women, for example, transmen. Experiences of menstruating later in life vary among menstruators as well. Some do not suffer from their periods in direct relation to their gender identity. Others do, as they disidentify with the body as a whole and/or with certain body parts such as the genitalia or the uterus, or with the bodily function of menstruation. This suffering is sometimes related to gender dysphoria. Testosterone treatments are a method adopted by some trans menstruators to get rid of unwanted bleeding. Preventing the menstrual period is not necessarily the main reason for using testosterone, but it can be one among several desired outcomes. Menstruators *are* of a variety of gender identities (far beyond those who identify as trans) and, hence, menstruation cannot be equated singularly with cis/womanhood.

## REVIEW

1. What is the menstrual cycle?
2. Why is the menstrual cycle necessary in order for pregnancy to occur?
3. What organs are involved in the menstrual cycle? What hormones control the cycle?
4. Identify the two major events that mark the beginning and end of the reproductive period in females. When do these events typically occur?
5. Discuss the average length of the menstrual cycle and menstruation, as well as variations that are considered normal.
6. Define the ovarian cycle.
7. Summarize the phases of the ovarian cycle.
8. Compare and contrast events that occur in the ovaries and uterus, depending on whether or not an egg is fertilized during the menstrual cycle.
9. Define the uterine cycle.
10. Give an overview of the phases of the uterine cycle.
11. If the LH surge did not occur in a menstrual cycle, what do you think would happen? Explain your answer.
12. Give one reason why FSH and LH levels drop in the luteal phase of the menstrual cycle.
13. What does the follicle that housed the ovulated egg become in the luteal phase of the menstrual cycle?
14. *True or False:* Day 1 of the menstrual cycle is when the secondary oocyte is released from its follicle.
15. *True or False:* The secretory phase of the uterine cycle generally aligns with the luteal phase of the ovarian cycle.

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# 15.8: FUNCTIONS OF THE FEMALE REPRODUCTIVE SYSTEM

## WAITING EXPECTANTLY

A mother-to-be waits patiently for her fetus to grow as her belly swells. Reproduction is all about making babies, and the female reproductive system is specialized for this purpose. Its functions include producing gametes called eggs, secreting sex hormones (such as estrogen), providing a site for fertilization, gestating a fetus if fertilization occurs, giving birth to a baby, and breastfeeding a baby after birth. The only thing missing is sperm.



Figure **15.8.1**: Pregnant woman

## EGG PRODUCTION

At birth, ovaries contain all the eggs that will ever be produced, which may include a million or more eggs. The eggs don't start to mature, however, until a female enters puberty and attains sexual maturity. After that, one egg typically matures each month and is released from an ovary. This continues until menopause (cessation of monthly periods), typically by age 52. By then, viable eggs may be almost depleted, and hormone levels can no longer support the monthly cycle. During the reproductive years, which of the two ovaries releases an egg in a given month seems to be a matter of chance. Occasionally, both ovaries will release an egg at the same time. If both eggs are fertilized, the offspring are fraternal twins (dizygotic, or "two-zygote," twins), and they are no more alike genetically than non-twin siblings.

### OOGENESIS

The process of producing eggs in the ovaries of a fetus carrying XX chromosomes is called **oogenesis.** Eggs are haploid gametes, and their production occurs in several steps that involve different types of cells, as summarized in Figure **15.8.2**. Oogenesis is completed long before birth. It occurs when diploid germ cells called **oogonia** (singular, oogonium) undergo mitosis. Each such cell division produces two diploid cells. One is called the primary oocyte, and the other is retained to help maintain a reserve of oogonia. The primary oocyte, in turn, starts to go through the first cell division of meiosis (meiosis I). However, it does not complete meiosis I until puberty.

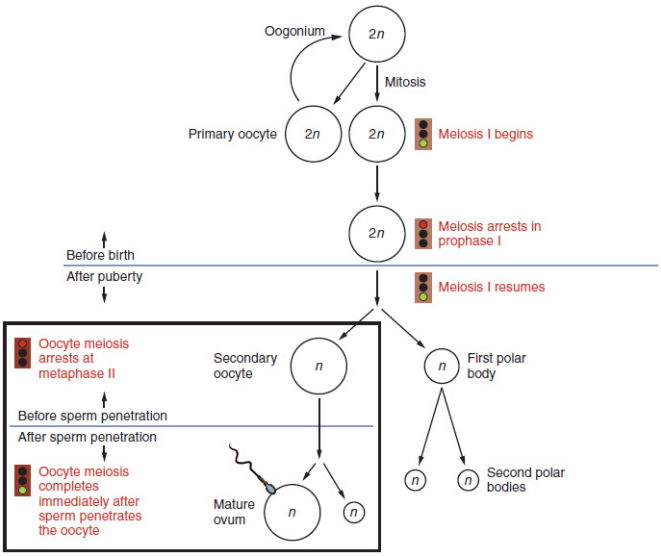



Figure **15.8.2**: Formation of a secondary oocyte that may become a zygote begins with the mitosis of an oogonium. Two meiotic cell divisions follow this. The first polar body does not undergo the second meiotic division in humans. The secondary oocyte completes meiosis II after the penetration of sperm.

### MATURATION OF A FOLLICLE

Beginning in puberty, about once a month, one of the follicles in an ovary undergoes maturation, and an egg is released. As the follicle matures, it goes through changes in the numbers and types of its cells. The primary oocyte within the follicle also resumes meiosis. It completes meiosis I, which began long before birth, to form a secondary oocyte and a smaller cell, called the first polar body. Both the secondary oocyte and the first polar body are haploid cells. The secondary oocyte has most of the cytoplasm from the primary oocyte and is much larger than the first polar body, which soon disintegrates and disappears. The secondary oocyte begins meiosis II, but only completes it if the egg is fertilized.

### RELEASE OF AN EGG

It typically takes 12 to 14 days for a follicle to mature in an ovary and for the secondary oocyte to form. Then, the follicle bursts open and the ovary ruptures, releasing the secondary oocyte from the ovary. This event is called **ovulation.** The now-empty follicle starts to change into a structure called a **corpus luteum.** The expelled secondary oocyte is usually swept into the nearby Fallopian tube by its waving, fingerlike fimbriae.

### UTERINE CHANGES

While the follicle matures in the ovary, the uterus also changes to prepare it for an embryo if fertilization occurs. For example, the endometrium gets thicker and becomes more vascular. Around ovulation, the cervix undergoes changes that help sperm reach the oocyte to fertilize it. The cervical canal widens, and the cervical

mucus becomes thinner and more alkaline. These changes help promote the passage of sperm from the vagina into the uterus and make the environment more hospitable to sperm.

## FERTILIZATION — OR NOT

Fertilization of an egg by a sperm normally occurs in a Fallopian tube, most often in the part of the tube that passes above the ovary (Figure **15.8.3**). In order for fertilization to occur, sperm must "swim" from the vagina where they are deposited, through the cervical canal to the uterus and then through the body of the uterus to one of the Fallopian tubes. Once sperm enter a Fallopian tube, tubular fluids help carry them through the tube toward the secondary oocyte at the other end. The secondary oocyte also functions to promote fertilization. It releases molecules that guide the sperm and allow the surface of the egg to attach to the surface of the sperm. The egg can then absorb the sperm, allowing fertilization to occur.

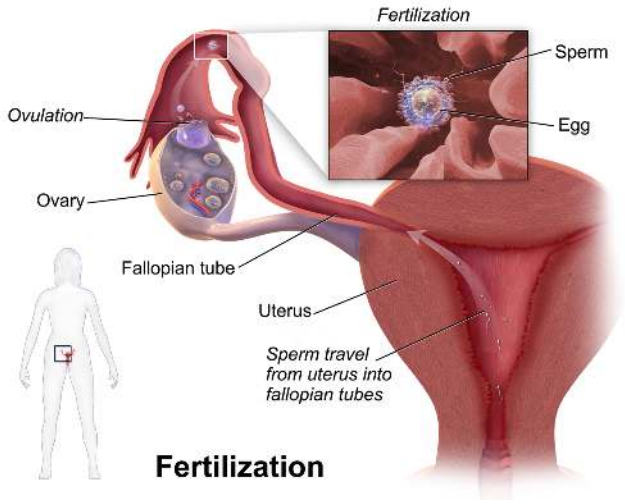



Figure **15.8.3**: The Fimbriae of the fallopian tube sweep the egg into the fallopian tube. Sperm travels through the cervix and uterus and enters the fallopian tube, fertilizing the egg. The embryo, then, travels towards the uterus.

### IF FERTILIZATION OCCURS

If the secondary oocyte is fertilized by a sperm as it passes through the Fallopian tube, the secondary oocyte quickly completes meiosis II, forming a diploid zygote and another polar body. (This second polar body, like the first, normally breaks down and disappears.) The zygote then continues the journey through the fallopian tube to the uterus, during which it undergoes several mitotic cell divisions. When it reaches the uterus, up to five days after fertilization, it consists of a ball of cells called a blastocyst. Within another day or two, the blastocyst implants itself in the endometrium lining the uterus, and gestation begins.

### IF FERTILIZATION DOES NOT OCCUR

What happens if the secondary oocyte is not fertilized by a sperm as it passes through the Fallopian tube? It continues on its way to the uterus without ever completing meiosis II. It is likely to disintegrate within a few days while still in the Fallopian tube. Any remaining material will be shed from the woman's body during the next menstrual period.

## PREGNANCY

**Pregnancy** is the carrying of one or more offspring from fertilization until birth. This is one of the major functions of the female reproductive system. It involves virtually every other body system, including the cardiovascular, urinary, and respiratory systems, to name just three. The maternal organism plays a critical role in the development of the offspring. They must provide all the nutrients and other substances needed for the normal growth and development of the offspring and remove the wastes excreted by the offspring. Most nutrients are needed in greater amounts by a pregnant individual to meet fetal needs, but some are especially important, including folic acid, calcium, iron, and omega-3 fatty acids. A healthy diet and prenatal vitamin supplements are recommended for the best pregnancy outcome. A pregnant person should also avoid ingesting substances (such as alcohol) that can damage the developing offspring, especially early in the pregnancy when all of the major organs and organ systems are forming.

When counted from the first day of the last menstrual period, the average duration of pregnancy is about 40 weeks (38 weeks when counted from the time of fertilization). However, a pregnancy that lasts between 37 and 42 weeks is still considered within the normal range. From the point of view of the maternal organism, the total duration of pregnancy is typically divided into three periods, called **trimesters,** each of which lasts about three months. This division of the total period of gestation is useful for summarizing the typical changes during pregnancy. From the point of view of the developing offspring, however, the major divisions are different. They are the embryonic and fetal stages. The offspring is called an embryo from the time it implants in the uterus through the first eight weeks of life. After that, it is called a fetus for the duration of the pregnancy.

### FIRST TRIMESTER

The first trimester begins at the time of fertilization and lasts for the next 12 weeks. Even before a pregnant person knows they are pregnant, they may experience signs and symptoms of pregnancy. They may notice a missed menstrual period, and they may also experience a tender nipple area, increased appetite, and more frequent urination. Many individuals also experience nausea and vomiting in the first trimester. This is often called "morning sickness" because it commonly occurs in the morning but may occur at any time of day. Some lose weight during the first trimester because of morning sickness.

### SECOND TRIMESTER

The second trimester occurs during weeks 13 to 28 of pregnancy. A pregnant person may feel more energized during this trimester. If she experienced nausea and vomiting during the first trimester, these symptoms often subside during the second trimester. Weight gain starts occurring during this trimester, as well. By about week 20, the fetus is getting large enough that the mother can feel its movements. The photo on the left in Figure **15.8.4** shows a pregnant woman at

week 26, toward the end of the second trimester. (For comparison, the same woman is shown on the right of Figure **15.8.4** at the end of the third trimester.)

### THIRD TRIMESTER

The third trimester occurs during weeks 29 through birth (at about 40 weeks). During this trimester, the uterus expands rapidly, making up a larger and larger portion of the woman's abdomen. Weight gain is also more rapid. During the third trimester, the movements of the fetus become stronger and more frequent, and they may become disruptive to the mother. As the fetus grows larger, its weight and the space it takes up may lead to symptoms in the mother such as back pain, swelling of the lower extremities, more frequent urination, varicose veins, and heartburn. By the end of the third trimester, the woman's abdomen often will transform in shape as it drops, due to the fetus turning to a downward position before birth so its head rests on the cervix. This relieves pressure on the upper abdomen, but reduces bladder capacity and increases pressure on the pelvic floor and rectum.



Figure **15.8.4**: The same woman is shown in both photos: on the left at week 26 of the pregnancy, and on the right at week 40 of the pregnancy

## CHILDBIRTH

Near the time of birth, the amniotic sac — a fluid-filled membrane that encloses the fetus within the uterus — breaks in a gush of fluid. This is commonly called “breaking water.” Labor usually begins within a day of this event, although it may begin prior to it. **Labor** is the general term for the process of childbirth in which regular uterine contractions push the fetus and placenta out of the body. Labor can be divided into three stages, which are illustrated in Figure **15.8.5**: dilation, birth, and after birth.

1. During the dilation stage of labor, uterine contractions begin and become increasingly frequent and intense. The contractions push the baby’s head (most often) against the cervix, causing the cervical canal to dilate, or become wider. This lasts until the cervical canal has dilated to about 10 cm (3.9 in.) in width, which may take 12 to 20 hours — or even longer. The cervical canal must be dilated to this extent in order for the baby’s head to fit through it.
2. During birth, the baby descends (usually headfirst) through the cervical canal and vagina, and into the world outside. This is the stage when the mother generally starts bearing down during the contractions to help push out the fetus. The fetus exits the vagina with its face facing the mother's posterior. It takes a 90-degree turn as the shoulders are delivered. This stage may last from about 20 minutes to two hours or more. Usually, within a minute or less of birth, the umbilical cord is cut, so the baby is no longer connected to the placenta.
3. During the afterbirth stage, the placenta is delivered. This stage may last from a few minutes to a half hour.

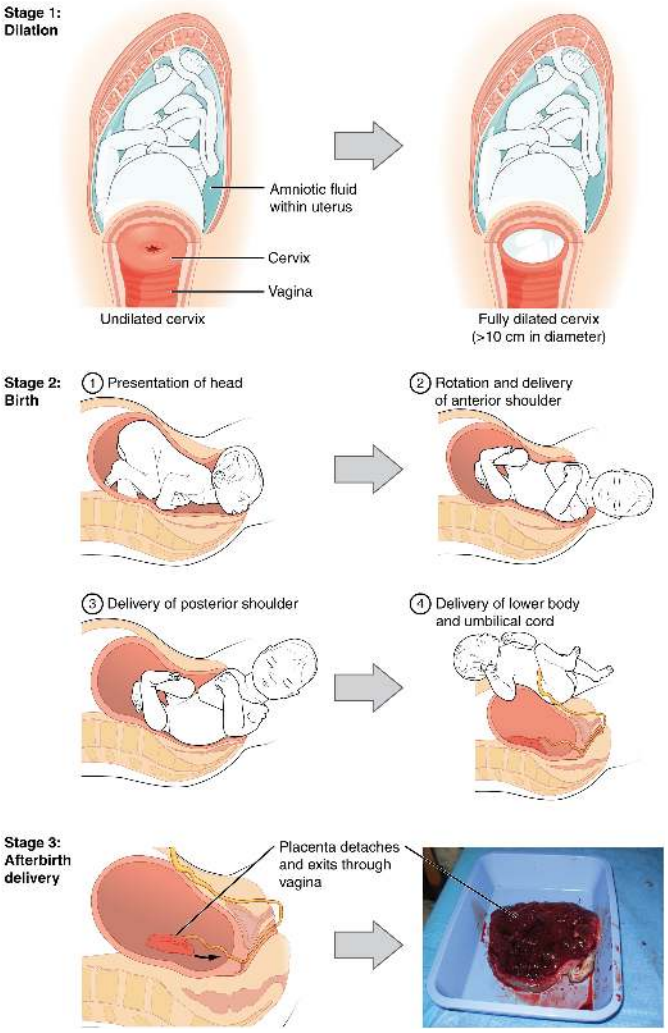



Figure **15.8.5**: The three stages of labor are dilation of the cervix, the birth of the baby, and the delivery of the afterbirth (placenta)

Delivery is a matter of concern for all individuals. However, additional concerns arise for individuals with disabilities. According to a study done by Lipson and Rogers, delivery decisions for disabled individuals are made arbitrarily without their consent. They are forced to deliver via cesarean section because they think that a disabled person wouldn't be able to handle the process.

### FEATURE: MYTH VS. REALITY

There are many myths associated with pregnancy. Most are harmless, but some may put the pregnant woman or fetus at risk. As always, knowledge is power.

**Myth:** You should avoid petting your cat during pregnancy.

**Reality:** Cat feces may be contaminated with microscopic parasites that can cause a disease called toxoplasmosis. Pregnant women who contract this disease are at risk of stillbirth, miscarriage, or giving birth to an infant with serious health problems. Pregnant women should not have contact with a cat's litter box or feces, but petting a cat poses no real risk of infection.

**Myth:** You should not dye your hair during pregnancy, because the chemicals can harm the fetus.

**Reality:** Whereas some chemicals (such as certain pesticides) have been shown to be associated with birth defects, there is no evidence that using hair dye during pregnancy increases this risk.

**Myth:** A pregnant woman needs to eat for two, so she should double her pre-pregnancy caloric intake.

**Reality:** Throughout a typical pregnancy, a person needs only about 300 extra calories per day, on average, to support her growing fetus. Most of the extra calories are needed during the last trimester when the fetus is growing most rapidly. Doubling her caloric intake during pregnancy is likely to cause too much weight gain, which can be detrimental to her baby. Babies that weigh much more than the average 7.5 pounds at birth are more likely to develop diabetes and obesity in later life.

**Myth:** Women who are pregnant have strange food cravings, such as ice cream with pickles.

**Reality:** Some women do have food cravings during pregnancy, but they are not necessarily cravings for strange foods or unusual food combinations. For example, a pregnant woman might crave starchy foods for a few weeks, or she may be put off by certain foods that she loved before pregnancy.

**Myth:** A pregnant woman has skin that glows.

**Reality:** Pregnancy can actually be hard on the skin and its appearance. Besides stretch marks on the abdomen and breasts, pregnancy may lead to spider veins, varicose veins, new freckles, darkening of moles, and acne flare-ups. In addition, as many as 75 percent of pregnant women experience chloasma, which is the emergence of blotchy brown patches of skin on the face due to high estrogen levels. Chloasma is often referred to as the "mask of pregnancy."

**Myth:** Men cannot carry a baby.

**Reality:** Transgender men can get pregnant using alternative methods.

## REVIEW

1. What is oogenesis? How does it occur?
2. Describe the maturation of an ovarian follicle.
3. Define ovulation.
4. What is happening in the uterus while a follicle in the ovary is maturing?
5. After a secondary oocyte is ovulated from the ovary, it may or may not be fertilized. Contrast what happens next in each of these different outcomes.
6. What is pregnancy, and what is the role of the maternal organism in pregnancy?
7. What is the average duration of pregnancy? Identify the trimesters of pregnancy.
8. Define labor. What event is often a sign that labor will soon begin?
9. Identify the stages of labor.
10. Describe the physiological function of female breasts. How is this function controlled?
11. Identify the functions of the female sex hormones estrogen and progesterone.
12. *True or False:* All of the developing gametes in an ovary complete meiosis I at the time of puberty.
13. *True or False:* After fertilization, meiosis II is completed, and then mitosis occurs.
14. A fertilized egg that has not yet implanted in the uterus is called a(n) _____.

A. embryo

B. zygote

C. fetus

D. secondary oocyte

15. Describe the roles of the cervix in fertilization and childbirth.

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# 15.9: DISORDERS OF THE FEMALE REPRODUCTIVE SYSTEM

## VACCINATING AGAINST CANCER

Can a vaccine prevent cancer? In the case of cervical cancer, it *can*. Cervical cancer is one of three disorders of the female reproductive system described in detail in this concept. Of the three, only cervical cancer can be prevented with a vaccine.



Figure **15.9.1**: Getting a vaccine

## CERVICAL CANCER

**Cervical cancer** occurs when cells of the cervix (neck of the uterus) grow abnormally and develop the ability to invade nearby tissues or spread to other parts of the body, such as the abdomen or lungs. Figure **15.9.2** shows the location of the cervix and the appearance of normal and abnormal cervical cells when examined with a microscope.

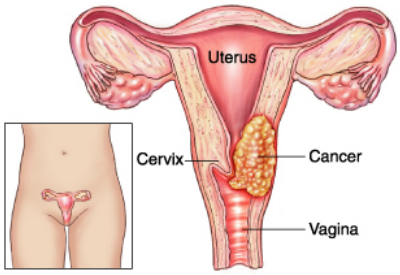



Figure **15.9.2**: Cancer of the cervix

### CERVICAL CANCER PREVALENCE AND DEATH RATES

Worldwide, cervical cancer is the second most common type of cancer (after breast cancer) and the fourth most common cause of cancer death. In the United States and other high-income nations, the widespread use of cervical cancer screening has detected many cases of precancerous cervical changes and has dramatically reduced rates of cervical cancer deaths. About three-quarters of cervical cancer cases occur in developing countries, where routine screening is less likely because of cost and other factors. Cervical cancer is also the most common cause of cancer death in low-income countries.

### SYMPTOMS OF CERVICAL CANCER

Early in the development of cervical cancer, there are typically no symptoms. As the disease progresses, however, symptoms are likely to occur. The symptoms may include abnormal vaginal bleeding, pelvic pain, or pain during sexual intercourse. Unfortunately, by the time symptoms start to occur, cervical cancer has typically progressed to a stage at which treatment is less likely to be successful.

### CERVICAL CANCER CAUSES AND RISK FACTORS

More than 90 percent of cases of cervical cancer are caused at least in part by human papillomavirus **(HPV)**, which is a sexually transmitted virus that also causes genital warts. HPV infection can cause cervical cancer by interfering with a normal cell division. When HPV is not present, cervical cells containing mutations are not allowed to divide, so the cervix remains healthy. When HPV is present, however, cervical cells with mutations may be allowed to divide, leading to uncontrolled growth of mutated cells and the formation of a tumor.

Other risk factors for cervical cancer include smoking, a weakened immune system (for example, due to HIV infection), use of birth control pills, becoming sexually active at a young age, and having many sexual partners. However, these risk factors are less important than HPV infection. Instead, the risk factors are more likely to increase the risk of cervical cancer in individuals who are *already* infected with HPV. For example, among HPV-infected, current and former smokers have roughly two to three times the incidence of cervical cancer as non-smokers. Passive smoking is also associated with an increased risk of cervical cancer but to a lesser extent.

### DIAGNOSIS OF CERVICAL CANCER

Diagnosis of cervical cancer is typically made by looking for microscopic abnormal cervical cells in a smear of cells scraped off the cervix. This is called a **Pap smear.** If cancerous cells are detected or suspected in the smear, this test is usually followed up with a biopsy to confirm the Pap smear results. Medical imaging (by CT scan or MRI, for example) is also likely to be done to provide more information, such as whether the cancer has spread.

### PREVENTION OF CERVICAL CANCER

It is now possible to prevent HPV infection with a vaccine. The first HPV vaccine was approved by the U.S. Food and Drug Administration in 2006. The vaccine protects against the strains of HPV that have the greatest risk of causing cervical cancer. It is thought that widespread use of the vaccine will prevent up to 90 percent of cervical cancer cases. Current recommendations are to be given the vaccine between the ages of nine and 26. (All sexes should be vaccinated against HPV, because the virus may also cause cancer of the penis and certain other cancers.) The vaccine is effective only if it is given *before* HPV infection has occurred. Using condoms during sexual intercourse can also help prevent HPV infection and cervical cancer, in addition to preventing pregnancy and sexually transmitted infections (such as HIV).

Even for those who have received the HPV vaccine, there is still a small risk of developing cervical cancer. Therefore, it is

recommended that individuals with cervix continue to be examined with regular Pap smears.

### TREATMENT OF CERVICAL CANCER

Treatment of cervical cancer generally depends on the stage at which the cancer is diagnosed, but it is likely to include some combination of surgery, radiation therapy, and/or chemotherapy. Outcomes of treatment depend largely on how early the cancer is diagnosed and treated. For surgery to cure cervical cancer, the entire tumor must be removed with no cancerous cells found at the margins of the removed tissue on microscopic examination. If cancer is found and treated very early when it is still in the microscopic stage, the five-year survival rate is virtually 100 percent.

## VAGINITIS

**Vaginitis** is inflammation of the vagina — and sometimes the vulva, as well. Symptoms may include a discharge that is yellow, gray, or green; itching; pain; and a burning sensation. There may also be a foul vaginal odor and pain or irritation with sexual intercourse.



Figure **15.9.3**: The yeast *Candida albicans* — shown here growing on a culture plate — is one of the most common causes of vaginitis.

### CAUSES OF VAGINITIS

About 90 percent of cases of vaginitis are caused by infection with microorganisms. Most commonly, vaginal infections are caused by the yeast *Candida albicans* (Figure **15.9.3**). Such infections are referred to as vaginal **candidiasis.** Other possible causes of vaginal infections include bacteria, especially *Gardnerella vaginalis*, and some single-celled parasites, notably the protist parasite *Trichomonas vaginalis*, which is usually transmitted through vaginal intercourse. The risk of vaginal infections may be greater in those who wear tight clothing, are taking antibiotics for another condition, use birth control pills, or have improper hygiene. Poor hygiene allows organisms that are normally present in the stool (such as yeast) to contaminate the vagina. Most of the remaining cases of vaginitis are due to irritation by — or allergic reactions to — various products. These irritants may include condoms, spermicides, soaps, douches, lubricants, and even semen. Using tampons or soaking in hot tubs may be additional causes of this type of vaginitis.

### DIAGNOSIS OF VAGINITIS

Diagnosis of vaginitis typically begins with symptoms reported by the patient. This may be followed by a microscopic examination or culture of the vaginal discharge in order to identify the specific cause. The color, consistency, acidity, and other characteristics of the discharge may be predictive of the causative agent. For example, infection with *Candida albicans* may cause a cottage cheese-like discharge with a low pH, whereas infection with *Gardnerella vaginalis* may cause a discharge with a fish-like odor and a high pH.

### PREVENTION OF VAGINITIS

Prevention of vaginitis includes wearing loose cotton underwear that helps keep the vulva dry. Yeasts and bacteria that may cause vaginitis tend to grow best in a moist environment. It is also important to avoid the use of perfumed soaps, personal hygiene sprays, and douches, all of which may upset the normal pH and bacterial balance in the vagina. To help avoid vaginitis caused by infection with *Trichomonas vaginalis*, the use of condoms during sexual intercourse is advised.

### TREATMENT OF VAGINITIS

The appropriate treatment of vaginitis depends on the cause. In many cases of vaginitis, there is more than one cause, and all of the causes must be treated to ensure a cure.

- Yeast infections of the vagina are typically treated with topical anti-fungal medications, which are available over the counter. The medications may be in the form of tablets or creams that are inserted into the vagina. Depending on the particular medication used, treatment may involve one, three, or seven days of application.
- Bacterial infections of the vagina are usually treated with antibiotics. These may be taken orally as pills or applied topically to the vagina in creams.
- *Trichomonas vaginalis* infections of the vagina are generally treated with a single dose of an oral antibiotic. Sexual partners should be treated at the same time, and intercourse should be avoided for at least a week until both partners have completed treatment and been followed up by a physician.

## ENDOMETRIOSIS

**Endometriosis** is a disease in which endometrial tissue, which normally grows inside the uterus, grows outside of the uterus (Figure **15.9.4**). Most often, the endometrial tissue grows around the ovaries, Fallopian tubes, and uterus. In rare instances, the tissue may grow elsewhere in the body. The areas of endometriosis typically bleed each month during the menstrual period, and this often results in inflammation, pain, and scarring. An estimated six to ten percent of individuals with a uterus are believed to have endometriosis. It is most common in their thirties and forties, and only rarely occurs before menarche or after menopause.

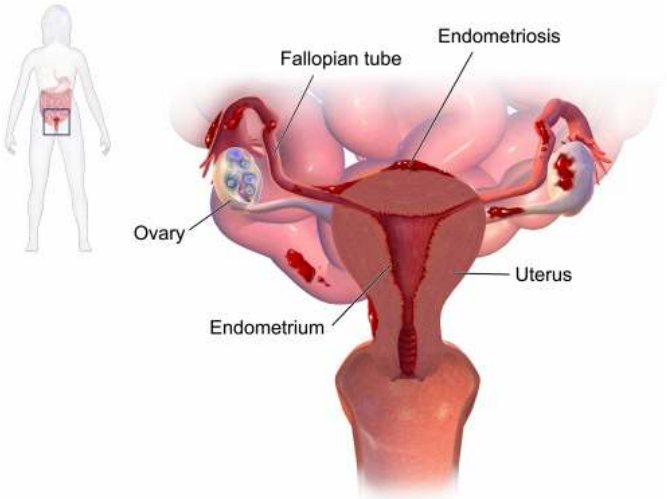



Figure 15.9.4: In endometriosis, endometrial tissue may grow outside the uterus and cause health problems such as pain, bleeding, scarring, and infertility. Here the endometrial tissue is growing in the fallopian tubes, ovaries, and on the outside of the fallopian tube and uterus.

## SIGNS AND SYMPTOMS OF ENDOMETRIOSIS

The main symptom of endometriosis is pelvic pain, which may range from mild to severe. There appears to be little or no relationship between the amount of endometrial tissue growing outside the uterus and the severity of the pain. For many with the disease, the pain occurs mainly during menstruation. However, nearly half of those affected have chronic pelvic pain. The pain of endometriosis may be caused by bleeding in the pelvis, which triggers inflammation. Pain can also occur from internal scar tissue that binds internal organs to each other.

Another problem often associated with endometriosis is infertility, or the inability to conceive or bear children. Among patients with endometriosis, up to half may experience infertility. Infertility can be related to scar formation or to anatomical distortions due to abnormal endometrial tissue. Other possible symptoms of endometriosis may include diarrhea or constipation, chronic fatigue, nausea and vomiting, headaches, and heavy or irregular menstrual bleeding.

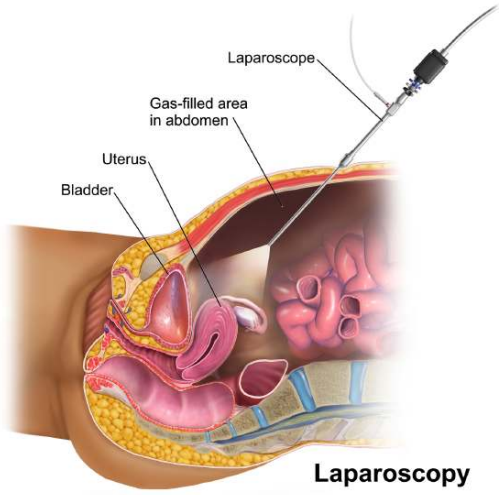



Figure 15.9.5: Laparoscopy: visually inspecting the abdomen for endometrial growth is the most reliable way to diagnose endometriosis. the camera is inserted through the abdominal wall.

## CAUSES OF ENDOMETRIOSIS

The causes of endometriosis are not known for certain, but several risk factors have been identified, including a family history of endometriosis. People who have a genetic relationship with a person with endometriosis have about six times the normal risk of developing the disease themselves. It has been suggested that endometriosis results from mutations in several genes. It is likely that endometriosis is multifactorial, involving the interplay of several factors.

At the physiological level, the predominant idea for how endometriosis comes about is retrograde menstruation. This happens when some of the endometrial debris from a menstrual flow exits the uterus through the Fallopian tubes, rather than through the vagina. The debris then attaches itself to the outside of organs in the abdominal cavity, or to the lining of the abdominal cavity itself. Retrograde menstruation, however, does not explain all cases of endometriosis, so other factors are apparently involved. Suggestions include environmental toxins and autoimmune responses.

## DIAGNOSIS OF ENDOMETRIOSIS

Diagnosis of endometriosis is usually based on self-reported symptoms and a physical examination by a doctor, often combined with medical imaging, such as ultrasonography. The only way to definitively diagnose endometriosis, however, is through visual inspection of the endometrial tissue. This can be done with a surgical procedure called **laparoscopy**, in which a tiny camera is inserted into the abdomen through a small incision (Figure 15.9.5). The camera allows the physician to visually inspect the area where endometrial tissue is suspected.

## TREATMENT OF ENDOMETRIOSIS

The most common treatments for endometriosis are medications to control the pain, and surgery to remove the abnormal tissue. Frequently used pain medications are non-steroidal inflammatory drugs (NSAIDS), such as naproxen. Opiates may be used in cases of

severe pain. Laparoscopy can be used to surgically treat endometriosis, as well as to diagnose the condition. In this type of surgery, an additional small incision is made to insert instruments that the surgeon can manipulate externally in order to burn (cauterize) or cut away the endometrial growths. In younger patients who want to have children, surgery is conservative to keep the reproductive organs intact and functional. However, with conservative surgery, endometriosis recurs in 20 to 40 percent of cases within five years of the surgery. In older patients who have completed childbearing, hysterectomy may be undertaken to remove all or part of the internal reproductive organs. This is the only procedure that is likely to cure endometriosis and prevent relapses.

### FEATURE: MY HUMAN BODY

A Pap smear is a method of cervical cancer screening used to detect potentially pre-cancerous and cancerous cells in the cervix. It is the most widely used screening test for this type of cancer, and it is very effective. The test may also detect vaginal infections and abnormal endometrial cells, but it is not designed for these purposes.

If you are sexually active, you should start receiving routine Pap smears by age 21. Because most cases of cervical cancer are caused by infection with human papillomavirus (HPV), which is a sexually transmitted infection, there is little or no benefit to screening people who have not had vaginal intercourse. Starting at age 21, general guidelines are for Pap smears to be repeated every three years until age 50, and then every five years until age 65. Screening may be discontinued after age 65 if the last three Pap smears were normal. If a person has a complete hysterectomy so they no longer have a cervix, there is also no need for further Pap smears. On the other hand, if a person has had a history of abnormal Pap smears or cancer, they will likely be screened more frequently. Pap smears can be done safely during the first several months of pregnancy and resumed about three months after childbirth. Generally, better results are obtained if Pap smears are not done during menstruation.

If you've never had a Pap smear, knowing what to expect may help prepare you for the procedure. The patient lies on the examining table with their feet in "stirrups" to hold the legs up and apart. An instrument called a speculum is inserted into the vagina to hold back the vaginal walls and give access to the cervix. A tiny amount of tissue is brushed off the cervix and smeared onto a microscope slide. The speculum is then removed, and the procedure is over. The slide is later examined under a microscope for abnormal cells. Some people experience light spotting or mild diarrhea after a Pap smear, but most have no lasting effects.

Pap smears are uncomfortable and may be somewhat painful for some people. there may also be a pelvic exam where doctors insert their fingers into the vagina during the Pap smear test. If you experience pain during a Pap smear, tell your health care provider. Many steps can be taken to minimize the pain, which might include using a smaller speculum, using warm instruments and a lubricant, and applying a topical anesthetic such as lidocaine to the cervix before obtaining the smear. Any pain is generally very brief, and the potential reward is worth it. Pap tests are estimated to reduce up to 80 percent of cervical cancer deaths. One of the lives saved could be your own.

## REVIEW

1. What is cervical cancer? Worldwide, how prevalent is it, and how does it rank as a cause of cancer deaths?
2. Identify the symptoms of cervical cancer.
3. What are the causes of — and risk factors for — cervical cancer?
4. What roles can Pap smears and HPV vaccines play in preventing cervical cancer cases and cervical cancer deaths?
5. How is cervical cancer treated?
6. Define vaginitis and identify its symptoms.
7. What are some of the causes of vaginitis? Which cause is responsible for most of the cases?
8. How is vaginitis diagnosed and treated?
9. What is endometriosis, and what are its symptoms?
10. Discuss possible causes of endometriosis.
11. How is endometriosis treated? Which treatment is most likely to prevent the recurrence of the disorder?
12. Which disorder below is the most likely to cause symptoms, specifically during menstruation?

    A. endometriosis
    B. cervical cancer
    C. HPV infection
    D. vaginitis

13. *True or False:* Yeast infections are normally treated with antibiotics.
14. *True or False:* In the absence of HPV, there are no mutated cells in the cervix.
15. In the case of infection with *Trichomonas vaginalis*, why is the woman's sexual partner usually treated at the same time?

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# 15.10: INFERTILITY

## FAMILY PORTRAIT

This family portrait in Figure **15.10.1** shows that human societies value having children. Indeed, for most people, parenthood is an important life goal. Unfortunately, some people are unable to achieve that goal because of infertility.



Figure **15.10.1**: Family portrait

## WHAT IS INFERTILITY?

**Infertility** is the inability of a sexually mature adult to reproduce by natural means. For scientific and medical purposes, infertility is generally defined as the failure to achieve a successful pregnancy after at least one year of regular, unprotected sexual intercourse. Infertility may be primary or secondary. Primary infertility applies to cases in which an individual has never achieved a successful pregnancy. Secondary infertility applies to cases in which an individual has had at least one successful pregnancy, but fails to achieve another after trying for at least a year. Infertility is a common problem. About ten percent (6.1 million) of U.S. women aged 15 to 44 have difficulty getting or staying pregnant.

## CAUSES OF INFERTILITY

Pregnancy is the result of a multi-step process. In order for a normal pregnancy to occur, an egg must be released from one of the ovaries, the egg must go through a Fallopian tube, a sperm must fertilize the egg as it passes through the Fallopian tube, and then the fertilized egg must implant in the uterus. If there is a problem with any of these steps, infertility can result.

### CAUSES OF MALE INFERTILITY

Male infertility occurs when there are no or too few sperms, or when the sperms are not healthy and motile and cannot travel through the female reproductive tract to fertilize an egg. A common cause of inadequate numbers or motility of sperm is varicocele, which is an enlargement of blood vessels in the scrotum. This may raise the temperature of the testes and adversely affect sperm production. In other cases, there is no problem with the sperm, but there is a blockage in the male reproductive tract that prevents the sperm from being ejaculated.

Factors that increase a man's risk of infertility include heavy alcohol use, drug abuse, cigarette smoking, exposure to environmental toxins (such as pesticides or lead), certain medications, serious diseases (such as kidney disease), and radiation or chemotherapy for cancer. Another risk factor is advancing age. Male fertility normally peaks in the mid-twenties and gradually declines after about age 40, although it may never actually drop to zero.

### CAUSES OF FEMALE INFERTILITY

Female infertility generally occurs due to one of two problems: failure to produce viable eggs by the ovaries, or structural problems in the Fallopian tubes or uterus. The most common cause of female infertility is a problem with ovulation. Without ovulation, there are no eggs to be fertilized. Anovulatory cycles (menstrual cycles in which ovulation does not occur) may be associated with no or irregular menstrual periods, but even regular menstrual periods may be anovulatory for a variety of reasons. The most common cause of anovulatory cycles is polycystic ovary syndrome (PCOS), which causes hormone imbalances that can interfere with normal ovulation. Another relatively common cause of anovulation is primary ovarian insufficiency. In this condition, the ovaries stop working normally and producing viable eggs at a relatively early age, generally before the age of 40.

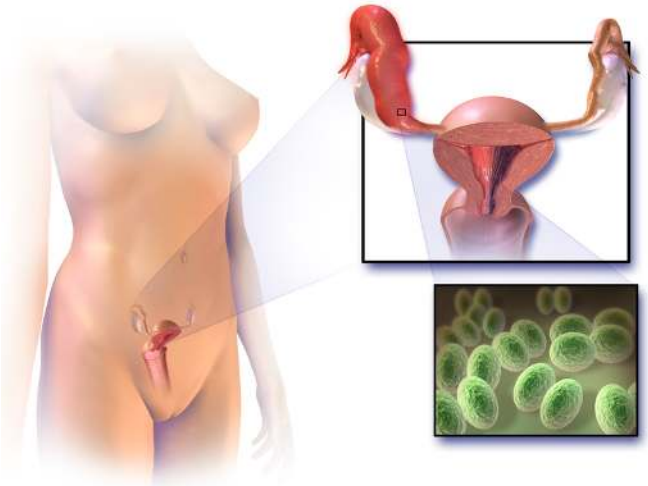


Figure **15.10.2**: An infection of the Fallopian tubes may cause scarring and blockage of the tubes, so sperm cannot reach eggs for fertilization.

Structural problems with the Fallopian tubes or uterus are less common causes of infertility. The Fallopian tubes may be blocked as a result of endometriosis. Another possible cause is a pelvic inflammatory disease, which occurs when sexually transmitted

infections spread to the Fallopian tubes or other female reproductive organs (Figure **15.10.2**). The infection may lead to scarring and blockage of the Fallopian tubes. If an egg is produced and the Fallopian tubes are functioning — and a woman has a condition such as uterine fibroids — implantation in the uterus may not be possible. Uterine fibroids are non-cancerous clumps of tissue and muscle that form on the walls of the uterus.

Factors that increase a woman's risk of infertility include tobacco smoking, excessive use of alcohol, stress, poor diet, strenuous athletic training, and being overweight or underweight. Advanced age is even more problematic for females than males. Female fertility normally peaks in the mid-twenties, and continuously declines after age 30 and until menopause around the age of 52, after which the ovary no longer releases eggs. About one-third of couples in which the woman is over age 35 have fertility problems. In older women, more cycles are likely to be anovulatory, and the eggs may not be as healthy.

### DIAGNOSING CAUSES OF INFERTILITY

Diagnosing the cause(s) of a couple's infertility often requires testing both partners for potential problems. The semen is likely to be examined for the number, shape, and motility of sperm. If problems are found with sperm, further studies are likely to be done, such as medical imaging to look for structural problems with the testes or ducts.

In individuals with ovaries and uterus, the first step is most often determining whether ovulation is occurring. This can be done at home by carefully monitoring body temperature (it rises slightly around the time of ovulation) or using a home ovulation test kit, which is available over the counter at most drugstores. Whether or not ovulation is occurring can also be detected with blood tests or ultrasound imaging of the ovaries. If ovulation is occurring normally, then the next step may be an X-ray of the Fallopian tubes and uterus to see if there are any blockages or other structural problems. Another approach to examining the reproductive tract for potential problems is laparoscopy. In this surgical procedure, a tiny camera is inserted into the abdomen through a small incision. This allows the doctor to directly inspect the reproductive organs.

## TREATING INFERTILITY

Infertility often can be treated successfully. The type of treatment depends on the cause of infertility.

### TREATING MALE INFERTILITY

Medical problems that interfere with sperm production may be treated with medications or other interventions that may lead to the resumption of normal sperm production. If, for example, if an infection is interfering with sperm production, antibiotics may resolve the problem. If there is a blockage in the ejaculation of sperm, surgery may be able to remove the blockage. Alternatively, the sperm may be removed from his body and then used for the artificial insemination of their partner. In this procedure, the sperms are injected into the uterus.

### TREATING FEMALE INFERTILITY

It is possible to correct blocked Fallopian tubes or uterine fibroids with surgery. Ovulation problems, on the other hand, are usually treated with hormones that act either on the pituitary gland or on the ovaries. Hormonal treatments that stimulate ovulation often result in more than one egg being ovulated at a time, thus increasing the chances of a person conceiving with twins, triplets, or even higher multiple births. Multiple fetuses are at greater risk of being born too early or having health and developmental problems. The mother is also at greater risk of complications arising during pregnancy. Therefore, the possibility of multiple fetuses should be weighed in making a decision about this type of infertility treatment.

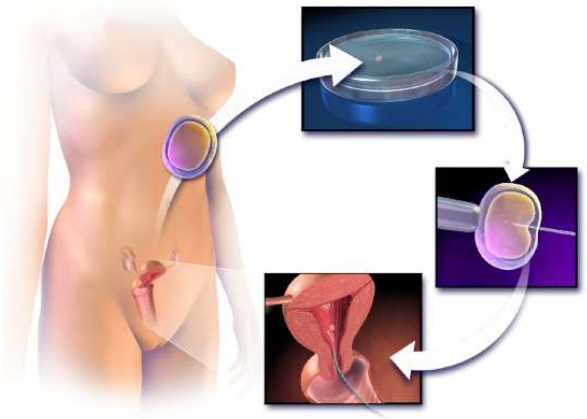


Figure **15.10.3**: This figure shows one way ART procedures may be used to treat infertility. An egg is removed from the female reproductive tract, injected with sperm from her partner, and allowed to develop into an embryo in the lab. Then, the embryo is placed inside the woman's uterus for implantation and development during the remainder of gestation.

### ASSISTED REPRODUCTIVE TECHNOLOGY

Some cases of infertility are treated with **assisted reproductive technology (ART)**. This is a collection of medical procedures in which eggs and sperms are removed to be manipulated in ways that increase the chances of fertilization occurring. The eggs and sperm may be injected into one of the Fallopian tubes for fertilization to take place *in vivo* (in the body). More commonly, however, the eggs and sperm are mixed together outside the body so fertilization takes place *in vitro* (in a test tube or dish in a lab). The latter approach is illustrated in Figure **15.10.3**. With *in vitro* fertilization, the fertilized eggs may be allowed to develop into embryos before being placed in the woman's uterus.

ART has about a 40 percent chance of leading to a live birth in women under the age of 35, but only about a 20 percent chance of success after the age of 35. Some studies have found a higher-than-average risk of birth defects in children produced by ART procedures, but this may be due to the generally higher ages of the parent — not the technologies used. Same-sex couples take advantage of the ART process to expand their family.

## OTHER APPROACHES

Other approaches for certain causes of infertility and same-sex couples include the use of a surrogate mother, a gestational carrier, or sperm donation.

- A **surrogate mother** is a woman who agrees to become pregnant using the man's sperm and her own egg. The child, who will be the biological offspring of the surrogate and the male partner, is given up at birth for adoption by the couple. Surrogacy might be selected by women with no eggs or unhealthy eggs. A woman who carries a mutant gene for a serious genetic disorder might choose this option to ensure that the defective gene is not passed on to the offspring.
- A **gestational carrier** is a woman who agrees to receive a transplanted embryo from a couple and carry it to term. The child, who will be the biological offspring of the couple, is given to the parents at birth. A gestational carrier might be used by women who have normal ovulation but no uterus, or who cannot safely carry a fetus to term because of a serious health problem (such as kidney disease or cancer). This method is commonly used by gay men couples.
- **Sperm donation** is the use of sperm from a fertile man (generally through artificial insemination) for cases in which the male partner in a couple is infertile, or in which a woman seeks to become pregnant without a male partner. A lesbian couple may use donated sperm to enable one of them to become pregnant and have a child. Sperm can be obtained from a sperm bank, which buys and stores sperm for artificial insemination, or a male friend or another individual may donate sperm to a specific woman.

### FEATURE: HUMAN BIOLOGY IN THE NEWS

More than 14 million people in the United States have polycystic ovary syndrome (PCOS), an endocrine disorder with a genetic basis that is the most common cause of infertility. Most patients with PCOS grow many small cysts on their ovaries. The cysts are not usually harmful, but they lead to hormone imbalances, such as higher-than-normal levels of testosterone in affected individuals. The hormonal imbalances are the primary cause of infertility associated with PCOS. The disorder also increases the risk of a whole slew of other serious health problems, including endometrial cancer, heart disease, high blood pressure, type 2 diabetes, asthma, obesity, depression, and anxiety.

Despite the prevalence of PCOS and its serious potential effects, until recently, its cause was poorly understood. There were also no effective early diagnostic or treatment strategies for it. All that appears to be changing now. A review of the research literature on PCOS published in 2016 provides new insights into causes, diagnosis, and treatment for the disorder.

Among the research cited in the review is promising new work on nonhuman animal models, including monkeys and mice. One line of research suggests that PCOS may be programmed into a fetus during the second trimester of pregnancy. Another line of research indicates that hair taken from an infant can be analyzed for early risk factors for PCOS, even though PCOS symptoms do not show up until puberty. In addition, the research is helping scientists identify a constellation of genes that are suspected to play a role in PCOS.

The new research on PCOS is important for those who suffer from the disorder and its consequences, including infertility and life-threatening chronic conditions (such as heart disease and diabetes). The hope is that such research will lead to new ways of diagnosing PCOS at an early age, when medical interventions and lifestyle choices may be used to head off the more serious complications. It is likely that the research will also eventually lead to new and more effective treatment options for the millions of people who battle PCOS.

## REVIEW

1. What is infertility? How is infertility defined scientifically and medically?
2. What percentage of infertility in couples is due to male infertility? What percentage is due to female infertility?
3. Identify causes of and risk factors for male infertility.
4. Identify causes of and risk factors for female infertility.
5. How are the causes of infertility in couples diagnosed?
6. How is infertility treated?
7. Discuss some of the social and ethical issues associated with infertility or its treatment.
8. Why is infertility an under-appreciated problem in developing countries?
9. Describe two similarities between the causes of male and female infertility.
10. *True or False:* A person who already has a biological child can suffer from infertility.
11. *True or False:* ART always involves fertilization outside of the body.
12. Explain the difference between males and females in terms of how age affects fertility.
13. If a woman has no viable eggs, which method below is the most likely to help her and her partner have a baby?

    A. gestational carrier
    B. surrogate mother
    C. *in vitro* fertilization
    D. *in vivo* fertilization

14. Do you think that taking medication to stimulate ovulation is likely to improve fertility in cases where infertility is due to endometriosis? Explain your answer.
15. If a semen sample shows no sperm, what is a possible cause?

    A. blockage in the male reproductive tract
    B. lack of spermatogenesis
    C. PCOS
    D. A and B

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## ATTRIBUTIONS


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# 15.11: CONTRACEPTION

## FAMILY PLANNING PIONEER

Her name was Marie Stopes, and she was a British author and paleobotanist who lived from 1880 to 1958. She is pictured here in her lab next to her microscope. Stopes made significant contributions to science and was the first woman on the faculty of the University of Manchester in England. Her primary claim to fame was her work as a family planning pioneer.



Figure **15.11.1**: Marie Stopes in her laboratory in 1904

Along with her husband, Stopes founded the first birth control clinic in Britain. She also edited a newsletter called *Birth Control News*, which gave explicit practical advice on how to avoid unwanted pregnancies. In 1918, she published a sex manual titled *Married Love. The book was* controversial and influential, bringing the subject of contraception into wide public discourse for the first time.

## TYPES OF CONTRACEPTION AND THEIR EFFECTIVENESS

Types of birth control methods include barrier methods, hormonal methods, intrauterine devices, behavioral methods, and sterilization. With the exception of sterilization, all of these methods are reversible. Examples of each type of birth control method and their failure rates with typical use are described below.

### BARRIER METHODS

**Barrier methods** are devices that are used to physically block sperm from entering the uterus. They include condoms and diaphragms. Eighteen out of 100 individuals who use this method may get pregnant.

#### *CONDOMS*

**Condoms** are the most commonly used method of birth control globally. There are condoms for vaginas and penises, but penis condoms are more widely used, less expensive, and more readily available. Both types of condoms are pictured in Figure **15.11.2**.

## WHAT IS CONTRACEPTION?

About a century after *Married Love*, more than half of all fertile married couples worldwide use some form of contraception. **Contraception,** also known as birth control, is any method or device used to prevent pregnancy. Birth control methods have been used for centuries, but safe and effective methods only became available in the 20th century, in part because of the work of people like Marie Stopes.

Many different birth control methods are currently available, but they differ considerably in their effectiveness at preventing pregnancy. The effectiveness of contraception is generally expressed as the failure rate, which is the percentage of women who become pregnant using a given method during the first year of use. Virtually no one uses any method of birth control perfectly, so the failure rate with typical use is almost always higher — and often much higher — than the failure rate *with* perfect use. For example, with perfect use, a birth control method might have a failure rate of just one percent, whereas, with typical use, the failure rate might be 25 percent. For comparison, there is an average one-year pregnancy rate of 85 percent if no contraception is used.

All methods of birth control have potential adverse effects, but their health risks are less than the health risks associated with pregnancy. Using contraception to space the children in a family is also good for the children's health and development, as well as for the health of the mother.

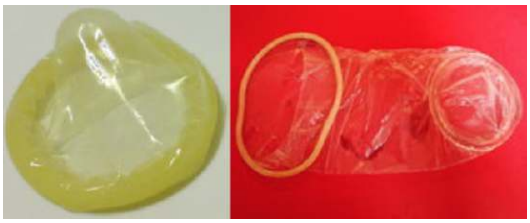


Figure **15.11.2**: (left) Rolled up penis condom. (right) An unrolled vagina condom

Whichever type of condom is used, it must be put in place before sexual intercourse occurs. Condoms work by physically blocking ejaculated sperm from entering the vagina of the sexual partner. With typical use, penis condoms have an 18 percent failure rate, and vagina condoms have a 21 percent failure rate. Unlike virtually all other birth control methods, condoms also help prevent the spread of sexually transmitted infections (STIs), in addition to helping to prevent pregnancy.

#### *DIAPHRAGMS*

**Diaphragms**, like the one in Figure **15.11.3**, ideally prevent sperm from passing through the cervical canal and into the uterus. A diaphragm is inserted vaginally before sexual intercourse occurs and must be placed over the cervix to be effective. It is usually recommended that a diaphragm be covered with spermicide before insertion for extra protection. It is also recommended that the diaphragm be left in place for at least six hours after intercourse. The

failure rate of diaphragms with typical use is about 12 percent, which is about half that of condoms. However, diaphragms do not help prevent the spread of STIs, and their use is also associated with an increased frequency of urinary tract infections.



Figure 15.11.3: A diaphragm is pictured here beside a U.S. quarter coin for size comparison. The diaphragm should fit snugly over the cervix so it blocks sperm from entering the cervical canal.

## HORMONAL METHODS

**Hormonal contraception** is the administration of hormones to prevent ovulation. Hormones can be taken orally in birth control pills, implanted under the skin, injected into a muscle, or received transdermally from a skin patch. Six to twelve pregnancies in hundred individuals who use this method may occur.

Hormonal methods are currently available only for individuals with uterus and ovaries. Birth control pills are the most common form of hormonal contraception. There are two types of pills: the combined pill (which contains both estrogen and progesterone) and the progesterone-only pill. Both types of pills inhibit ovulation and thicken cervical mucus. The failure rate of birth control pills is only about one percent or less if used perfectly. However, the failure rate rises to about ten percent with typical use, because individuals do not always remember to take the pill at the same time every day. The combined pill is associated with a slightly increased risk of blood clots, but a reduced risk of ovarian and endometrial cancers. The progesterone-only pill does not increase the risk of blood clots, but it may cause irregular menstrual periods. It may take a few weeks or even months for fertility to return to normal after the long-term use of birth control pills.

## INTRAUTERINE DEVICES

An **intrauterine device (IUD)** is a T-shaped or coiled plastic structure that is inserted into the uterus via the vagina and cervix that contains either copper or a hormone. You can see an IUD in the uterus in the drawing in Figure 15.11.4. An IUD is inserted by a physician and may be left in place for months or even years. A physician also must remove an IUD, using the strings attached to the device. The copper in copper IUDs prevents pregnancy by interfering with the movement of sperm so they cannot reach and fertilize an egg. The copper may also prevent implantation in the unlikely circumstance of a sperm managing to reach and fertilize an egg. Almost no one gets pregnant who uses this method.

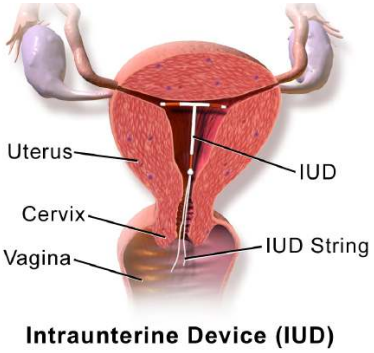



Figure 15.11.4: An IUD is a T-shaped structure. two ends of the IUD block the openings of the two fallopian tubes and the third end contains IUD string that hangs out of the cervix into the vagina.

The hormones in hormonal IUDs prevent pregnancy by thickening cervical mucus and trapping sperm. The hormones may also interfere with ovulation, so there is no egg to fertilize. For both types of IUDs, the failure rates are less than one percent, and failure rates with typical use are virtually the same as failure rates with perfect use. Their effectiveness is one reason that IUDs are among the most widely used forms of reversible contraception. Once removed, even after long-term use, fertility returns to normal immediately. On the other hand, IUDs do have a risk of complications, including increased menstrual bleeding and more painful menstrual cramps. IUDs are also occasionally expelled from the uterus, and there is a slight risk of perforation of the uterus by the IUD.

## BEHAVIORAL METHODS

The least effective methods of contraception are behavioral methods. They involve regulating the timing or method of intercourse to prevent the introduction of sperm into the uterus, either altogether or when an egg may be present. Behavioral methods include fertility awareness methods and withdrawal. Abstinence from sexual activity, or at least from vaginal intercourse, is sometimes considered a behavioral method, as well — but it is unlikely to be practiced consistently enough by most people to prevent pregnancy. Even teens who receive abstinence-only sex education do not have reduced rates of pregnancy. Abstinence is also ineffective in cases of non-consensual sex.

## FERTILITY AWARENESS METHODS

**Fertility awareness methods** involve estimating the most fertile days of the menstrual cycle and then avoiding unprotected vaginal intercourse on those days. The most fertile days are generally a few days before ovulation occurs, the day of ovulation, and another day or two after that. Unless unprotected sex occurs on those days, pregnancy is unlikely. Techniques for estimating the most fertile days include monitoring and detecting minor changes in basal body temperature or cervical secretions. This requires daily motivation and diligence, so it is not surprising that typical-use failure rates of these methods are at least 20 to 25 percent, and for some individuals may be as high as using no contraception at all (85 percent).

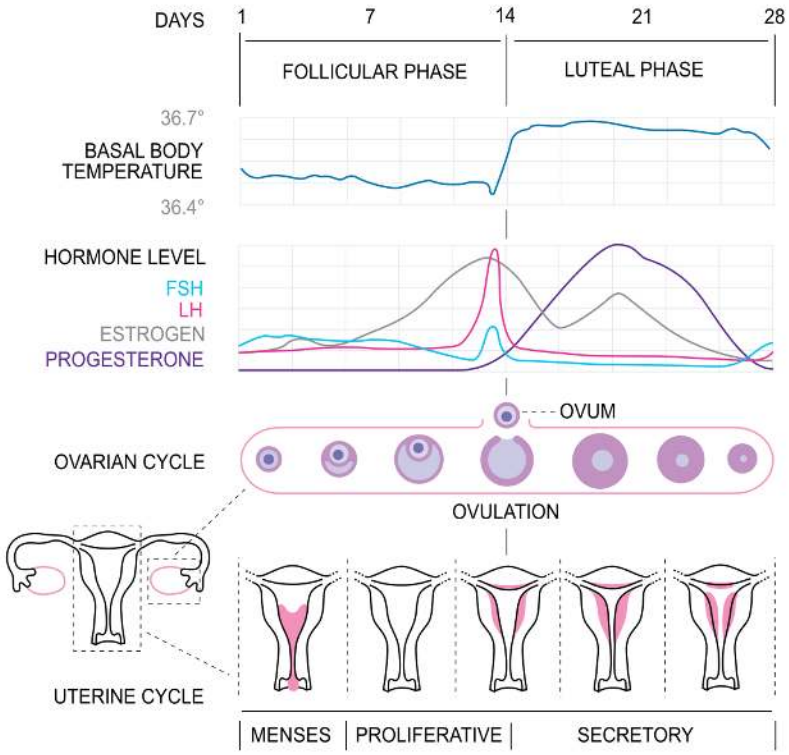



Figure **15.11.5**: A woman's basal body temperature rises slightly when ovulation occurs and stays slightly elevated until the start of the next menstrual period. The follicular phase of the ovaries lasts from day 1 to 14 of the menstrual cycle. After ovulation, the luteal phase lasts from day 14 to day 28. During ovulation, the levels of follicle stimulating, luteinizing, and estrogen hormones increase. The level of progesterone increases after ovulation that builds and prepares the endometrium for implantation.

Basal body temperature is the lowest body temperature when the body is at rest (usually during sleep). It is most often estimated by a temperature measurement taken immediately upon awakening in the morning and before any physical activity has occurred. Basal body temperature normally rises after ovulation occurs, as shown in Figure **15.11.5**. The increase in temperature is small but consistent and may be used to determine when ovulation occurs, around which time unprotected intercourse should be avoided to prevent pregnancy. However, basal body temperature only shows when ovulation has already occurred, and it cannot predict in advance when ovulation will occur. Sperm can live for up to a week in the female reproductive tract, so determining the occurrence of ovulation only after the fact is a major drawback of this method.

Monitoring cervical mucus has the potential for being more effective than monitoring basal body temperature because it can predict ovulation ahead of time. As ovulation approaches, cervical secretions usually increase in the amount and become thinner (which helps sperm swim through the cervical canal). By recognizing the changing characteristics of cervical mucus, ovulation timing can be predicted. From this information, it can be determined when to avoid unprotected sex to prevent pregnancy.

### WITHDRAWAL

**Withdrawal** (also called coitus interruptus) is the practice of withdrawing the penis from the vagina before ejaculation occurs. The main risk of the withdrawal method is that penis is not withdrawn in a timely manner. The fluid typically released from the penis before ejaculation occurs may also contain some sperm. In addition, if sperms are ejaculated just outside of the vagina, there is a chance they will be able to enter the vagina and travel up to fertilize an egg. For all these reasons, the withdrawal method has a relatively high failure rate of about 22 percent with typical use.

## STERILIZATION

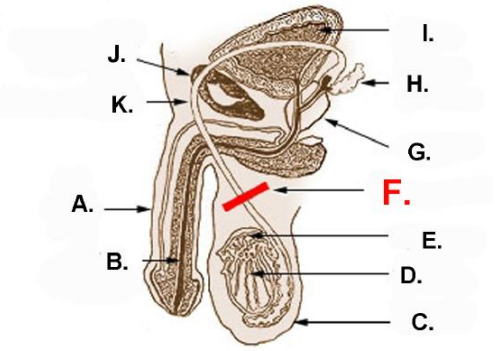



Figure **15.11.6**: The red line (F in the upper portion of the scrotum) shows where each vas deferens (K) is clamped or cut in a vasectomy. The other structures are A. penis, B. urethra, C. scrotum, D. testis, E. epididymis, G. prostate, H. seminal vesicle, I. bladder, J. pubic bone

The most effective contraceptive method is **sterilization.** In both sexes, sterilization generally involves surgical procedures that are considered irreversible. Additional surgery may be able to reverse a sterilization procedure, but there are no guarantees. Male

sterilization is generally less invasive and less risky than female sterilization.

### MALE STERILIZATION

Male sterilization is usually achieved with a **vasectomy**. In this surgery, the vas deferens from each testis is clamped, cut, or otherwise sealed (Figure **15.11.6**). This prevents sperm from traveling from the epididymis to the ejaculatory ducts and being ejaculated from the penis. The same amount of semen will still be ejaculated, but it will not contain any sperm, making fertilization impossible. After a vasectomy, the testes continue to produce sperm, but the sperms are reabsorbed. It usually takes several months after a vasectomy for all remaining sperm to be ejaculated or reabsorbed. In the meantime, another method of birth control should be used.

### FEMALE STERILIZATION

The procedure undertaken for female sterilization is usually **tubal ligation.** The Fallopian tubes may be tied or cut in a surgical procedure, which permanently blocks the tubes. Alternatively, tiny metal implants may be inserted into the Fallopian tubes in a nonsurgical procedure. Over time, scar tissue grows around the implants and permanently blocks the tubes. Either method stops eggs from traveling from the ovaries through the Fallopian tubes, where fertilization usually takes place.

## EMERGENCY CONTRACEPTION

**Emergency contraception** is any form of contraception that is used after unprotected vaginal intercourse. One method is the so-called “morning-after” pill. This is essentially a high-dose birth control pill that helps prevent pregnancy by temporarily preventing ovulation. It works only if ovulation has not already occurred, and when taken within five days after unprotected sex. The sooner the pill is taken, the more likely it is to work. Another method of emergency contraception is the IUD. An IUD that is inserted up to five days after unprotected sex can prevent nearly 100 percent of pregnancies. It keeps sperm from reaching and fertilizing an egg or inhibits implantation if an egg has already been fertilized. The IUD can then be left in place to prevent future pregnancies.

## REVIEW

1. Define contraception. Globally, how prevalent is the use of contraception by fertile married couples?
2. How is the effectiveness of contraceptive methods typically measured?
3. List five different types of birth control methods. Which (if any) methods are reversible? Which (if any) methods can prevent the spread of sexually transmitted infections, as well as pregnancies?
4. What are barrier methods? Give two examples.
5. Describe hormonal contraception. What is the most commonly used form of hormonal contraception?
6. What is an IUD?
7. Generally, describe behavioral methods of contraception, and identify two specific behavioral methods.
8. Discuss sterilization as a birth control method. How is sterilization typically achieved in males? In females?
9. What is emergency contraception? When is it used? What are the two forms of emergency contraception?
10. How does the thickness of cervical mucus relate to fertility? How do two methods of contraception take advantage of this relationship?
11. Arrange the following methods of contraception in order of typical effectiveness, from the least effective to most effective: *birth control pill; fertility awareness method; IUD; male condom*
12. If a newly developed method of contraception had a 35 percent failure rate, would you consider this to be an effective method? Explain your answer.
13. Which method of contraception prevents ovulation?\
    A. female condom
    B. tubal ligation
    C. birth control pill
    D. fertility awareness method
14. *True or False:* A vasectomy prevents the production of sperm.
15. *True or False:* If a man and woman have unprotected intercourse four days before ovulation occurs, the woman cannot get pregnant.

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5. Intrauterine Device (IUD) by Blausen.com staff (2014). "Medical gallery of Blausen Medical 2014". WikiJournal of Medicine 1 (2). DOI:10.15347/wjm/2014.010. ISSN 2002-4436. CC BY 3.0 via Wikimedia Commons
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# 15.12: CASE STUDY CONCLUSION- TRYING TO CONCEIVE AND CHAPTER SUMMARY

## CASE STUDY CONCLUSION: TRYING TO CONCEIVE

The person in Figure **15.12.1** is holding a home pregnancy test. The two pink lines in the middle are the type of result that Isabella and Omar are desperately hoping to see themselves one day—a positive pregnancy test. At the beginning of the chapter, you learned that Isabella and Omar have been actively trying to get pregnant for a year, which, as you now know, is the timeframe necessary for infertility to be diagnosed.



Figure **15.12.1**: Pregnancy test

Isabella and Omar tried having sexual intercourse on day 14 of her menstrual cycle to optimize their chances of having his sperm meet her egg. Why might this not be successful, even if they do *not* have fertility problems? As you have learned, although the average menstrual cycle is 28 days, with ovulation occurring around day 14, many women vary widely from these averages (either consistently or variably) from month to month. Recall, for example, that menstrual cycles may vary from 21 to 45 days in length, and a woman's cycle is considered to be regular if it varies within as many as eight days from shortest to longest cycle. This variability means that ovulation often does not occur on or around day 14, particularly if the woman has significantly shorter, longer, or irregular cycles—as Isabella does. Therefore, by aiming for day 14 without knowing when Isabella is actually ovulating, they may not be successful in helping Omar's sperm encounter Isabella's egg.

Lack of ovulation entirely can also cause variability in menstrual cycle length. As you have learned, the regulation of the menstrual cycle depends on an interplay of hormones from the pituitary and ovary, including FSH and LH from the pituitary and estrogen and progesterone from the ovary—specifically from the follicle which surrounds the maturing egg and becomes the corpus luteum after ovulation. Shifts in these hormones and processes can affect ovulation and menstrual cycle length. This is why Isabella was concerned about her long and irregular menstrual cycles. If there is a sign that she is not ovulating, that could be the reason why she is having trouble getting pregnant.

In order to get a better idea of whether Isabella is ovulating, Dr. Bashir recommended that she take her basal body temperature (BBT) each morning before getting out of bed, and track it throughout her menstrual cycle. As you have learned, BBT typically rises slightly and stays high after ovulation. While tracking BBT is not a particularly effective form of contraception, since the temperature rise occurs only after ovulation, it can be a good way to see whether a person is ovulating at all. Although not every individual will see a clear shift in BBT after ovulation, it is a relatively easy way to start assessing fertility and is used as part of a more comprehensive fertility assessment by some physicians.

Dr. Bashir also recommended that Isabella use a home ovulation predictor kit. This is another relatively cheap and easy way to assess ovulation. Most ovulation predictor kits work by detecting the hormone LH in urine using test strips, like the ones shown in Figure **15.12.2**. Why can this predict ovulation? Think about what you have learned about how ovulation is triggered. Rising levels of estrogen from the maturing follicle in the ovary causes a surge in the level of LH secreted from the pituitary gland, which triggers ovulation. This surge in LH can be detected by the home kit, which compares the level of LH in urine to that of a control on the strip. After the LH surge is detected, ovulation will typically occur within one to two days.



Figure **15.12.2**: Ovulation test strips. The pink line towards the right in both strips is the control line that is used as a comparison to the test line that detects LH in the woman's urine, located to the left of the control line. In the top strip, the test line is barely visible, indicating that LH levels are low. In the bottom strip, the light pink line on the left indicates that the level of LH is starting to increase. When the test line is equal in intensity to, or darker than, the control line, the LH surge is likely occurring.

By tracking her BBT and using the ovulation predictor kit, Isabella has learned that she is most likely ovulating—but not in every cycle, and sometimes she ovulates much later than day 14. Because frequent anovulatory cycles can be a sign of an underlying hormonal disorder, such as polycystic ovary syndrome (PCOS) or problems with the pituitary or other glands that regulate the reproductive system, Dr. Bashir orders blood tests for Isabella and sets up an appointment for a physical exam.

But because Isabella is sometimes ovulating, the problem may not lie solely with her. Recall that infertility occurs in equal proportions in all sexes, and can be due to problems in both partners. This is why it is generally recommended that both partners get assessed for fertility issues when they are having trouble getting pregnant after a year of trying.

Therefore, Omar proceeds with the semen analysis that Dr. Bashir recommended. In this process, the man provides a semen sample by ejaculating into a cup or special condom, and the semen is then

examined under a microscope. As you have learned, the semen is then checked for sperm number, shape, and motility. Sperm with an abnormal shape or trouble moving will likely have trouble reaching and fertilizing an egg. A low amount of sperm will also reduce the chances of conception. In this way, a semen analysis can provide insight into the possible underlying causes of infertility. For instance, a low sperm count could indicate problems in sperm production or a blockage that is preventing sperm from being emitted from the penis. Further testing would have to be done to dissociate between these two possible causes.

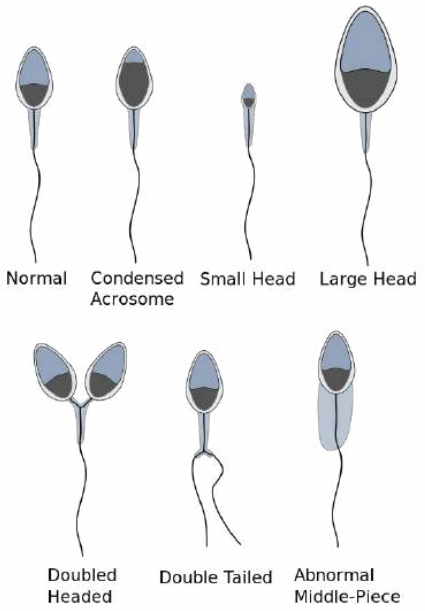



Figure 15.12.3: The image compares normal sperm to malformed sperm

Omar had been worried that past injuries to his testes may have affected his fertility. As you have learned, the testes are where sperm are produced, and because they are external to the body, they are vulnerable to injury. In addition to physical damage to the testes and other parts of the male reproductive tract, a testicular injury could potentially cause the creation of antibodies against a person's own sperm. As you have learned, Sertoli cells lining the seminiferous tubules are tightly packed so that the developing sperm are normally well-separated from the body's immune system. However, in the case of an injury, this barrier can be breached, which can cause the creation of anti-sperm antibodies. These antibodies can hamper fertility by killing the sperm or otherwise interfering with their ability to move or fertilize an egg. When infertility is due to such antibodies, it is called "immune infertility."

However, Omar's semen analysis shows that he has normal numbers of healthy sperm. Dr. Bashir recommends that while they investigate whether Isabella has an underlying medical issue, she continues to track her BBT and use ovulation predictor kits to try to pinpoint when she is ovulating. She recommends that once Isabella sees an LH surge, the couple try to have intercourse within three days to maximize their chances of conception. If Isabella is found to have a medical problem that is inhibiting ovulation, depending on what it is, they may either address the problem directly, or she can take medication that stimulates ovulation, such as clomiphene citrate (often sold under the brand name Clomid). This medication works by increasing the amount of FSH secreted by the pituitary.

Fortunately, tracking ovulation at home and timing intercourse appropriately was all Isabella and Omar needed to do to finally get pregnant! After their experience, they, like you, now have a much deeper understanding of the intricacies of the reproductive system and the complex biology that is involved in the making of a new human organism.

## CHAPTER SUMMARY

In this chapter, you learned about the male and female reproductive systems. Specifically, you learned that:

- The reproductive system is the human organ system responsible for the production and fertilization of gametes and the carrying of a fetus.
- Both male and female reproductive systems have organs called gonads (testes in males, ovaries in females) that produce gametes (sperm or eggs) and sex hormones (such as testosterone and estrogen). Sex hormones are endocrine hormones that control the prenatal development of sex organs, sexual maturation at puberty, and reproduction after puberty.
- The reproductive system is the only organ system that is significantly different between male and female sexes. A Y-chromosome gene called SRY is responsible for undifferentiated embryonic tissues developing into a male reproductive system. Without a Y chromosome, the undifferentiated embryonic tissues develop into a female reproductive system.
- Male and female reproductive systems are different at birth but immature and nonfunctioning. Maturation of the reproductive system occurs during puberty when hormones from the hypothalamus and pituitary gland stimulate the gonads to produce sex hormones again. The sex hormones, in turn, cause the changes of puberty.
- Male reproductive system organs include the testes, epididymis, penis, vas deferens, prostate gland, and seminal vesicles.
    - The two testes are sperm- and testosterone-producing male gonads. They are contained within the scrotum, a pouch that hangs down behind the penis. The testes are filled with hundreds of tiny, tightly coiled seminiferous tubules, where sperm are produced. The tubules contain sperm in different stages of development, as well as Sertoli cells, which secrete substances needed for sperm production. Between the tubules are Leydig cells, which secrete testosterone.
    - The two epididymes are contained within the scrotum. Each epididymis is a tightly coiled tubule where sperms mature and are stored until they leave the body during an ejaculation.
    - The two vas deferens are long, thin tubes that run from the scrotum up into the pelvis. During ejaculation, each vas deferens carries sperm from one of the epididymes to one of the pair of ejaculatory ducts.

- The two seminal vesicles are glands within the pelvis that secrete fluid through ducts into the junction of each vas deferens and ejaculatory duct. This alkaline fluid makes up about 70 percent of semen, the sperm-containing fluid that leaves the penis during ejaculation. Semen contains substances and nutrients that sperm need to survive and "swim" in the female reproductive tract.
- The prostate gland is located just below the seminal vesicles and surrounds the urethra and its junction with the ejaculatory ducts. The prostate secretes an alkaline fluid that makes up close to 30 percent of semen. The prostatic fluid contains a high concentration of zinc, which sperm need to be healthy and motile.
- The ejaculatory ducts form where the vas deferens joins with the ducts of the seminal vesicles in the prostate gland. They connect the vas deferens with the urethra. The ejaculatory ducts carry sperm from the vas deferens whereas the secretions from the seminal vesicles and prostate gland form semen.
- The paired bulbourethral glands are located just below the prostate gland. They secrete a tiny amount of fluid into semen. The secretions help lubricate the urethra and neutralize any acidic urine it may contain.
- The penis is the external male organ that has the reproductive function of intromission, which is delivering sperm to the female reproductive tract. The penis also serves as the organ that excretes urine. The urethra passes through the penis and carries urine or semen out of the body. Internally, the penis consists largely of columns of spongy tissue that can fill with blood and make the penis stiff and erect. This is necessary for sexual intercourse so intromission can occur.

- Parts of a mature sperm include the head, acrosome, midpiece, and flagellum. The process of producing sperm is called spermatogenesis. This normally starts during puberty and continues uninterrupted until death.
  - Spermatogenesis occurs in the seminiferous tubules in the testes and requires high concentrations of testosterone. Sertoli cells in the testes play many roles in spermatogenesis, including concentrating testosterone under the influence of follicle-stimulating hormone (FSH) from the pituitary gland.
  - Spermatogenesis begins with a diploid stem cell called a spermatogonium, which undergoes mitosis to produce a primary spermatocyte. The primary spermatocyte undergoes meiosis I to produce haploid secondary spermatocytes, and these cells in-turn, undergo meiosis II to produce spermatids. After the spermatids grow a tail and undergo other changes, they become sperm.
  - Before sperms are able to "swim," they must mature in the epididymis. The mature sperms are then stored in the epididymis until ejaculation occurs.
- Ejaculation is the process in which semen is propelled by peristalsis in the vas deferens and ejaculatory ducts from the urethra in the penis.
- Leydig cells in the testes secrete testosterone under the control of luteinizing hormone (LH) from the pituitary gland. Testosterone is needed for male sexual development and to maintain normal spermatogenesis after puberty. It also plays a role in the prostatatic function and the ability of the penis to become erect.
- Disorders of the male reproductive system include erectile dysfunction (ED), epididymitis, prostate cancer, and testicular cancer.
  - ED is a disorder characterized by the regular and repeated inability of a sexually mature male to obtain and maintain an erection. ED is a common disorder that occurs when normal blood flow to the penis is disturbed or there are problems with the nervous control of penile engorgement or arousal.
    - Possible physiological causes of ED include aging, illness, drug use, tobacco smoking, and obesity, among others. Possible psychological causes of ED include stress, performance anxiety, and mental disorders.
    - Treatments for ED may include lifestyle changes, such as stopping smoking and adopting a healthier diet and regular exercise. However, the first-line treatment is prescription drugs such as Viagra® or Cialis® that increase blood flow to the penis. Vacuum pumps or penile implants may be used to treat ED if other types of treatment fail.
  - Epididymitis is inflammation of the epididymis. It is a common disorder, especially in young men. It may be acute or chronic and is often caused by a bacterial infection. Treatments may include antibiotics, anti-inflammatory drugs, and painkillers. Treatment is important to prevent the possible spread of infection, permanent damage to the epididymis or testes, and even infertility.
  - Prostate cancer is the most common type of cancer in men and the second leading cause of cancer death in men. If there are symptoms, they typically involve urination, such as frequent or painful urination. Risk factors for prostate cancer include older age, family history, high-meat diet, and sedentary lifestyle, among others.
    - Prostate cancer may be detected by a physical exam or a high level of prostate-specific antigen (PSA) in the blood, but a biopsy is required for a definitive diagnosis. Prostate cancer is typically diagnosed relatively late in life and is usually slow growing, so no treatment may be necessary. In younger patients or those with faster-growing tumors, treatment is likely to include surgery to remove the prostate, followed by chemotherapy and/or radiation therapy.
  - Testicular cancer, or cancer of the testes, is the most common cancer in males between the ages of 20 and 39 years. It is more common in males of European than African ancestry. A lump or swelling in one testis, fluid in the scrotum, and testicular pain or tenderness are possible signs and symptoms of testicular cancer.

    - Testicular cancer can be diagnosed by a physical exam and diagnostic tests, such as ultrasound or blood tests. Testicular cancer has one of the highest cure rates of all cancers. It is typically treated with surgery to remove the affected testis, and this may be followed by radiation therapy, and/or chemotherapy. Normal male reproductive functions are still possible after one testis is removed if the remaining testis is healthy.
- The female reproductive system is made up of internal and external organs that function to produce haploid female gametes called eggs, secrete female sex hormones (such as estrogen), and carry and give birth to a fetus.
- Female reproductive system organs include the ovaries, Fallopian tubes, uterus, vagina, clitoris, and labia.
    - The vagina is an elastic, muscular canal that can accommodate the penis. It is where sperm are usually ejaculated during sexual intercourse. The vagina is also the birth canal, and it channels the flow of menstrual blood from the uterus. A healthy vagina has a balance of symbiotic bacteria and an acidic pH.
    - The uterus is a muscular organ above the vagina where a fetus develops. Its muscular walls contract to push out the fetus during childbirth. The cervix is the neck of the uterus that extends down into the vagina. It contains a canal connecting the vagina and uterus for sperm or an infant to pass through. The innermost layer of the uterus, the endometrium, thickens each month in preparation for an embryo but is shed in the following menstrual period if fertilization does not occur.
    - The Fallopian tubes extend from the uterus to the ovaries. Waving fimbriae at the ovary ends of the Fallopian tubes guide ovulated eggs into the tubes where fertilization may occur as the eggs travel to the uterus. Cilia and peristalsis help eggs move through the tubes. Tubular fluid helps nourish sperm as they swim up the tubes toward eggs.
    - The ovaries are gonads that produce eggs and secrete sex hormones including estrogen. Nests of cells called follicles in the ovarian cortex are the functional units of ovaries. Each follicle surrounds an immature egg. At birth, a baby girl's ovaries contain at least a million eggs, and they will not produce any more during her lifetime. One egg matures and is typically ovulated each month during a woman's reproductive years.
    - The vulva is a general term for external female reproductive organs. The vulva includes the clitoris, two pairs of labia, and openings for the urethra and vagina. Secretions from Bartholin's glands near the vaginal opening lubricate the vulva.
    - The breasts are technically not reproductive organs, but their mammary glands produce milk to feed an infant after birth. Milk drains through ducts and sacs and out through the nipple when a baby sucks.
- Oogenesis is the process of producing eggs in the ovaries of a female fetus. Oogenesis begins when a diploid oogonium divides by mitosis to produce a diploid primary oocyte. The primary oocyte begins meiosis I and then remains at this stage in an immature ovarian follicle until after birth.
- After puberty, one follicle a month matures and its primary oocyte completes meiosis I to produce a secondary oocyte, which begins meiosis II. During ovulation, the mature follicle bursts open and the secondary oocyte leaves the ovary and enters a Fallopian tube.
- While a follicle is maturing in an ovary each month, the endometrium in the uterus is building up to prepare for an embryo. Around the time of ovulation, cervical mucus becomes thinner and more alkaline to help sperm reach the secondary oocyte.
- If the secondary oocyte is fertilized by a sperm, it quickly completes meiosis II and forms a diploid zygote, which will continue through the Fallopian tube. The zygote will go through multiple cell divisions before reaching and implanting in the uterus. If the secondary oocyte is not fertilized, it will not complete meiosis II, and will soon disintegrate.
- Pregnancy is the carrying of one or more offspring from fertilization until birth. The maternal organism must provide all the nutrients and other substances needed by the developing offspring, and also remove its wastes. She should also avoid exposures that could potentially damage the offspring, especially early in the pregnancy when organ systems are developing.
    - The average duration of pregnancy is 40 weeks (from the first day of the last menstrual period) and is divided into three trimesters of about three months each. Each trimester is associated with certain events and conditions that a pregnant woman may expect, such as morning sickness during the first trimester, feeling fetal movements for the first time during the second trimester, and rapid weight gain in both fetus and mother during the third trimester.
    - Labor, which is the general term for the birth process, usually begins around the time the amniotic sac breaks and its fluid leaks out. Labor occurs in three stages: dilation of the cervix, the birth of the baby, and delivery of the placenta (afterbirth).
- The physiological function of female breasts is lactation or the production of breastmilk to feed an infant. Sucking on the breast by the infant stimulates the release of the hypothalamic hormone oxytocin from the posterior pituitary, which causes the flow of milk. The release of milk stimulates the baby to continue sucking, which in turn keeps the milk flowing. This is one of the few examples of positive feedback in the human organism.
- The ovaries produce female sex hormones, including estrogen and progesterone. Estrogen is responsible for sexual maturation and secondary sex characteristics at puberty. It is also needed to help regulate the menstrual cycle and ovulation after puberty until menopause. Progesterone prepares the uterus for pregnancy each month during the menstrual cycle and helps maintain the pregnancy if fertilization occurs.

- The menstrual cycle refers to natural changes that occur in the female reproductive system each month during the reproductive years, except when a woman is pregnant. The cycle is necessary for the production of eggs and the preparation of the uterus for pregnancy. It involves changes in both the ovaries and uterus and is controlled by pituitary hormones (FSH and LH) and ovarian hormones (estrogen and progesterone).
  - The female reproductive period is delineated by menarche, or the first menstrual period, which usually occurs around age 12 or 13; and by menopause, or the cessation of menstrual periods, which typically occurs around age 52. A typical menstrual cycle averages 28 days in length but may vary normally from 21 to 45 days. The average menstrual period is five days long but may vary normally from two to seven days. These variations in the menstrual cycle may occur both between women and within individual women from month to month.
  - The events of the menstrual cycle that take place in the ovaries make up the ovarian cycle. It includes the follicular phase, when a follicle and its egg mature due to rising levels of FSH; ovulation, when the egg is released from the ovary due to a rise in estrogen and a surge in LH; and the luteal phase, when the follicle is transformed into a structure called a corpus luteum that secretes progesterone. In a 28-day menstrual cycle, the follicular and luteal phases typically average about two weeks in length, with ovulation generally occurring around day 14 of the cycle.
  - The events of the menstrual cycle that take place in the uterus make up the uterine cycle. It includes menstruation, which generally occurs on days 1 to 5 of the cycle and involves shedding of endometrial tissue that built up during the preceding cycle; the proliferative phase, during which the endometrium builds up again until ovulation occurs; and the secretory phase, which follows ovulation and during which the endometrium secretes substances and undergoes other changes that prepare it to receive an embryo.
- Disorders of the female reproductive system include cervical cancer, vaginitis, and endometriosis.
  - Cervical cancer occurs when cells of the cervix grow abnormally and develop the ability to invade nearby tissues, or spread to other parts of the body. Worldwide, cervical cancer is the second-most common type of cancer in females and the fourth-most common cause of cancer death in females. Early on, cervical cancer often has no symptoms; later, symptoms such as abnormal vaginal bleeding and pain are likely.
    - Most cases of cervical cancer occur because of infection with human papillomavirus (HPV), so the HPV vaccine is expected to greatly reduce the incidence of the disease. Other risk factors include smoking and a weakened immune system. A Pap smear can diagnose cervical cancer at an early stage. Where Pap smears are done routinely, cervical cancer death rates have fallen dramatically. Treatment of cervical cancer generally includes surgery, which may be followed by radiation therapy or chemotherapy.
  - Vaginitis is an inflammation of the vagina. A discharge is likely, and there may be itching and pain. About 90 percent of cases of vaginitis is caused by infection with microorganisms, typically by the yeast *Candida albicans*. A minority of cases are caused by irritants or allergens in products such as soaps, spermicides, or douches.
    - Diagnosis of vaginitis may be based on characteristics of the discharge, which can be examined microscopically or cultured. Treatment of vaginitis depends on the cause and is usually an oral or topical anti-fungal or antibiotic medication.
  - Endometriosis is a disease in which endometrial tissue grows outside the uterus. This tissue may bleed during the menstrual period and cause inflammation, pain, and scarring. The main symptom of endometriosis is pelvic pain, which may be severe. Endometriosis may also lead to infertility.
    - Endometriosis is thought to have multiple causes, including genetic mutations. Retrograde menstruation may be the immediate cause of endometrial tissue escaping the uterus and entering the pelvic cavity. Endometriosis is usually treated with surgery to remove the abnormal tissue and medication for pain. If surgery is more conservative than hysterectomy, endometriosis may recur.
- Infertility is the inability of a sexually mature adult to reproduce by natural means. It is defined scientifically and medically as the failure to achieve a successful pregnancy after at least one year of regular, unprotected sexual intercourse.
- About 30 percent of infertility in couples is due to female infertility, and another 30 percent is due to male infertility. In the remaining cases, a couple's infertility is due to problems in both partners or to unknown causes.
- Male infertility occurs when there are no or too few healthy, motile sperm. This may be caused by problems with spermatogenesis or by blockage of the male reproductive tract that prevents sperm from being ejaculated. Risk factors for male infertility include heavy alcohol use, smoking, certain medications, and advancing age, to name just a few.
- Female infertility occurs due to failure to produce viable eggs by the ovaries or structural problems in the Fallopian tubes or uterus. Polycystic ovary syndrome is the most common cause of failure to produce viable eggs. Endometriosis and uterine fibroids are possible causes of structural problems in the Fallopian tubes and uterus. Risk factors for female infertility include smoking, stress, poor diet, and older age, among others.
- Diagnosing the cause(s) of a couple's infertility generally requires testing both the man and the woman for potential problems. For men, semen is likely to be examined for adequate

numbers of healthy, motile sperm. For women, signs of ovulation are monitored, for example, with an ovulation test kit or ultrasound of the ovaries. For both partners, the reproductive tract may be medically imaged to look for blockages or other abnormalities.

  - Treatments for infertility depend on the cause. For example, if a medical problem is interfering with sperm production, medication may resolve the underlying problem so sperm production is restored. Blockages in either the male or the female reproductive tract can often be treated surgically. If there are problems with ovulation, hormonal treatments may stimulate ovulation.
  - Some cases of infertility are treated with assisted reproductive technology (ART). This is a collection of medical procedures in which eggs and sperm are taken from the couple and manipulated in a lab to increase the chances of fertilization occurring and an embryo forming. Other approaches for certain causes of infertility include the use of a surrogate mother, gestational carrier, or sperm donation.
- Infertility can negatively impact a couple socially and psychologically, and it may be a major cause of marital friction or even divorce. Infertility treatments may raise ethical issues relating to the costs of the procedures and the status of embryos that are created *in vitro* but not used for pregnancy. Infertility is an under-appreciated problem in developing countries where birth rates are high and children have high economic as well as a social value. In these countries, poor health care is likely to lead to more problems with infertility and fewer options for treatment.
- More than half of all fertile couples worldwide use contraception (birth control), which is any method or device used to prevent pregnancy. Different methods of contraception vary in their effectiveness, typically expressed as the failure rate, or the percentage of women who become pregnant using a given method during the first year of use. For most methods, the failure rate with typical use is much higher than the failure rate with perfect use.
- Types of birth control methods include barrier methods, hormonal methods, intrauterine devices, behavioral methods, and sterilization. Except for sterilization, all of the methods are reversible.
  - Barrier methods are devices that block sperm from entering the uterus. They include condoms and diaphragms. Of all birth control methods, only condoms can also prevent the spread of sexually transmitted infections.
  - Hormonal methods involve the administration of hormones to prevent ovulation. Hormones can be administered in various ways, such as in an injection, through a skin patch, or, most commonly, in birth control pills. There are two types of birth control pills: those that contain estrogen and progesterone, and those that contain only progesterone. Both types are equally effective, but they have different potential side effects.
  - An intrauterine device (IUD) is a small T-shaped plastic structure containing copper or a hormone that is inserted into the uterus by a physician and left in place for months or even years. It is highly effective even with typical use, but it does have some risks, such as increased menstrual bleeding and, rarely, perforation of the uterus.
  - Behavioral methods involve regulating the timing or method of intercourse to prevent the introduction of sperm into the female reproductive tract, either altogether or when an egg may be present. In the fertility awareness methods, unprotected intercourse is avoided during the most fertile days of the cycle as estimated by basal body temperature or the characteristics of cervical mucus. In withdrawal, the penis is withdrawn from the vagina before ejaculation occurs. Behavioral methods are the least effective methods of contraception.
  - Sterilization is the most effective contraceptive method, but it requires a surgical procedure and may be irreversible. Male sterility is usually achieved with a vasectomy, in which the vas deferens are clamped or cut to prevent sperm from being ejaculated in semen. Female sterility is usually achieved with a tubal ligation, in which the Fallopian tubes are clamped or cut to prevent sperm from reaching and fertilizing eggs.
  - Emergency contraception is any form of contraception that is used after unprotected vaginal intercourse. One method is the “morning after” pill, which is a high-dose birth control pill that can be taken up to five days after unprotected sex. Another method is an IUD, which can be inserted up to five days after unprotected sex.

In this chapter, you learned how the male and female reproductive systems work together to produce a zygote. In the next chapter, you will learn about how the human organism grows and develops throughout life—from a zygote all the way through old age.

## CHAPTER SUMMARY REVIEW

1. Which glands produce semen? What is the rough percentage of each fluid in semen?
2. What is one reason why semen's alkalinity assists in reproduction?
3. *True or False:* The hormones FSH and LH are involved in regulating the female reproductive system, but not the male reproductive system.
4. *True or False:* A majority of American males have some cancerous cells in their prostate gland by age 80.
5. *True or False:* The secretory phase of the menstrual cycle is when menstruation occurs.
6. Menarche is:
   A. the part of the menstrual cycle known as a period
   B. the first menstrual period
   C. the conclusion of menstrual periods when a woman is around 50
   D. an anovulatory menstrual cycle

7. Where are sperm located when they develop tails?
    A. the testes
    B. the epididymis
    C. the vas deferens
    D. the seminal vesicles
8. For each of the descriptions below, choose whether it applies to the male or female reproductive systems.
    A. The gametes are present at birth.
    B. Gametogenesis begins at puberty.
    C. The gametes complete meiosis II upon fertilization.
    D. The mature gametes have a reduced amount of cytoplasm.
9. What are three things that pass through the cervical canal of females, going in either direction?
10. If a man and a woman have unprotected vaginal intercourse, what are the structures of the female reproductive tract, in order, that sperm would move through? (Assume that these sperm do not die prematurely before they reach their final destination.)
11. Other than where the cancer originates, what is one difference between the prostate and testicular cancer?
12. Progesterone is relatively high...
    A. in the follicular phase of the menstrual cycle
    B. in the luteal phase of the menstrual cycle
    C. during pregnancy
    D. B and C
13. If a woman is checking her basal body temperature each morning as a form of contraception, and today is day 12 of her menstrual cycle and her basal body temperature is still low, is it safe for her to have unprotected sexual intercourse today? Why or why not?
14. *True or False:* If a young woman does not get pregnant after nine months of regular, unprotected intercourse, the couple will be diagnosed with infertility.
15. *True or False:* In the developing male fetus, the gonads start out as ovaries, but then differentiate into testes because of the Y chromosome.
16. *True or False:* A cause of endometriosis can be retrograde menstruation, where some of the endometrial tissue flows backward from the uterus out through the Fallopian tubes.
17. Where are sperm produced?
    A. the seminal vesicles
    B. the spermatogonium
    C. the epididymis
    D. the seminiferous tubules
18. Which of the following methods of contraception is the most effective, while also being reversible? A. withdrawal B. tubal ligation C. intrauterine device D. condoms
19. Where is a diaphragm placed? How does it work to prevent pregnancy?
20. Why are the testes located outside of the body?
21. Why is it important to properly diagnose the causative agent when a woman has vaginitis?
22. *True or False:* When a baby nurses, the stimulation negatively feeds back to decrease milk flow to the nipple.
23. *True or False:* Part of the penis is located inside of the male body.
24. What is the best description of what occurs at menopause?
    A. Eggs stop maturing in the ovaries on a monthly basis.
    B. Oogenesis stops occurring.
    C. Ovulated eggs cannot be fertilized, so they are automatically reabsorbed.
    D. The endometrium can no longer support a fetus, so fertilized eggs cannot implant.
25. The transition from spermatid to sperm involves
    A. mitosis
    B. meiosis I
    C. meiosis II
    D. no cell division
26. Describe two ways in which sperm can move through the male and/or female reproductive tracts.

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2.9: Energy in Chemical Reactions
exocrine glands
8.2: Introduction to the Endocrine System
exocytosis
3.8: Active Transport and Homeostasis
exon
3.14: Protein Synthesis
eye
7.7: Human Senses

## F

facilitated diffusion
3.7: Cell Transport
Fallopian tubes
15.6: Structures of the Female Reproductive System
fast food
13.8: Case Study Conclusion- Fast Food and Chapter Summary
fatty acids
2.6: Lipids
fermentation
3.10: Fermentation
fertilization
3.24: Sexual Reproduction- Meiosis and gametogenesis
fibroblast cells
1.3: Human Cells and Tissues
fibrocartilage
1.3: Human Cells and Tissues
fibrous joint
5.6: Joints
flagella
3.4: Plasma Membrane
flexibility exercise
6.5: Physical Exercise
follicle
8.5: Thyroid Gland

Foodbourne disease
13.7: Foodborne Diseases
frameshift mutation
3.16: Mutations
frontal lobe
7.5: Central Nervous System

## G

G0 phase
3.21: Cell Cycle and Cell Division
G1 phase
3.21: Cell Cycle and Cell Division
G2 phase
3.21: Cell Cycle and Cell Division
gallbladder
12.6: Accessory Organs of Digestion
gamete
3.24: Sexual Reproduction- Meiosis and gametogenesis
15.2: Introduction to the Reproductive System
gametogenesis
3.24: Sexual Reproduction- Meiosis and gametogenesis
Ganglia
1.3: Human Cells and Tissues
gas exchange
11.3: Breathing
gastroenteritis
12.7: Disorders of the Gastrointestinal Tract
gastrointestinal tract
12.2: Introduction to the Digestive System
gene
3.13: Chromosomes and Genes
3.27: Case Study Conclusion- Genes and Chapter Summary
gene expression
3.17: Regulation of Gene Expression
general senses
7.7: Human Senses
genes
3.13: Chromosomes and Genes
genetic code
3.15: Genetic Code
genome
3.18: The Human Genome
germline mutations
3.16: Mutations
gestational carrier
15.10: Infertility
Ghrelin
13.4: Eating Disorders
GI Tract
12.2: Introduction to the Digestive System
giardiasis
12.7: Disorders of the Gastrointestinal Tract
glial cells
7.2: Introduction to the Nervous System
Glomerulus
14.3: Kidneys
glucose
2.5: Carbohydrates
glycogen
2.5: Carbohydrates
glycolysis
3.9: Cellular Respiration
goiter
8.5: Thyroid Gland
Golgi apparatus
3.6: Cell Organelles
gonads
15.2: Introduction to the Reproductive System
Graves disease
8.5: Thyroid Gland
gray matter
1.3: Human Cells and Tissues
growth factor
3.23: Mutations and Cancer
guanine
2.8: Nucleic Acids

## H

hair
4.4: Hair and Nails
hair follicle
4.4: Hair and Nails
hair root
4.4: Hair and Nails
hair shaft
4.4: Hair and Nails
haploid
3.24: Sexual Reproduction- Meiosis and gametogenesis
Hashimoto thyroiditis
8.5: Thyroid Gland
hearing
7.7: Human Senses
heart
9.3: Heart
heart failure
6.4: Muscle Contraction
hematopoiesis
5.2: Introduction to the Skeletal System
hemispheres'
7.5: Central Nervous System
hemodialysis
14.5: Disorders of the Urinary System
hemolytic disease of the newborn
9.6: Blood Types
hemophilia
9.5: Blood
heterotroph
3.9: Cellular Respiration
histamine
10.4: Innate Immune System
HIV
10.6: Disorders of the Immune System
HLA
3.20: Case Study- Genetic Similarities and Differences
Homeobox Genes
3.17: Regulation of Gene Expression
homeostasis
1.7: Homeostasis and Feedback
homologous chromosomes
3.24: Sexual Reproduction- Meiosis and gametogenesis
homologus structures
15.2: Introduction to the Reproductive System
hormonal contraception
15.11: Contraception
hormone
8.8: Case Study Conclusion- Hormonal and Chapter Summary
human body
1.1: Case Study- Getting to Know Your Body
Human Body Cavities
1.5: Human Body Cavities
human genome
3.19: Case Study Conclusion- Parmacogenomics and Chapter Summary
human genome project
3.18: The Human Genome
human leukocyte antigen
3.20: Case Study- Genetic Similarities and Differences
humanpapillomavirus
15.9: Disorders of the Female Reproductive System
hyaline cartilage
1.3: Human Cells and Tissues
hydrogen bond
2.3: Chemical Bonding
2.11: Biochemical Properties of Water
hyperopia
7.7: Human Senses
hypersecretion
8.2: Introduction to the Endocrine System
hypertension
9.7: Cardiovascular Disease
hyperthyroidism
8.5: Thyroid Gland
hypertonic
3.7: Cell Transport
hyperventilating
11.3: Breathing
hyposecretion
8.2: Introduction to the Endocrine System
hypothalamus
7.5: Central Nervous System
hypothyroidism
8.5: Thyroid Gland
hypotonic
3.7: Cell Transport

## I

Ileum
12.5: Lower Gastrointestinal Tract
immune surveillance
10.2: Introduction to the Immune System
immune system
10: The Lymphatic and Immune Systems
10.1: Case Study- Your Defense System
10.2: Introduction to the Immune System
immunity
10.5: Adaptive Immune System
immunization
10.5: Adaptive Immune System
immunodeficiency
10.6: Disorders of the Immune System

immunotherapy
10.6: Disorders of the Immune System
10.8: Case Study Conclusion- Lymphoma and Chapter Summary
incubation period
13.7: Foodborne Diseases
independent assortment
3.25: Genetic Variation
Infectious dose
13.7: Foodborne Diseases
inferior vena cava
9.4: Blood Vessels
infertility
15.10: Infertility
inflammation
10.4: Innate Immune System
inflammatory bowel disease
12.7: Disorders of the Gastrointestinal Tract
infundibulum
8.4: Pituitary Gland
innate immune system
10.4: Innate Immune System
Insoluble fiber
13.2: Nutrients
integumentary
1.4: Human Organs and Organ Systems
integumentary system
4: The Integumentary System
intergumentary system
4.2: Introduction to the Integumentary System
intermediate filaments
3.5: Cytoplasm and Cytoskeleton
Interneurons
7.3: Neurons
interphase
3.21: Cell Cycle and Cell Division
intrauterine device
15.11: Contraception
intron
3.14: Protein Synthesis
ion
2.2: Elements and Compounds
ionic bond
2.3: Chemical Bonding
isometric
6.4: Muscle Contraction
isotonic
3.7: Cell Transport
6.4: Muscle Contraction

J

jaundiced eye
12.6: Accessory Organs of Digestion
jejunum
12.5: Lower Gastrointestinal Tract
joint hypermobility
5.6: Joints
joints
5.6: Joints

K

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3.26: Mitosis vs. Meiosis and Disorders
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3.5: Cytoplasm and Cytoskeleton
keratinocytes
4.2: Introduction to the Integumentary System
keratins
4.2: Introduction to the Integumentary System
kidney
14.3: Kidneys
kidney failure
14.5: Disorders of the Urinary System
kidney stone
14.5: Disorders of the Urinary System
kinase
3.23: Mutations and Cancer
kinetic energy
3.7: Cell Transport
Klinefelter's syndrome
3.26: Mitosis vs. Meiosis and Disorders
Krebs cycle
3.9: Cellular Respiration
Kwashiokor
13.6: Undernutrition

L

labia
15.6: Structures of the Female Reproductive System
lactation
15.8: Functions of the Female Reproductive System
Lactic Acid Fermentation
3.10: Fermentation
lagging strand
3.12: DNA and RNA
lamin
3.5: Cytoplasm and Cytoskeleton
large intestine
12.5: Lower Gastrointestinal Tract
larynx
11.2: Structure and Function of the Respiratory System
lateralization
7.5: Central Nervous System
leading strand
3.12: DNA and RNA
leptin
13.4: Eating Disorders
leukemia
3.20: Case Study- Genetic Similarities and Differences
9.5: Blood
ligaments
5.2: Introduction to the Skeletal System
linked genes
3.13: Chromosomes and Genes
lipid
2.4: Biochemical Compounds
2.6: Lipids
13.2: Nutrients
liver
12.6: Accessory Organs of Digestion
loose connective tissue proper
1.3: Human Cells and Tissues
lower gastrointestinal tract
12.5: Lower Gastrointestinal Tract
lung
11.2: Structure and Function of the Respiratory System
lung cancer
11.4: Disorders of the Respiratory System
lymph
10.3: Lymphatic System
lymph node
10.3: Lymphatic System
lymphatic system
1.4: Human Organs and Organ Systems
10.3: Lymphatic System
lymphoma
10.8: Case Study Conclusion- Lymphoma and Chapter Summary

M

macronutrient
13.2: Nutrients
major histocompatibility complex
10.2: Introduction to the Immune System
malnutrition
13.3: Healthy Eating
mandible
5.3: Divisions of the Skeletal System
marasmus
13.6: Undernutrition
Marie Stopes
15.11: Contraception
matter
2.2: Elements and Compounds
maxillae
5.3: Divisions of the Skeletal System
mechanical digestion
12.3: Digestion and Absorption
mechanoreceptor
7.7: Human Senses
medulla
14.2: Introduction to the Urinary System
medulla oblongata
7.5: Central Nervous System
meiosis
3.24: Sexual Reproduction- Meiosis and gametogenesis
melanoma
4.5: Case Study Conclusion- Skin Cancer and Chapter Summary
melting point
2.11: Biochemical Properties of Water
membrane
3.7: Cell Transport
menarche
15.7: Menstrual Cycle
meninge
1.5: Human Body Cavities
menopause
15.7: Menstrual Cycle
menstrual cycle
15.7: Menstrual Cycle
metabolism
2.10: Chemical Reactions in Living Things
metaphase
3.22: Mitotic Phase - Mitosis and Cytokinesis

metastasis
4.5: Case Study Conclusion- Skin Cancer and Chapter Summary
microbiome
10.7: Human Microbiome
micronutrient
13.2: Nutrients
microscope
3.2: Discovery of Cells and Cell Theory
microtubules
3.5: Cytoplasm and Cytoskeleton
3.21: Cell Cycle and Cell Division
microvilli
3.5: Cytoplasm and Cytoskeleton
12.2: Introduction to the Digestive System
midbrain
7.5: Central Nervous System
mitochondria
3.1: Case Study- The Importance of Cells
3.6: Cell Organelles
mitosis
3.22: Mitotic Phase - Mitosis and Cytokinesis
mitotic phase
3.21: Cell Cycle and Cell Division
mixed nerves
7.6: Peripheral Nervous System
molecule
2.2: Elements and Compounds
monomers
2.4: Biochemical Compounds
Monosaccharide
2.4: Biochemical Compounds
2.5: Carbohydrates
motor nerves
7.6: Peripheral Nervous System
motor neurons
7.3: Neurons
mucous membrane
1.3: Human Cells and Tissues
mucus
1.3: Human Cells and Tissues
muscle
6.1: Case Study- Muscles and Movement
muscle contraction
6.4: Muscle Contraction
muscle fascicles
6.3: Types of Muscle Tissue
muscle fibers
6.2: Introduction to the Muscular System
muscle strain
6.6: Disorders of the Muscular System
muscle tissue
1.3: Human Cells and Tissues
6.3: Types of Muscle Tissue
muscular dystrophy
6.6: Disorders of the Muscular System
muscular system
1.4: Human Organs and Organ Systems
6.2: Introduction to the Muscular System
Musculoskeletal System
6.6: Disorders of the Muscular System
mutations
3.16: Mutations
Myasthenia gravis
6.6: Disorders of the Muscular System
myelin sheath
7.3: Neurons
myocyte
6.2: Introduction to the Muscular System
6.3: Types of Muscle Tissue
myofibril
6.4: Muscle Contraction
myokines
6.5: Physical Exercise
myometrium
15.6: Structures of the Female Reproductive System
myopia
7.7: Human Senses
MyPlate
13.3: Healthy Eating

## N

nail plate
4.4: Hair and Nails
nail root
4.4: Hair and Nails
nails
4.4: Hair and Nails
nasal cavity
11.2: Structure and Function of the Respiratory System
nephron
14.2: Introduction to the Urinary System
nephrons
14.2: Introduction to the Urinary System
nerve impulse
7.4: Nerve Impulses
nerves
1.3: Human Cells and Tissues
nervous system
1.4: Human Organs and Organ Systems
7.1: Case Study- The Control Center of Your Body
7.2: Introduction to the Nervous System
nervous tissue
1.3: Human Cells and Tissues
neurogenesis
7.3: Neurons
neuroimmune system
10.2: Introduction to the Immune System
neuromuscular disorders
6.6: Disorders of the Muscular System
neuromuscular junction
6.4: Muscle Contraction
neurons
7.3: Neurons
neurotransmitter
7.4: Nerve Impulses
neutron
2.2: Elements and Compounds
nicotine
11.5: Smoking and Health
nitrogenous base
2.8: Nucleic Acids
nociceptors
7.7: Human Senses
nodes of Ranvier
7.3: Neurons
nondisjunction
3.26: Mitosis vs. Meiosis and Disorders
nonessential nutirents
13.2: Nutrients
nuclear force
2.2: Elements and Compounds
nucleic acids
2.4: Biochemical Compounds
2.8: Nucleic Acids
nucleoplasm
3.5: Cytoplasm and Cytoskeleton
nucleotide
2.8: Nucleic Acids
nucleus
3.6: Cell Organelles
nutrient
13.2: Nutrients
nutrient density
13.3: Healthy Eating
nutrition
13.1: Case Study- Fueling Our Bodies Properly
13.3: Healthy Eating

## O

obesity
13.5: Obesity
occipital lobe
7.5: Central Nervous System
Okazaki fragment
3.12: DNA and RNA
olfactory receptor
7.7: Human Senses
oncogene
3.23: Mutations and Cancer
oogenesis
3.24: Sexual Reproduction- Meiosis and gametogenesis
15.8: Functions of the Female Reproductive System
oogonia
15.8: Functions of the Female Reproductive System
opioids
7.8: Psychoactive Drugs
organ system
1.6: Interaction of Organ Systems
1.8: Case Study Conclusion- Pressure and Chapter Summary
organelle
3.3: Variation in Cells
3.6: Cell Organelles
organelles
3.2: Discovery of Cells and Cell Theory
organism
1.2: Organization of the Body
osmosis
3.7: Cell Transport
ossification
5.5: Bone Growth, Remodeling, and Repair
osteoarthritis
5.7: Disorders of the Skeletal System
osteoblast
5.4: Structure of Bone
osteoblasts
1.3: Human Cells and Tissues
5.5: Bone Growth, Remodeling, and Repair
osteocalcin
5.2: Introduction to the Skeletal System

osteoclast
5.4: Structure of Bone
osteocyte
5.4: Structure of Bone
osteogenic cells
5.4: Structure of Bone
osteon
1.3: Human Cells and Tissues
osteoporosis
5.7: Disorders of the Skeletal System
outer energy level
2.3: Chemical Bonding
ovulation
15.8: Functions of the Female Reproductive System
Oxydative phosphorylation
3.9: Cellular Respiration
oxytocin
8.4: Pituitary Gland

## P

pacemaker
9.3: Heart
pancreas
8.7: Pancreas
12.6: Accessory Organs of Digestion
pancreatic islet
8.7: Pancreas
Pancreatitis
8.7: Pancreas
Pap smear
15.9: Disorders of the Female Reproductive System
papillary layer
4.3: Skin
paralysis
7.5: Central Nervous System
parietal lobe
7.5: Central Nervous System
Parkinson’s disease
6.6: Disorders of the Muscular System
passive immunity
10.5: Adaptive Immune System
passive transport
3.7: Cell Transport
pathogen
10.2: Introduction to the Immune System
pelvic girdle
5.3: Divisions of the Skeletal System
penis
15.3: Structures of the Male Reproductive System
peptic ulcers
12.7: Disorders of the Gastrointestinal Tract
peptide bond
2.7: Proteins
perimetrium
15.6: Structures of the Female Reproductive System
perimysium
6.3: Types of Muscle Tissue
Peripheral artery disease
9.7: Cardiovascular Disease
peripheral immune system
10.2: Introduction to the Immune System
peripheral nervous system
7.2: Introduction to the Nervous System
7.6: Peripheral Nervous System
peristalsis
6.2: Introduction to the Muscular System
pH scale
2.12: Acids and Bases
phagocytosis
3.8: Active Transport and Homeostasis
pharmacogenomics
3.18: The Human Genome
Pharmocogenomics
3.19: Case Study Conclusion- Parmacogenomics and Chapter Summary
pharynx
11.2: Structure and Function of the Respiratory System
phosphate group
2.8: Nucleic Acids
phospholipid
2.6: Lipids
phospholipid bilayer
2.6: Lipids
3.4: Plasma Membrane
phospholipids
3.4: Plasma Membrane
photoautotroph
3.9: Cellular Respiration
photoreceptors
7.7: Human Senses
physiology
1.2: Organization of the Body
phytochemicals
13.2: Nutrients
pinocytosis
3.8: Active Transport and Homeostasis
pituitary gland
8.4: Pituitary Gland
placenta
15.6: Structures of the Female Reproductive System
plasma
9.5: Blood
plasma membrane
3.2: Discovery of Cells and Cell Theory
3.4: Plasma Membrane
platelets
9.5: Blood
pneumonia
11.4: Disorders of the Respiratory System
point mutation
3.16: Mutations
polar covalent bond
2.3: Chemical Bonding
polar molecule
2.11: Biochemical Properties of Water
polarity
2.11: Biochemical Properties of Water
polycystic kidney disease
14.5: Disorders of the Urinary System
polymer
2.4: Biochemical Compounds
polynucleotide
2.8: Nucleic Acids
polypeptide
2.7: Proteins
polysaccharide
2.4: Biochemical Compounds
2.5: Carbohydrates
pons
7.5: Central Nervous System
posterior pituitary
8.4: Pituitary Gland
presbyopia
7.7: Human Senses
pressure
1.8: Case Study Conclusion- Pressure and Chapter Summary
primary active transport
3.8: Active Transport and Homeostasis
primase
3.12: DNA and RNA
probiotic
10.7: Human Microbiome
product
2.9: Energy in Chemical Reactions
2.10: Chemical Reactions in Living Things
progesterone
15.8: Functions of the Female Reproductive System
prokaryote
3.3: Variation in Cells
prokaryotic cell
3.3: Variation in Cells
prolactin
8.4: Pituitary Gland
promoter
3.14: Protein Synthesis
prophase
3.22: Mitotic Phase - Mitosis and Cytokinesis
prostate cancer
15.5: Disorders of the Male Reproductive System
prostate gland
15.3: Structures of the Male Reproductive System
protein
2.4: Biochemical Compounds
2.7: Proteins
3.14: Protein Synthesis
13.2: Nutrients
protein primary structure
2.7: Proteins
protein Quaternary structure
2.7: Proteins
protein secondary structure
2.7: Proteins
protein tertiary structure
2.7: Proteins
proton
2.2: Elements and Compounds
Psychoactive Drugs
7.8: Psychoactive Drugs
pulmonary circulation
9.2: Introduction to the Cardiovascular System
pump
3.8: Active Transport and Homeostasis

## R

random fertilization
3.25: Genetic Variation

reactant
2.9: Energy in Chemical Reactions
2.10: Chemical Reactions in Living Things
receptor mediated endocytosis
3.8: Active Transport and Homeostasis
recombination
3.25: Genetic Variation
recticular layer
4.3: Skin
rectum
12.5: Lower Gastrointestinal Tract
red blood cell
9.5: Blood
reflexes
7.5: Central Nervous System
regulatory elements
3.17: Regulation of Gene Expression
regulatory proteins
3.17: Regulation of Gene Expression
renal pelvis
14.2: Introduction to the Urinary System
renal tubule
14.3: Kidneys
reproductive system
1.4: Human Organs and Organ Systems
15.1: Case Study- Making Babies
15.12: Case Study Conclusion- Trying to Conceive and Chapter Summary
respiration
11.2: Structure and Function of the Respiratory System
respiratory center
11.3: Breathing
respiratory system
1.4: Human Organs and Organ Systems
11.1: Case Study- Respiratory System and Gas Exchange
respiratory tract
11.2: Structure and Function of the Respiratory System
Resting Potential
7.4: Nerve Impulses
reticular connective tissue
1.3: Human Cells and Tissues
reticular fibers
1.3: Human Cells and Tissues
retina
7.7: Human Senses
Rhesus blood group system
9.6: Blood Types
rib cage
5.3: Divisions of the Skeletal System
ribose
3.12: DNA and RNA
ribose sugar
2.8: Nucleic Acids
ribosome
3.2: Discovery of Cells and Cell Theory
ribosomes
3.6: Cell Organelles
RNA
2.8: Nucleic Acids
3.14: Protein Synthesis
rough endoplasmic reticulum
3.6: Cell Organelles

## S

S phase
3.21: Cell Cycle and Cell Division
saliva
12.4: Upper Gastrointestinal Tract
salivary glands
12.4: Upper Gastrointestinal Tract
Sanger Dideoxynucleotides
3.18: The Human Genome
sarcomere
6.3: Types of Muscle Tissue
Saturated fatty acid
2.6: Lipids
Schistosoma
10.2: Introduction to the Immune System
scrotum
15.3: Structures of the Male Reproductive System
sebaceous gland
4.3: Skin
secondary active transport
3.8: Active Transport and Homeostasis
secondary sex characteristics
15.2: Introduction to the Reproductive System
secondhand smoke
11.5: Smoking and Health
seman
15.3: Structures of the Male Reproductive System
seminiferous tubule
15.3: Structures of the Male Reproductive System
sensory nerves
7.6: Peripheral Nervous System
sensory neurons
7.3: Neurons
sensory receptor
7.7: Human Senses
Sertoli cell
15.3: Structures of the Male Reproductive System
Sex Hormones
15.2: Introduction to the Reproductive System
sexual reproduction
3.24: Sexual Reproduction- Meiosis and gametogenesis
3.25: Genetic Variation
simple difussion
3.7: Cell Transport
single nucleotide polymorphisms
3.19: Case Study Conclusion- Parmacogenomics and Chapter Summary
sinus rhythm
9.3: Heart
skeletal muscles
1.3: Human Cells and Tissues
6.3: Types of Muscle Tissue
skeletal system
1.4: Human Organs and Organ Systems
5.1: Case Study- Your Support System
5.2: Introduction to the Skeletal System
5.8: Case Study Conclusion- Heels and Chapter Summary
skin
4.2: Introduction to the Integumentary System
4.3: Skin
skin cancer
4.1: Case Study- Skin Cancer
skull
5.3: Divisions of the Skeletal System
sleep apnea
11.4: Disorders of the Respiratory System
sliding filament theory
6.4: Muscle Contraction
small intestine
12.5: Lower Gastrointestinal Tract
smooth endoplasmic reticulum
3.6: Cell Organelles
smooth muscle
1.3: Human Cells and Tissues
sodium potassium pump
3.8: Active Transport and Homeostasis
Soluble fiber
13.2: Nutrients
solute
3.7: Cell Transport
solution
2.12: Acids and Bases
3.7: Cell Transport
solvent
3.7: Cell Transport
somatic mutations
3.16: Mutations
somatic nervous system
7.6: Peripheral Nervous System
somatostatin
8.7: Pancreas
special senses
7.7: Human Senses
sperm
3.24: Sexual Reproduction- Meiosis and gametogenesis
15.4: Functions of the Male Reproductive System
sperm donation
15.10: Infertility
spermatogenesis
3.24: Sexual Reproduction- Meiosis and gametogenesis
15.4: Functions of the Male Reproductive System
sphincter
12.4: Upper Gastrointestinal Tract
spinal cavity
1.5: Human Body Cavities
spinal cord
7.5: Central Nervous System
spleen
10.3: Lymphatic System
spongy bone tissue
5.4: Structure of Bone
squamous cell carcinoma
4.5: Case Study Conclusion- Skin Cancer and Chapter Summary
stages of cellular respiration
3.9: Cellular Respiration
starch
2.5: Carbohydrates
Sterilization
15.11: Contraception
steroid hormone
8.3: Endocrine Hormones
steroids
2.6: Lipids

stomach
12.4: Upper Gastrointestinal Tract
stroke
6.4: Muscle Contraction
7.5: Central Nervous System
9.7: Cardiovascular Disease
stunting
13.6: Undernutrition
sugars
2.5: Carbohydrates
sunburn
4.3: Skin
superior vena cava
9.4: Blood Vessels
surface tension
2.11: Biochemical Properties of Water
surrogate mother
15.10: Infertility
sweat glands
4.3: Skin
synapse
7.4: Nerve Impulses
synovial joint
5.6: Joints
systemic circulation
9.2: Introduction to the Cardiovascular System
systole
9.3: Heart

## T

T cell
10.5: Adaptive Immune System
target cell
8.3: Endocrine Hormones
taste bud
7.7: Human Senses
TATA box
3.17: Regulation of Gene Expression
telophase
3.22: Mitotic Phase - Mitosis and Cytokinesis
temporal lobe
7.5: Central Nervous System
tendon
6.3: Types of Muscle Tissue
testes
15.3: Structures of the Male Reproductive System
testicular cancer
15.5: Disorders of the Male Reproductive System
testosterone
15.2: Introduction to the Reproductive System
tetrad
3.25: Genetic Variation
thalamus
7.5: Central Nervous System
thermoreceptors
7.7: Human Senses
thymine
2.8: Nucleic Acids
thymus
10.3: Lymphatic System
thyroid gland
8.5: Thyroid Gland
thyroxine
8.5: Thyroid Gland
tissue
1.2: Organization of the Body
Tonsillitis
10.3: Lymphatic System
tonsils
10.3: Lymphatic System
touch
7.7: Human Senses
trachea
11.2: Structure and Function of the Respiratory System
trans fat
13.2: Nutrients
transformation of pyruvate
3.9: Cellular Respiration
triad
6.4: Muscle Contraction
triglyceride
2.6: Lipids
triiodothyronine
8.5: Thyroid Gland
Triple X syndrome
3.26: Mitosis vs. Meiosis and Disorders
trisomy 21
3.26: Mitosis vs. Meiosis and Disorders
tubal ligation
15.11: Contraception
tubulin
3.6: Cell Organelles
tumor
3.21: Cell Cycle and Cell Division
tumor suppressor gene
3.23: Mutations and Cancer
tunica albuginea
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tunica vaginalis
15.3: Structures of the Male Reproductive System
tunica vasculosa
15.3: Structures of the Male Reproductive System
Turner Syndrome
3.26: Mitosis vs. Meiosis and Disorders
type 2 diabetes
8.7: Pancreas
type I diabetes mellitus
8.7: Pancreas

## U

Ulcerative colitis
12.7: Disorders of the Gastrointestinal Tract
underdraining
1.8: Case Study Conclusion- Pressure and Chapter Summary
undernutrition
13.6: Undernutrition
unsaturated fatty acid
2.6: Lipids
Upper Gastrointestinal Tract
12.4: Upper Gastrointestinal Tract
uracil
2.8: Nucleic Acids
3.12: DNA and RNA
ureters
14.4: Ureters, Urinary Bladder, and Urethra
urethra
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urinary bladder
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urinary system
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urination
14.2: Introduction to the Urinary System
urine
14.2: Introduction to the Urinary System

## V

vacuole
3.6: Cell Organelles
vagina
15.6: Structures of the Female Reproductive System
Vaginitis
15.9: Disorders of the Female Reproductive System
varicose veins
9.4: Blood Vessels
vas deferens
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vasectomy
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vasodilation
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vision
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vital organ
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vitamin
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vulva
15.6: Structures of the Female Reproductive System

## W

wasting
13.6: Undernutrition
water
13.2: Nutrients
white blood cell
9.5: Blood

white matter

1.3: Human Cells and Tissues

# Glossary

**Sample Word 1** | Sample Definition 1

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