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CHAPTER 9

Structure and Integrative Functions of the Main Organ Systems

Read This Chapter to Learn About

- Integumentary System
- Muscular System
- Skeletal System
- Circulatory System
- Respiratory System
- Digestive System
- Urinary System
- Lymphatic System
- Immune System
- Reproductive Systems

INTEGUMENTARY SYSTEM

The **integumentary system**, or **skin**, is composed of a variety of specialized tissue types to meet its diverse functions. The skin has also been described as a membrane but, because it is made of two or more tissue types, it also qualifies as an organ. The skin serves as a protective barricade against abrasion and infection, it conserves water, eliminates wastes, synthesizes vitamin D, regulates temperature to maintain homeostasis, and relays sensory information to the central nervous system.

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Structure of the Skin

The structure of the skin can be seen in Figure 9-1. There are two layers within the skin, each of which is composed of a variety of tissue types. In addition, there is an underlying layer, which provides support to the skin.

EPIDERMIS

The **epidermis** is a thin layer found on the surface of the body. It is composed of five layers of **stratified squamous epithelial tissue**, which is connected to the dermis via a basement membrane. Cells in the **basal (bottom) layer** of the epidermis constantly divide by mitosis to provide enough skin cells to replace those lost due to shedding. An overgrowth of epidermal cells causes calluses. Because the epidermis only contains epithelial tissues, there are no blood vessels present to provide O_2 and nutrients. These items must be provided from the dermis via diffusion.

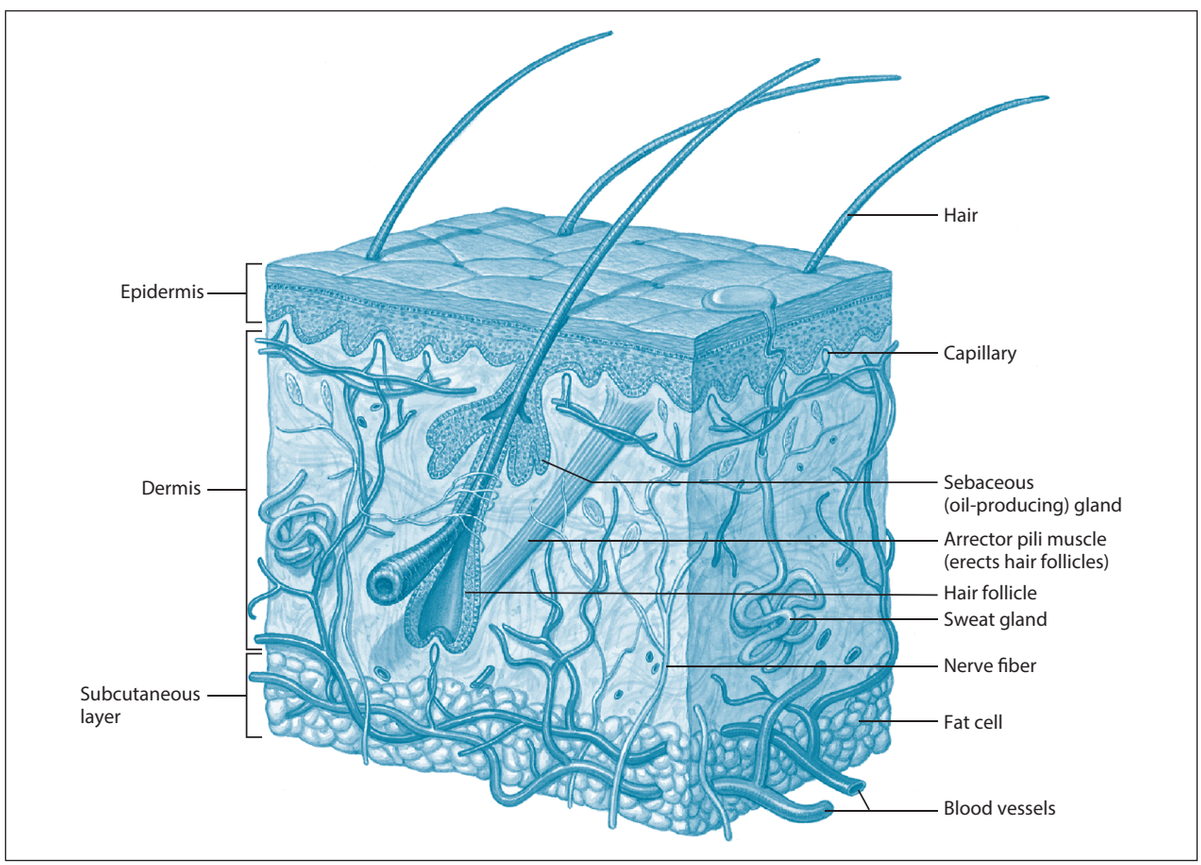

FIGURE 9-1 The skin is composed of a variety of tissue types and contains accessory structures in the form of glands, follicles, and hair. *Source:* From George B. Johnson, *The Living World*, 3rd ed., McGraw-Hill, 2003; reproduced with permission of The McGraw-Hill Companies.

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As cells move upward in the epidermis, they die due to lack of O_2 and nutrients. They are also filled with the waterproofing protein called **keratin**. The cells near the top of the epidermis are dead, keratinized cells that are relatively impenetrable to water. Nails are a specialized structure containing highly keratinized cells growing from a nail bed. They are used for protection at the ends of the extremities.

In the bottom layers of the epidermis, **melanocytes** are present. These cells make the protein **melanin**, which protects the cells from UV damage and provides the skin with pigmentation. Those with more melanin, and thus darker skin, have better protection against UV damage to the skin.

DERMIS

The **dermis** is much thicker than the epidermis. Its primary function is to support the epidermis and anchor it to deeper tissues. The main tissue type is relatively dense connective tissue containing **collagen** and **elastic fibers**. There is a good blood supply as well as many sensory neurons located within the dermis. There are also accessory structures found within the dermis:

- **Hair follicles and hair.** Hair follicles allow for the growth of hair. Hair itself is composed of dead, keratinized epidermal cells that are pushed up and out of the follicle. In mammals, hair is used to help regulate body temperature. Since humans lack significant amounts of hair on most of their body, it does not help with temperature regulation. Each hair follicle has attached to it a small **arrector pili muscle**, which can adjust the positioning of the hair follicle. In animals with a lot of hair, this raises the hair to help provide insulation around the body to conserve heat. In humans, the contraction of these muscles causes goosebumps. Since muscle contractions generate heat, the shivering that occurs due to rapid muscle contractions, including the arrector pili muscles, is a way to generate heat when the body is cold.
- **Sweat glands.** Sweat glands are used for dual purposes, including the cooling of the body by the evaporative action of water on the skin's surface, as well as the excretion of waste products such as urea and electrolytes in small concentrations. Some sweat glands secrete directly to the skin's surface, while others secrete into hair follicles. Sweat glands are under the control of the nervous system.
- **Sebaceous glands.** Each hair follicle is associated with a sebaceous (oil) gland. These glands secrete a fluid called **sebum** into the follicles to lubricate the follicle and the skin. In individuals that excrete excess sebum, bacteria may accumulate in the follicles, resulting in the inflammation characteristic of acne.

SUBCUTANEOUS LAYER

The subcutaneous layer is also known as the **hypodermis**, and it has the job of supporting the skin. It contains a large proportion of loose connective tissue as well as an

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excellent blood supply. The subcutaneous layer anchors the skin to tissues and muscle deeper within the body. It also serves as an insulator that helps with thermoregulation in the body due to the presence of adipose tissue also known as subcutaneous fat.

Because blood is warmer than body temperature, the patterns of circulation in the surface capillaries of the dermis and subcutaneous layer can be used to conserve or release heat as needed. During **vasoconstriction**, blood vessels constrict, keeping blood and heat near the body's core. During **vasodilation**, the blood vessels dilate, allowing some of the heat from the blood to escape through the surface of the skin.

MUSCULAR SYSTEM

Muscles provide structural support, help maintain body posture, regulate openings into the body, assist in thermoregulation via contractions (shivering) that generate heat, and contract to help move blood in the veins toward the heart, thus assisting in peripheral circulation. In Chapter 5, three types of muscle tissue were introduced. Skeletal muscle and cardiac muscle are striated, whereas smooth muscle is not. Cardiac and smooth muscle are involuntary, whereas skeletal muscle is under voluntary control.

Skeletal Muscle

Skeletal muscles are responsible for voluntary movement. The cells in skeletal muscle have multiple nuclei as the result of the fusing of multiple cells. The muscle cells also contain high levels of mitochondria to provide ATP needed for contraction and the protein myoglobin that acts as an O_2 reserve for muscles.

The fibers of skeletal muscle can be classified as fast-twitch or slow-twitch fibers. **Fast-twitch fibers** are designed for a fast rate of contraction, but they lack stamina and fatigue easily because their primary energy source is **anaerobic cellular respiration**. They have less myoglobin and mitochondria than slow-twitch cells. The **slow-twitch fibers** contain more mitochondria and more myoglobin, giving them longer endurance as they obtain most of their ATP from **aerobic cellular respiration**.

STRUCTURAL ORGANIZATION OF SKELETAL MUSCLE

Muscles are a bundle of muscle cells held together by connective tissue as seen in Figure 9-2. The muscle cells have **sarcoplasm** (cytoplasm), a modified endoplasmic reticulum called the **sarcoplasmic reticulum**, and a plasma membrane called the **sarcolemma**, which interacts with the nervous system via the **transverse tubule system** (T tubule). This system provides channels for ion flow through the muscle and has anchor points for sarcomeres.

Within the muscle cells are bundles of muscle fibers called **myofibrils** made of the proteins actin, troponin, tropomyosin, and myosin. **Actin fibers** have a thin diameter and associate with the proteins **troponin** and **tropomyosin** to produce

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thin filaments. **Myosin** fibers have a thick diameter with protruding heads and are called **thick filaments**.

In skeletal muscles, the actin and myosin fibers overlap each other in highly organized, repeating units called **sarcomeres**. The overlapping of the fibers is what causes striation of the muscle. The shortening of sarcomeres is what causes muscle contraction. The structure of a sarcomere can be seen in Figure 9-3.

The major regions of the sarcomere are as follows:

- **M line.** Marks the center of the sarcomere
- **Z line.** Separates one saromere from the next
- **H zone.** Area where only thick filaments are present; shortens during contraction
- **I band.** Area where only thin filaments are present; shortens during contraction
- **A band.** Area where thick and thin filaments overlap

Sliding Filament Model. Muscle tissues have regions where the sarcolemma is in contact (via a synapse) with the synaptic knobs of a motor neuron from the somatic

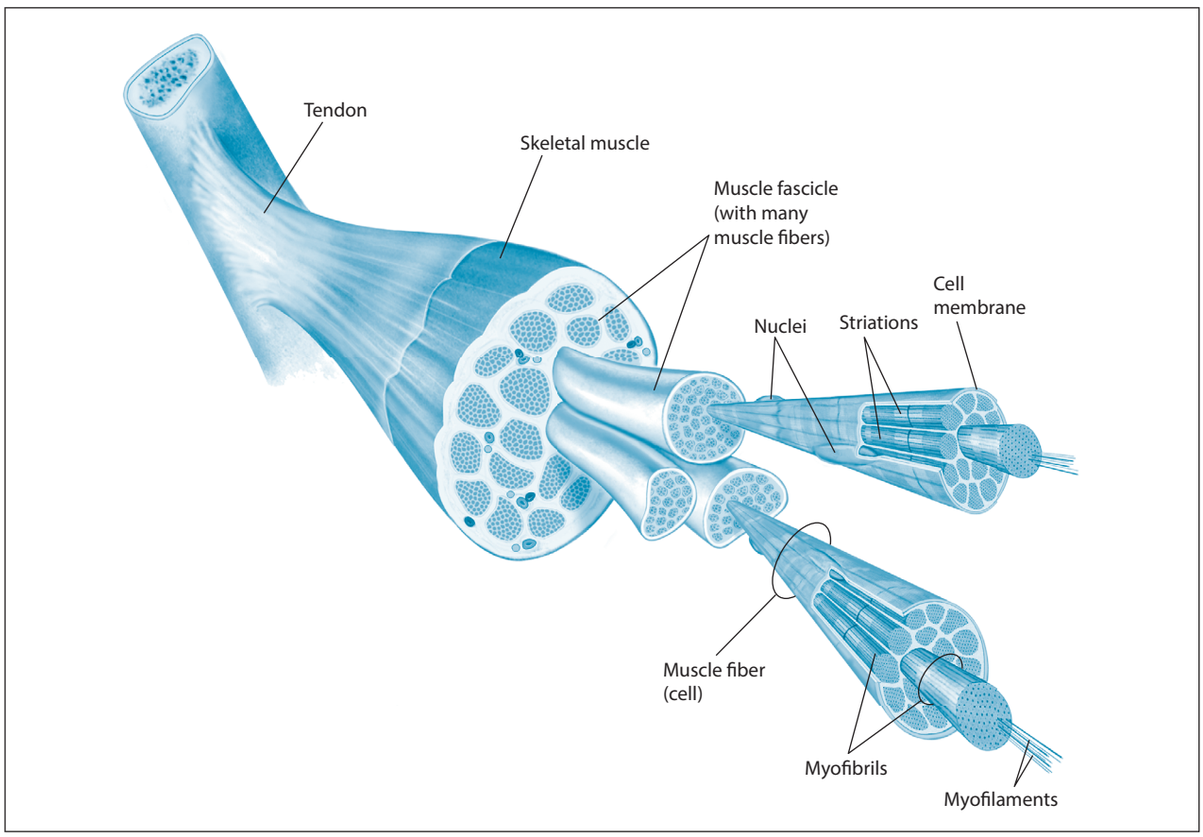

FIGURE 9-2 Skeletal muscle structure. Skeletal muscles are composed of bundles of muscle cells or fibers. Each fiber is composed of myofibrils, which are in turn composed of myofilaments. *Source:* From George B. Johnson, *The Living World*, 3rd ed., McGraw-Hill, 2003; reproduced with permission of The McGraw-Hill Companies.

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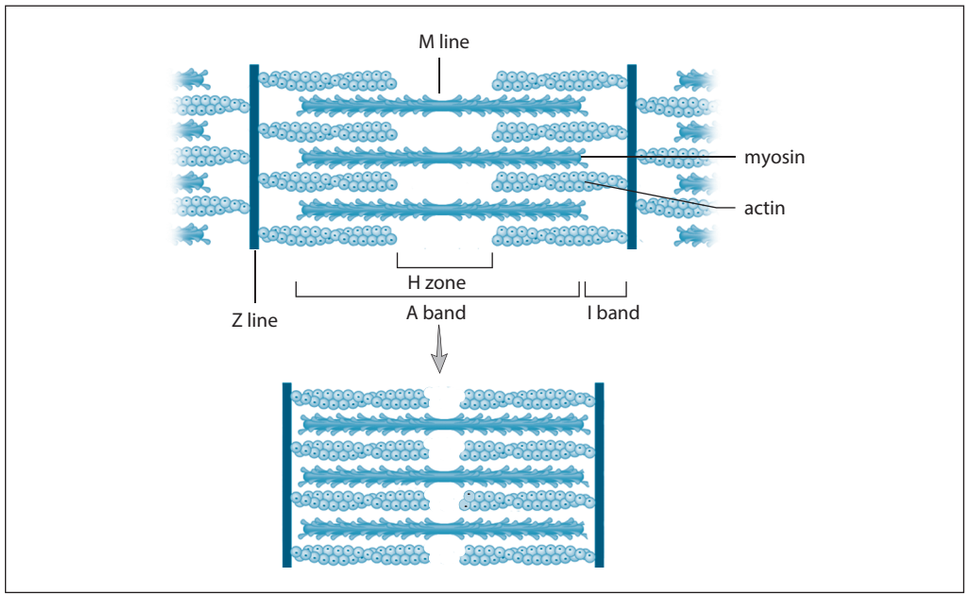

FIGURE 9-3 Sarcomere structure. Shortening of the sarcomere occurs when actin filaments move toward the center of the sarcomere. This shortening of the sarcomere is responsible for skeletal muscle contraction. *Source:* From Sylvia S. Mader, *Biology*, 8th ed., McGraw-Hill, 2004; reproduced with permission of The McGraw-Hill Companies.

branch of the peripheral nervous system. This area is the **neuromuscular junction**. A neurotransmitter called **acetylcholine** is released from the motor neuron and binds to receptors on the sarcolemma, causing the initiation of an action potential that will initiate shortening of the sarcomeres. The muscle fibers influenced by a single neuromuscular junction are termed a **motor unit**.

The action potential that occurs based on stimulation from the motor neuron will cause the release of calcium from the sarcoplasmic reticulum into the sarcoplasm. The calcium binds to the troponin in the thin filaments. This causes a conformational shift in the tropomyosin protein in the thin filament. This change in shape allows for the exposure of myosin binding sites on the actin. The myosin heads can now bind to the myosin binding sites on the actin, forming **cross-bridges**. Hydrolysis of ATP allows for the power stroke to occur, which pulls the thin filaments toward the center of the sarcomere. The release of the myosin heads from the actin occurs when another ATP binds to the myosin heads. Calcium is used again to expose the myosin binding sites on actin so that the myosin heads can bind and the power stroke can occur. The process repeats, each time pulling the thin filaments closer in toward the center of the sarcomere.

When the sarcolemma is no longer stimulated by the motor neuron, the process of contraction ends. ATP binds to myosin heads, causing them to dissociate from actin. The calcium is collected and transported back to the sarcoplasmic reticulum. Without calcium, the myosin binding sites are blocked by troponin and tropomyosin, and the sarcomere will return to its original length.

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Smooth Muscle

Smooth muscle can be found in multiple parts of the body, including the bladder, digestive tract, reproductive tracts, and surrounding blood vessels. Each cell in smooth muscle contains a single nucleus, as opposed to the multiple nuclei found in skeletal muscle. Smooth muscle contains actin and myosin, but it is not organized as sarcomeres, which is why smooth muscle lacks striations. The actin and myosin slide over each other. This sliding is regulated by calcium and requires energy provided by ATP.

The **autonomic branch of the peripheral nervous system** innervates smooth muscles via sympathetic and parasympathetic stimulation to produce involuntary contractions. The **sympathetic response** generally uses the neurotransmitters epinephrine (adrenaline) and norepinephrine (noradrenaline) to prepare the body for physical activity. The **parasympathetic response**, on the other hand, responds to acetylcholine and is used to return the body and muscles to a relaxation state. Smooth muscle can perform **myogenic activity**, meaning it can also contract without stimulation from the nervous system.

Cardiac Muscle

Cardiac muscle is only found in the myocardium of the heart. It is striated due to the presence of sarcomeres (which require calcium and ATP for contraction, just as in skeletal muscle) but is not multinucleated like skeletal muscle. A typical cardiac muscle cell has one, or possibly two, nuclei. Cardiac muscle is innervated by the **autonomic branch of the peripheral nervous system**. Like smooth muscle, it can also perform myogenic activity, contracting without stimulation from the nervous system.

SKELETAL SYSTEM

Skeletons can exist as **exoskeletons** found on the exterior of the body or **endoskeletons** found on the interior of the body. The disadvantage of an exoskeleton (found in many arthropods) is that it does not grow with the organism, making it necessary to shed the skeleton and produce a new one to accommodate growth. An endoskeleton is found in vertebrates, including fish, birds, and mammals.

The human endoskeleton, seen in Figure 9-4, is made of bone and associated cartilage. It is divided into two major parts: the axial skeleton and the appendicular skeleton. The **axial skeleton** is composed of the skull, vertebral column, sternum, and rib cage. The pelvic and shoulder girdles and limbs in the body are part of the **appendicular skeleton**.

The skeleton is used for protection of internal organs, support, storage of calcium and phosphates, production of blood cells, and movement. The skeleton itself is composed of bones and associated cartilage.

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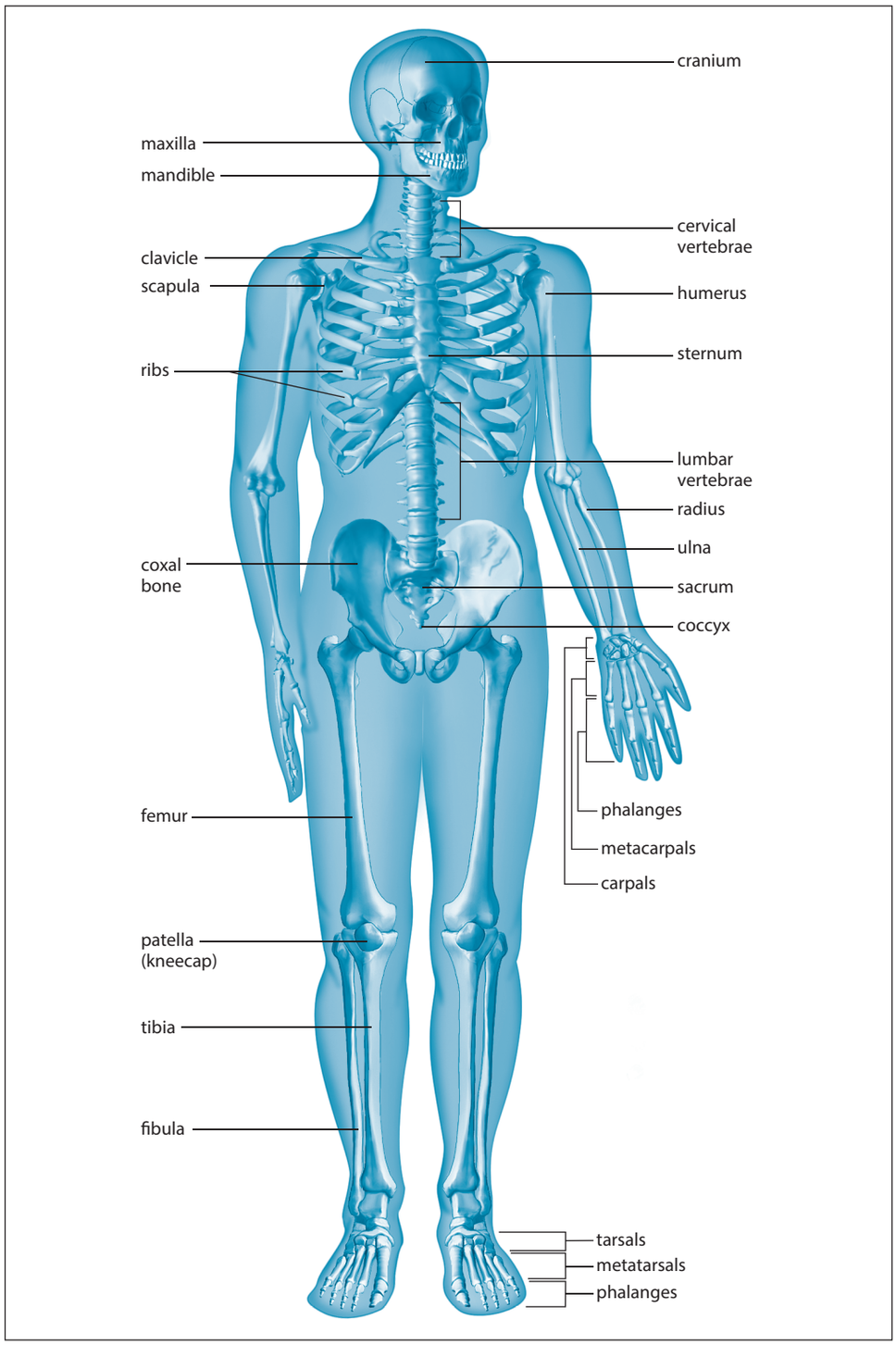

FIGURE 9-4 The human skeleton. The axial skeleton is composed of the skull, vertebral column, sternum, and ribs. The remaining bones in the body are part of the appendicular skeleton. *Source:* From Sylvia S. Mader, *Biology*, 8th ed., McGraw-Hill, 2004; reproduced with permission of The McGraw-Hill Companies.

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Cartilage Structure

Cartilage is a connective tissue. The matrix is termed **chondrin** and the primary cell type is the **chondrocyte**. During embryonic development, the skeleton begins as cartilage. During the developmental period, much of the cartilage is subject to **ossification**, where it is turned into bone by a calcification process. Only a small amount of cartilage remains in the adult skeleton, because most of it has been converted to bone. The primary areas where cartilage is found in the adult skeleton are the nose, ears, discs between vertebrae, rib cage, joints, and trachea. Cartilage is unique in that it contains no blood vessels, nor is it innervated.

Bone Structure

Bone tissue is found as compact bone and spongy bone. **Compact bone** is very dense, whereas **spongy bone** is less dense and contains marrow cavities. Within marrow cavities, there is yellow and red bone marrow. **Red bone marrow** contains the hematopoietic stem cells that differentiate into red blood cells, white blood cells, and platelets. **Yellow bone marrow** is primarily a reserve for adipose (fat) tissue.

Long bones within the body have a characteristic structure, as seen in Figure 9-5. The ends of the bone are typically covered in cartilage and are termed the **epiphyses**. The ends are made primarily of spongy bone covered in a thin layer of compact bone. The shaft of the bone, the **diaphysis**, is made of compact bone surrounding a marrow cavity. The **epiphyseal plate** is a disc of cartilage that separates the diaphysis from each epiphysis, and this is where bone lengthening and growth occur. The **periosteum** surrounds the bone in a fibrous sheath and acts as a site for the attachment of muscles via tendons.

The microscopic structure of bone consists of the **matrix**, which is found within **osteons** seen in Figure 9-6. Within each osteon, there is a **Haversian canal** that contains blood vessels, nerves, and lymphatic vessels. The canal is surrounded by lamellae, which are concentric circles of hard matrix. Within the matrix of the **lamellae**, there are small spaces called **lacunae**, where mature bone cells reside. Small bridges of **canaliculi** connect the lacunae within an osteon and merge into the Haversian canal in order to distribute nutrients and wastes.

Bone Cells

Within the bone, there are three major cell types: osteocytes, osteoblasts, and osteoclasts. The **osteocytes** are found within the lacunae of osteons. They are mature bone cells involved in the maintenance of bone tissue. Osteoblasts and ostoeclasts are found within bone tissue as well and are immature cells. Both are involved in the constant process of breaking down and building bone known as **bone remodeling**. **Osteoblasts** build bone by producing components of the matrix, whereas osteoclasts break down

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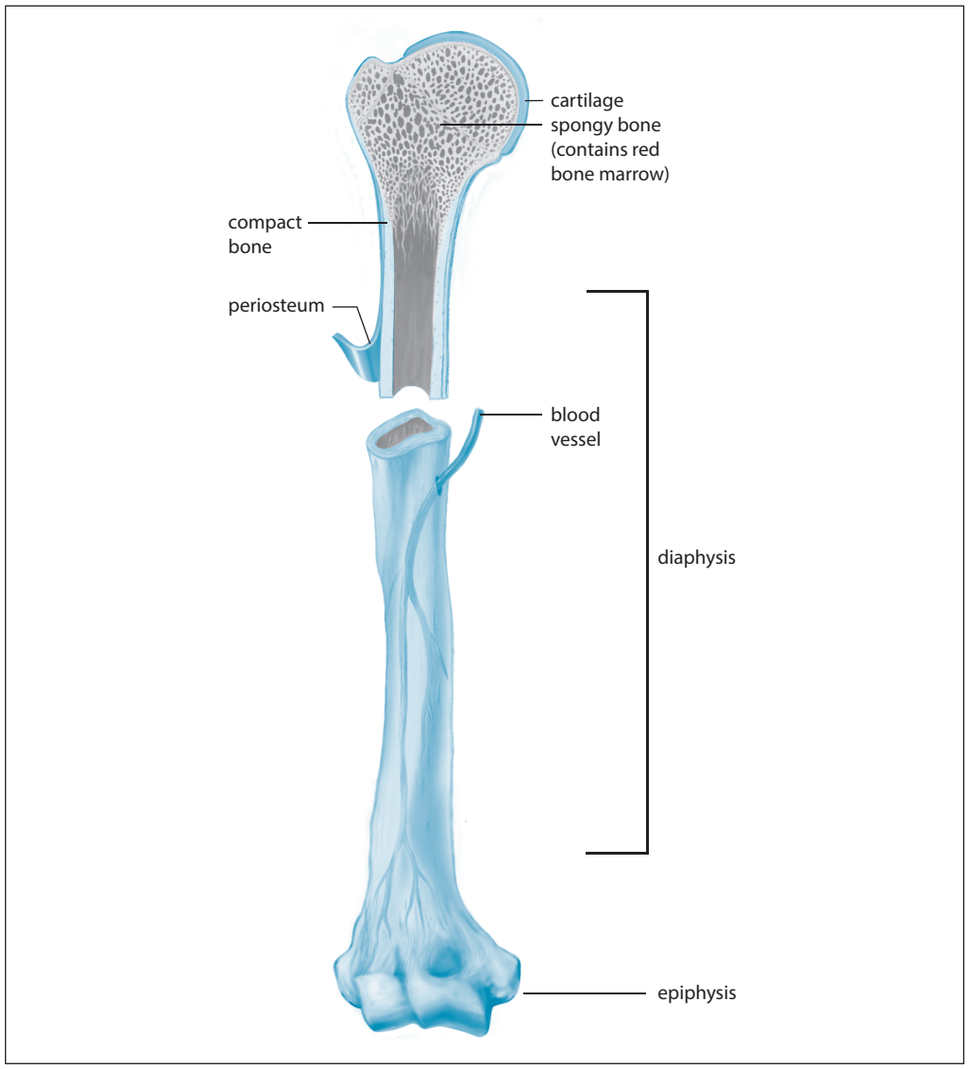

FIGURE 9-5 Long-bone structure. Spongy bone tissue contains red bone marrow and is located at the ends of long bones. The hollow marrow cavity located in the shaft of the bone contains yellow bone marrow. *Source:* From Sylvia S. Mader, *Biology*, 8th ed., McGraw-Hill, 2004; reproduced with permission of The McGraw-Hill Companies.

bone in the process of bone reabsorption. Eventually, osteoblasts and osteoclasts become trapped within matrix of bone tissue and become osteocytes. **Osteoblasts** are also responsible for bone growth and ossification during development. Ideally, the levels of matrix break down and building will be in equilibrium once growth is complete.

The hormone **calcitonin** from the thyroid gland and **parathyroid hormone** from the parathyroid glands are responsible for the process of bone remodeling. When blood calcium levels are high, calcium is stored in the matrix, thus building bone. When blood calcium levels are low, calcium is released from the matrix by breaking down bone

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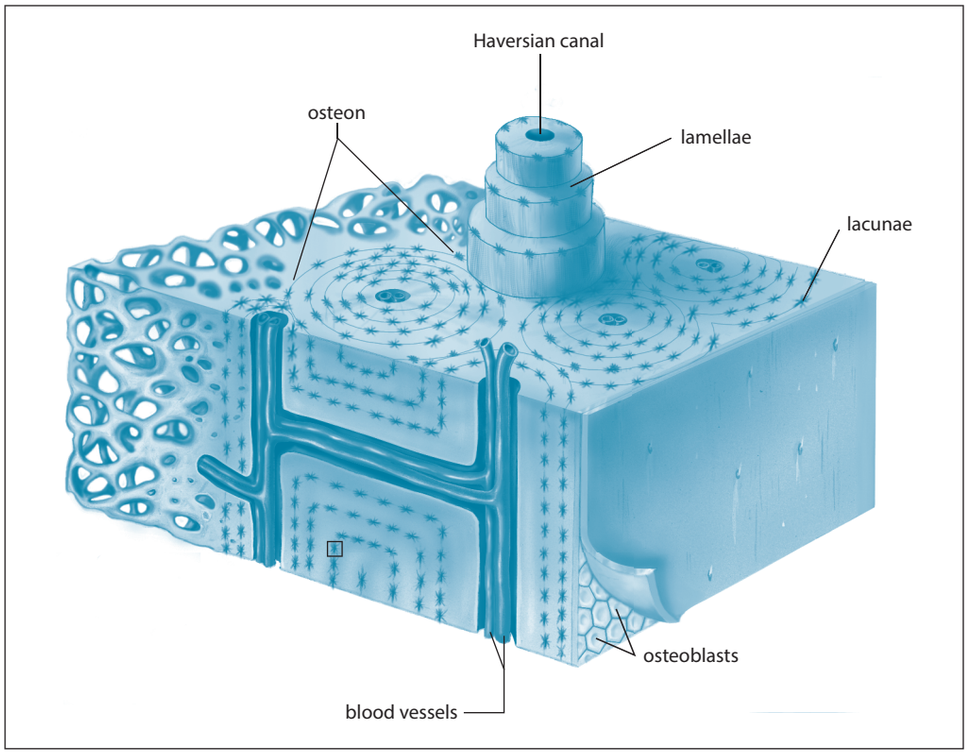

FIGURE 9-6 Bone tissue structure. *Source:* From Sylvia S. Mader, *Biology*, 8th ed., McGraw-Hill, 2004; reproduced with permission of The McGraw-Hill Companies.

tissues. The levels of blood calcium must be carefully regulated, as calcium is needed for muscle contraction, nervous system communication, and other functions.

Joints

Joints are areas where two bones meet and are composed of connective tissues.

Immovable joints such as those involved with skull bones do not move at all. **Partially movable joints** have some degree of flexibility, such as the vertebrae in the spinal column. **Synovial joints**, such as the hip or knee, have a much larger range of motion and have a fluid-filled joint cavity. **Ligaments** are made of dense connective tissue and attach one bone to another within a synovial joint.

CIRCULATORY SYSTEM

The **circulatory system** in humans consists of a **four-chambered heart** to pump blood and a series of **vessels** needed to transport blood in the body. **Blood** is a connective tissue used to deliver O_2, nutrients, water, hormones, and ions to all the cells of the body. It is also used to pick up the CO_2 and wastes produced by cells and to move these

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to the appropriate areas for elimination. Further, it assists in thermoregulation in the body as well as fighting infectious agents.

The circulatory system is closely linked to the following organ systems in the body:

- **Respiratory system.** For the elimination of CO_2, the pickup of O_2, and assistance regulating blood pH
- **Urinary system.** For the filtration of blood, removal of nitrogenous wastes, regulation of blood volume and pressure, and regulation of blood pH
- **Digestive system.** For the pickup of nutrients to be distributed to the body

Blood

The critical functions of the circulatory system are achieved by blood, which is transported through the system. **Blood** consists of a **liquid matrix**, **plasma**, and **formed elements** or cells. Humans contain between 4 and 6 liters of blood, and this entire volume can be circulated through the body in less than 1 minute. The pH of blood is 7.4 (slightly basic), and the temperature is slightly warmer than body temperature. Because the temperature of blood is warmer than the body, changing patterns of circulation can help distribute heat to where it is needed in the body. **Vasoconstriction** decreases the diameter of vessels, keeping blood closer to the core to warm the body, whereas **vasodilation** increases the diameter of the vessels, allowing them to release heat toward the surface of the skin to cool the body.

PLASMA

Plasma is the liquid portion of the blood, and it occupies approximately 55 percent of the total volume of blood. The primary component of plasma is **water**. In order to adjust the volume of blood in the body, the water levels of plasma can be altered. This is one role for the kidneys, which can retain or release water via urine to adjust the **blood volume**. An increase in blood volume increases blood pressure, while a decrease in blood volume decreases blood pressure.

In addition to water, plasma also contains nutrients, cellular waste products, respiratory gases, ions, hormones, and proteins. There are three classes of plasma proteins produced by the liver: immunoglobulins, albumins, and fibrinogen. **Immunoglobulins** are primarily used in the immune response, **albumins** are used to transport certain molecules within the blood, and **fibrinogen** is an inactive form of one protein needed to clot blood.

FORMED ELEMENTS

The **formed elements**, or cells, of the blood are all derived from **hematopoietic stem cells** in the bone marrow. The three types of cells found in the blood are **erythrocytes** (red blood cells), **leukocytes** (white blood cells), and **thrombocytes** (platelets), all seen in Figure 9-7.

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The **hematocrit value** of blood is a relative comparison of cell volume to plasma volume. The percentage of blood occupied by cells is considered the hematocrit value and is generally about 45. Because red blood cells are by far the most abundant blood cell, hematocrit values are primarily influenced by red blood cells.

Erythrocytes. **Erythrocytes** are the most abundant type of blood cell. As they mature from **hematopoietic stem cells** in the bone marrow due to the influence of the hormone **erythropoietin (EPO)**, they do something odd in that they lose their **organelles**. Without organelles, these cells are unable to perform aerobic cellular respiration and they cannot perform mitosis to replace themselves. These cells live only about 120 days, at which point they are destroyed by the liver and spleen. The end product of red blood cells' hemoglobin breakdown is **bilirubin**, which is ultimately excreted into the small intestine via bile from the liver.

In order to make new red blood cells, more hematopoietic stem cells in the bone marrow must be coerced to differentiate into red blood cells by the hormone EPO. Red blood cells also have an unusual biconcave disc shape that provides them with increased surface area and the ability to be flexible as they move through small vessels.

Transport of Gases. The critical component of erythrocytes is the protein **hemoglobin**. Each erythrocyte contains about 250 million hemoglobin molecules. Functional hemoglobin consists of 4 protein chains, each wrapped around an iron (heme) core.

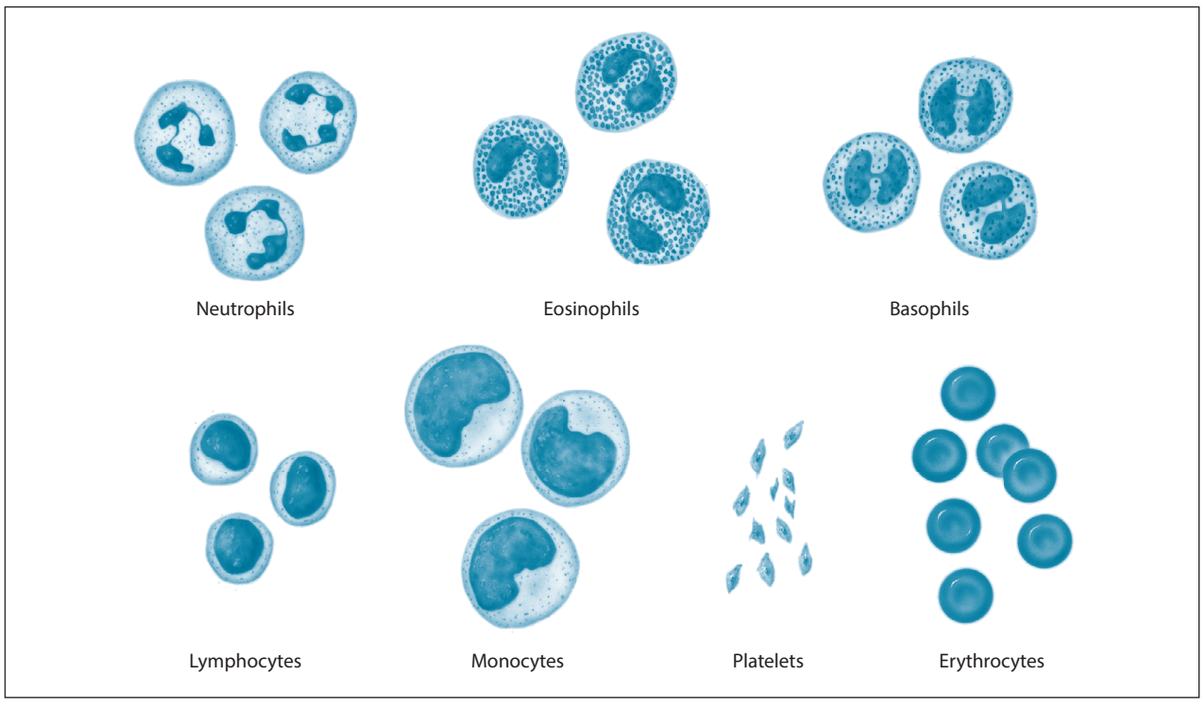

FIGURE 9-7 A comparison of blood cell types: red blood cells, white blood cells, and platelets all have different structures and functions. *Source:* From Eldon D. Enger, Frederick C. Ross, and David B. Bailey, *Concepts in Biology*, 11th ed., McGraw-Hill, 2005; reproduced with permission of The McGraw-Hill Companies.

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A molecule of hemoglobin is capable of carrying 4 molecules of O_2. In total, a single red blood cell can carry about a billion O_2 molecules. The affinity of hemoglobin for O_2 is good; however, fetal hemoglobin has a higher affinity for O_2 than does adult hemoglobin. Further, the respiratory poison carbon monoxide (CO) has a much greater affinity for hemoglobin than does O_2. Carbon monoxide binds to hemoglobin at the expense of O_2, ultimately starving the cells of O_2.

As hemoglobin binds to 1 O_2 molecule, a conformational change in the shape of hemoglobin occurs to allow for the loading of the next 3 O_2 molecules. The same process occurs during the unloading of O_2. Once O_2 is unloaded in the capillary beds of the body, some of the CO_2 produced by the cells is carried by hemoglobin. CO_2 also combines with water to produce carbonic acid, which dissociates into hydrogen ions and bicarbonate ions. The hemoglobin carries the hydrogen ions whereas the bicarbonate ions are carried by plasma. The **Bohr effect** states that increasing concentrations of hydrogen ions (which decrease blood pH) and increasing concentrations of CO_2 will decrease hemoglobin's affinity for O_2. This allows for O_2 to unload from hemoglobin into tissues of the body, such as muscle, when CO_2 levels are high in tissues. In the lungs, a high level of O_2 encourages the dissociation of hydrogen ions from hemoglobin and these hydrogen ions will join with bicarbonate ions in the plasma to form CO_2 and water. The CO_2 is then exhaled. The enzyme carbonic anhydrase catalyzes the formation and disassociation of carbonic acid.

Blood Type. The **ABO blood type** is genetically determined based on the presence or absence of specific antigens on the red blood cells, as discussed in Chapter 3. The immune system does not produce antibodies against any self antigens (ones that are present in the body), but it does have the ability to produce antibodies against any antigens that are considered foreign (absent from the body). When an incompatible blood transfusion occurs, the antibodies in the recipient attack the foreign antigens of the incompatible blood type, causing agglutination of the blood. Because type O blood has no surface antigens, it is considered the universal donor. Those with type AB blood make no antibodies, so they are considered universal recipients. The following table displays some important characteristics of blood types and compatibilities.

TABLE 9-1 Blood Types and Compatibilities

Blood Type	Antigens Present	Antibodies Produced	Can Donate to Types	Can Receive from Types
Type A	A	anti-B	A, AB	A, O
Type B	B	anti-A	B, AB	B, O
Type AB	A and B	none	AB	A, B, AB, O
Type O	none	anti-A and anti-B	A, B, AB, O	O

There is another red blood cell antigen, the **Rh factor**, that is controlled by a separate gene. If the Rh factor is present, this is considered Rh^+ and no antibodies are made against the Rh factor. If the Rh factor is absent, this is considered Rh^- and anti-Rh antibodies can be made. Those that are Rh^+ can receive blood matched for ABO type

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that is Rh^+ or Rh^-. Those who are Rh^- can only receive blood matched by ABO type and that is also Rh^-.

Leukocytes. **Leukocytes**, or **white blood cells**, are a diverse collection of cells, all of which are derived from stem cells in the red bone marrow and function throughout the body. They are found in much lower levels than red blood cells; however, the white blood cell level can fluctuate greatly, particularly when a person is fighting infection. Details of the specific types of white blood cells will be discussed later in this chapter with the immune system.

White blood cells can be categorized in the following manner and are distinguished based on their microscopic appearance:

- **Granulocytes** have cytoplasm with a granular appearance. These cells include **neutrophils**, **basophils**, and **eosinophils**. Neutrophils are used to perform phagocytosis. Basophils are involved in inflammation and allergies. Eosinophils are involved in dealing with parasitic infections.
- **Agranulocytes** have cytoplasm that does not have a grainy appearance. They include **monocytes**, which mature into **macrophages**, and **lymphocytes**, which are further subdivided into **T cells** and **B cells**. Monocytes and macrophages perform **phagocytosis**, whereas lymphocytes function in the adaptive defenses of the immune system.

Thrombocytes. **Thrombocytes**, or **platelets**, are fragments of bone marrow cells called **megakaryocytes**. Platelets live only 10 to 12 days once mature, so they are replaced often. During injury to blood vessels, a complex series of reactions is initiated, which ultimately converts the inactive plasma protein fibrinogen to fibrin. The platelets release **thromboplastin**, which converts the inactive plasma protein **prothrombin** to the active form, thrombin. **Thrombin** then converts **fibrinogen** to fibrin. **Fibrin** forms a meshwork around the injury that serves to trap other cells to form a clot. The process of blood clotting requires multiple plasma proteins as well as calcium and vitamin K.

Blood Vessels

Blood flow progresses in unidirectional loops as seen in Figure 9-8. One loop is the **systemic circuit**, which moves blood from the heart throughout the body and back to the heart. The other loop is the **pulmonary circuit**, which moves blood from the heart to the lungs and back to the heart. The blood flows in these loops through a series of **vessels**, the major ones being arteries and veins.

ARTERIES AND VEINS

Arteries are large blood vessels leaving the heart. The arteries have thick walls and are very elastic to accommodate blood pressure. As arteries leave the heart, they branch

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into smaller vessels called **arterioles**, which become more and more narrow, eventually forming the **capillaries**, which are the smallest vessels. **Capillary beds** are the site of gas exchange within tissues and are so small that red blood cells have to line up single file to pass through them. In the capillary beds O_2 is releases and CO_2 is picked up.

Once the gases have been exchanged, the capillaries become wider in diameter and become **venules**, which head back toward the heart. The venules become larger veins that ultimately merge into the heart. **Veins** are not as thick-walled as arteries, because they do not have to deal with the forces exerted by blood pressure. Although blood pressure pushes blood through arteries and arterioles, the movement of blood in venules and veins is facilitated by smooth muscles that contract to push the blood along and by valves that close to prevent backflow of blood. **Vasoconstriction** and

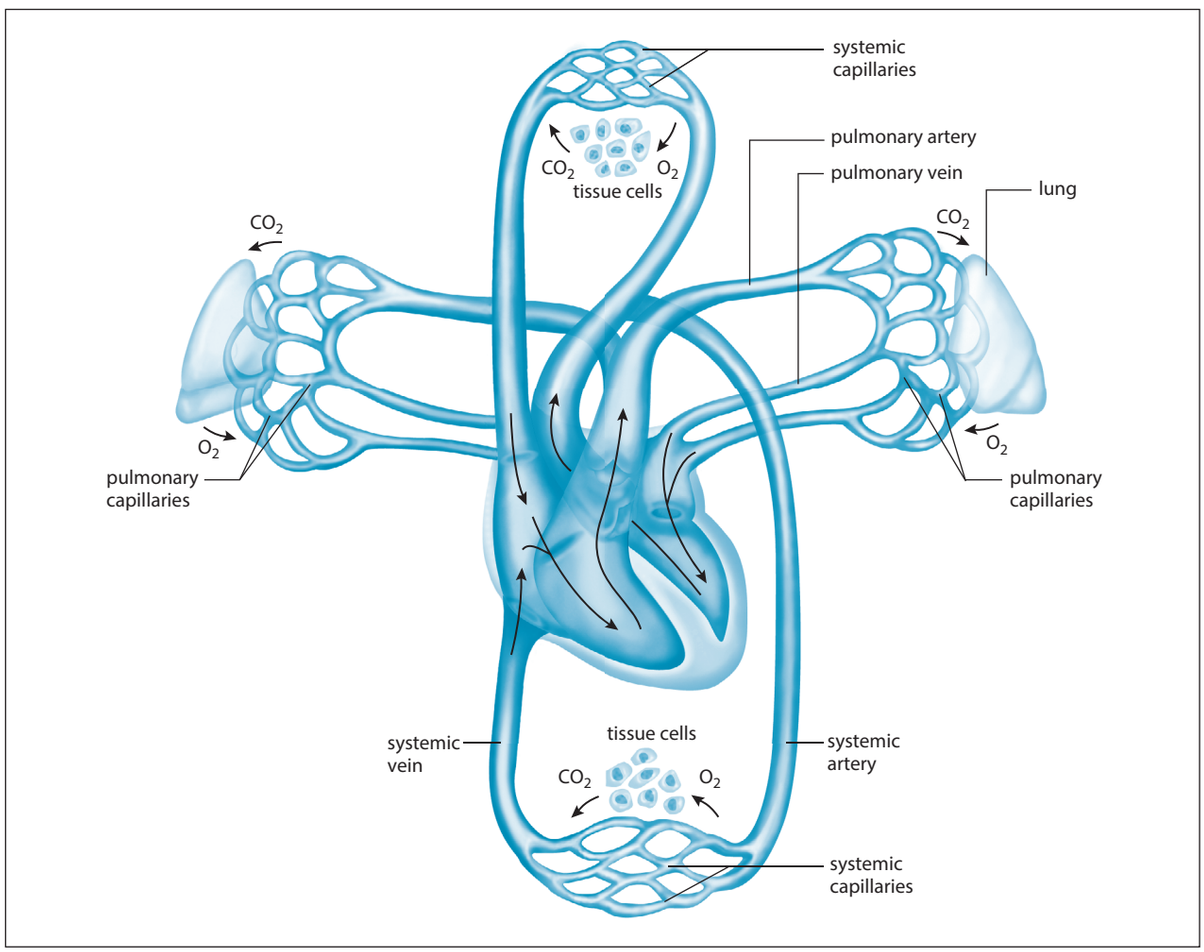

FIGURE 9-8 Blood flow through the body. The right side of the heart pumps blood to the lungs, where external respiration occurs, whereas the left side of the heart pumps blood to the body, where internal respiration occurs. *Source:* From Sylvia S. Mader, *Biology*, 8th ed., McGraw-Hill, 2004; reproduced with permission of The McGraw-Hill Companies.

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vasodilation of arteries serves as a means of regulating blood flow, blood pressure, and temperature.

The arteries of the systemic circuit branch off the left side of the heart and carry oxygenated blood to the capillaries of the body where gas exchange occurs. Deoxygenated blood returns to the right side of the heart via systemic veins. The pulmonary circuit involves pulmonary arteries that branch off the right side of the heart and carry deoxygenated blood toward the lungs. The pulmonary capillaries allow for gas exchange with the **alveoli** (air sacs) of the lungs. The newly oxygenated blood now moves back toward the left side of the heart via pulmonary veins.

CAPILLARY BEDS

A **capillary bed** is a collection of capillaries all branching off a single arteriole that serves a specific location in the body. The blood entering the systemic capillary bed is oxygenated and high in nutrients. As blood moves through the capillary bed, O_2 and nutrients diffuse out into tissues and CO_2 and wastes diffuse in. After this has happened, the capillaries merge into a venule, which carries the deoxygenated blood back toward the heart. In **pulmonary circulation**, deoxygenated blood enters the pulmonary capillary bed, where CO_2 diffuses out and O_2 diffuses in, causing oxygenation of the blood. **Precapillary sphincters** guard the entrance to the capillary beds.

The movement of materials into and out of the capillaries is based on pressure. **Hydrostatic pressure** on the arteriole end of the capillary bed pushes fluid containing O_2 and nutrients out of the capillaries. Most of the water that is pushed out must be reclaimed on the venule end of the capillary bed. Because the solute concentration in the capillaries is higher than the fluids surrounding them, osmosis draws the water back into the capillaries at the venule end of the capillary bed as CO_2 and wastes diffuse in. Any excess water that is not reclaimed will be returned to circulation by the lymphatic system. Some materials may enter or exit the capillaries via endocytosis or exocytosis.

Structure of the Heart

The structure of the heart can be seen in Figure 9-9. The **myometrium** is the cardiac muscle of the heart. Tissues other than muscle compose supporting structures such as valves and chamber linings. The right and left sides of the heart have very distinct functions and are kept separate from each other by the **septum**, which is a thick barricade between the two sides of the heart. Each side of the heart has two chambers. The upper chamber is the **atrium** and the lower chamber is the **ventricle**. The atrium and ventricle are separated by **atrioventricular (AV) valves**. **Semilunar valves** regulate the flow of blood out of the ventricles. A fluid-filled sac called the **pericardium** surrounds the entire heart.

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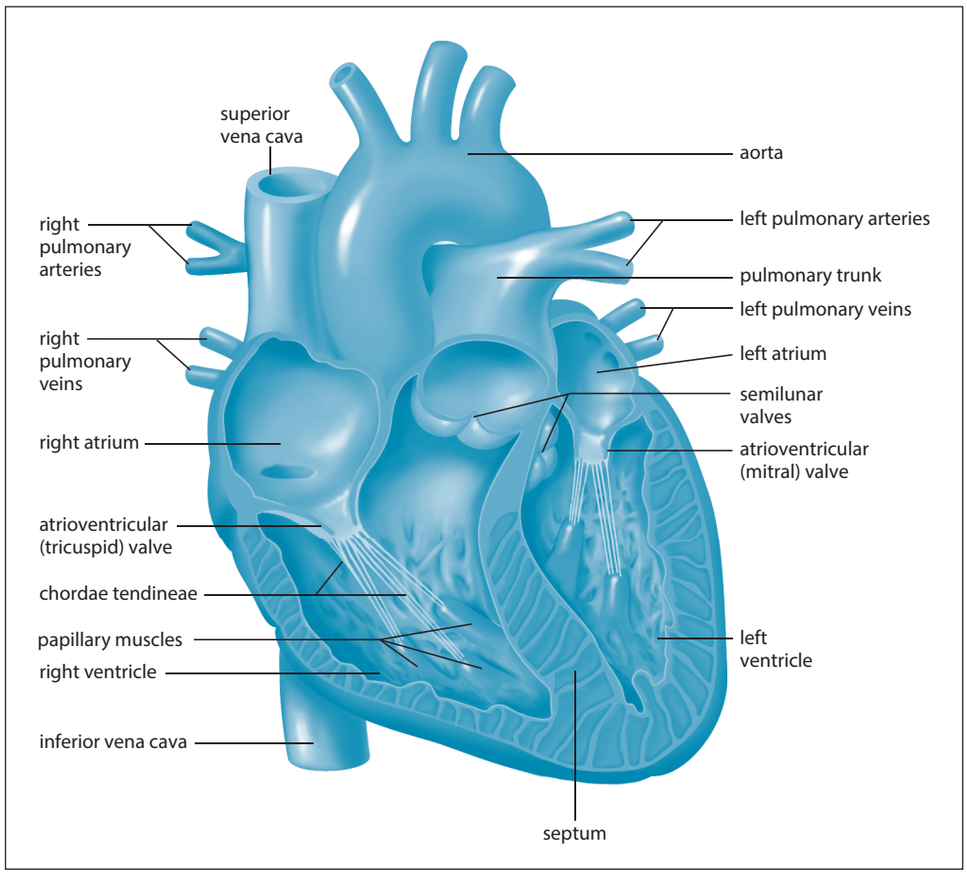

FIGURE 9-9 Heart structure. The venae cavae carries deoxygenated blood into the right side of the heart. The aorta carries oxygenated blood out of the left side of the heart. *Source:* From Sylvia S. Mader, *Biology*, 8th ed., McGraw-Hill, 2004; reproduced with permission of The McGraw-Hill Companies.

Blood Flow Through the Heart

Blood essentially flows in two loops, or circuits, within the body. The right side of the heart receives deoxygenated blood from the body and pumps this blood to the lungs to be oxygenated. The right side is considered the **pulmonary circuit**. The left side of the heart receives oxygenated blood from the lungs and pumps it to the body. This is the **systemic circuit**.

PULMONARY CIRCUIT

The pulmonary circuit begins when veins within the body eventually merge into the venae cavae, which lie on the dorsal wall of the thoracic and abdominal cavities. The **superior vena cava** comes from the head and neck, whereas the **inferior vena cava** comes from the lower extremities. These vessels carry deoxygenated blood and merge into the right atrium of the heart. As the atrium contracts, blood passes through an

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AV valve (the tricuspid valve) into the right ventricle. As the ventricle contracts, blood passes through a semilunar valve (the pulmonary semilunar valve) into the pulmonary arteries. The **pulmonary arteries** carry blood to the lungs and are the only arteries in the body that do not carry oxygenated blood. They branch into capillaries that surround the alveoli (air sacs) in the lungs. Once gas exchange has occurred, pulmonary veins carry the oxygenated blood toward the left side of the heart into the systemic circuit. The pulmonary veins in the body are the only veins to carry oxygenated blood.

SYSTEMIC CIRCUIT

The oxygenated blood carried by the **pulmonary veins** enters the heart through the left atrium. As the atrium contracts (in sync with contraction of the right atrium), blood is pushed through another AV valve (the **bicuspid valve**) to the left ventricle. When the ventricle contracts (also in sync with the right ventricle), the blood is pushed into the aorta via a semilunar valve (the **aortic semilunar valve**). The **aorta** is the largest artery in the body, running along the dorsal wall of the body next to the inferior vena cava. The aorta splits into arteries, arterioles, and eventually capillaries where the blood is once again deoxygenated and must be pushed back to the right side of the heart to begin the process all over again.

The first branches off the aorta are the **coronary arteries**, which serve to provide circulation to the surface of the heart. Blockage of the coronary arteries can stop blood flow to the cardiac muscle, causing death of the cardiac muscle, which is characteristic of a heart attack. After blood flows through the coronary arteries, deoxygenated blood is returned to the right side of the heart by **coronary veins**.

Cardiac Cycle and Regulation of Heart Rate

During the cardiac cycle, the events of a single heartbeat, two contractions occur. First, the two atria contract simultaneously, pushing blood into the ventricles. Next, the two ventricles contract (**systole**), pushing blood out of the heart. A brief resting period (**diastole**) will occur to allow the two atria to refill with blood and then the cycle begins again. An **electrocardiogram** (ECG) can be used to visualize the electrical currents that are generated by the heart during the cardiac cycle.

Cardiac muscle is involuntary and has the ability to contract on its own without stimulation from the nervous system. The impulses that generate heart contraction are spread through the conducting system of the heart as seen in Figure 9-10. The **sinoatrial (SA) node**, also known as the pacemaker, is a bundle of conducting cells in the top of the right atrium that initiates contractions. The SA node sends electrical impulses through the two atria, causing them to contract. The impulse arrives at the **atrioventricular (AV) node** and then is spread through the **bundle of His** and through **Purkinje fibers** in the walls of the ventricles, causing ventricular contraction.

Although the SA node generates its own rate of contraction at an average of 70 contractions per minute, the heart is innervated by the autonomic nervous system, which

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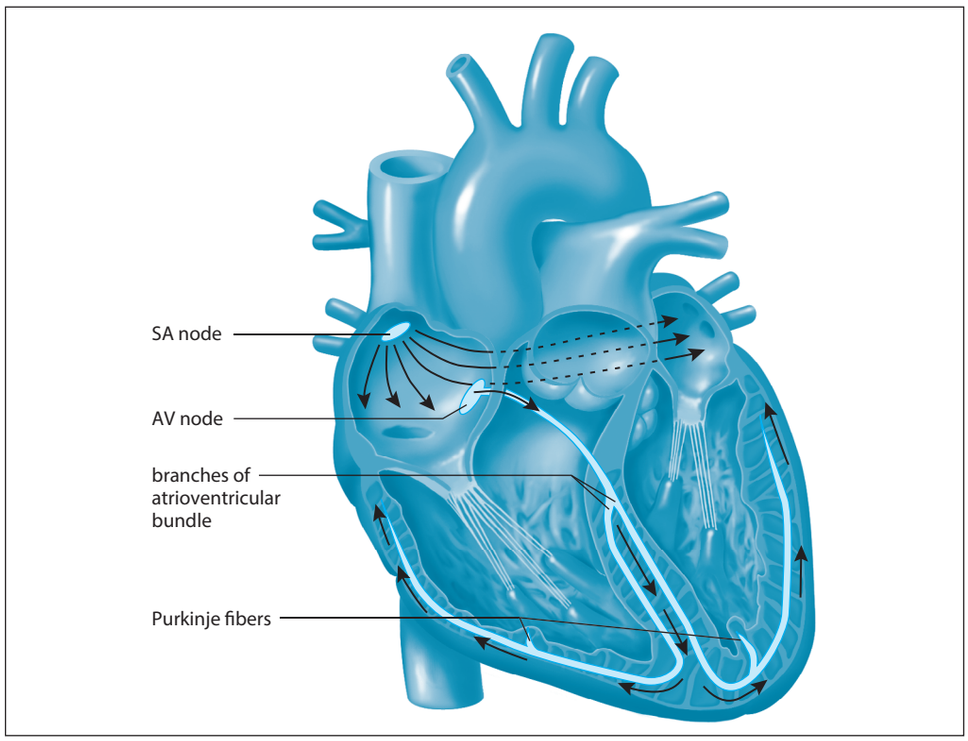

FIGURE 9-10 Conducting system of the heart. The SA node located in the right atrium serves as the pacemaker of the heart. *Source:* From Sylvia S. Mader, *Biology*, 8th ed., McGraw-Hill, 2004; reproduced with permission of The McGraw-Hill Companies.

can adjust the rate of contraction. The **sympathetic branch** of the autonomic nervous system can increase the rate of contraction, whereas the **parasympathetic branch** can decrease the rate of contraction. The **medulla oblongata** in the brain monitors conditions such as blood pH level (which is an indicator of CO_2 and O_2 levels) and signals adjustments in the heart rate as appropriate for the situation.

Blood Pressure

Blood pressure is a measurement of the force that blood exerts on the walls of a blood vessel. Typically it is measured within arteries. The pressure has to be enough to overcome the peripheral resistance of the arteries and arterioles. It is expressed with two values: a systolic pressure and a diastolic pressure. The **systolic pressure** is the higher value and is the pressure exerted on arteries as the ventricles contract. The **diastolic pressure** is the lower value and is a measurement of pressure on the arteries during ventricular relaxation. The primary means of regulation of blood pressure is by regulation of blood volume through the kidneys. The higher the blood volume, the higher the blood pressure is. A **sphygmomanometer** is used to measure blood pressure.

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RESPIRATORY SYSTEM

The **respiratory system** has the primary job of providing the body with O_2 and eliminating CO_2. **Pulmonary arteries**, which are low in O_2 and high in CO_2, come off the right side of the heart and carry deoxygenated blood to the lungs. These arteries branch off into **pulmonary capillaries** surrounding the alveoli in the lungs. CO_2 diffuses from the pulmonary capillaries into the **alveoli** to be exhaled. O_2 that enters the lungs is distributed to hemoglobin in the **erythrocytes** within the capillaries. The newly oxygenated blood travels via **pulmonary veins** back to the left side of the heart, from which it is distributed throughout the body.

In addition to oxygenating blood, the respiratory structures are responsible for pH regulation, vocal communication, the sense of smell, and protection from infectious agents and particles.

Structure of the Respiratory System

The respiratory system is essentially a series of tubes that conducts air into the alveoli located in the lung tissues. The major structures of the system can be seen in Figure 9-11.

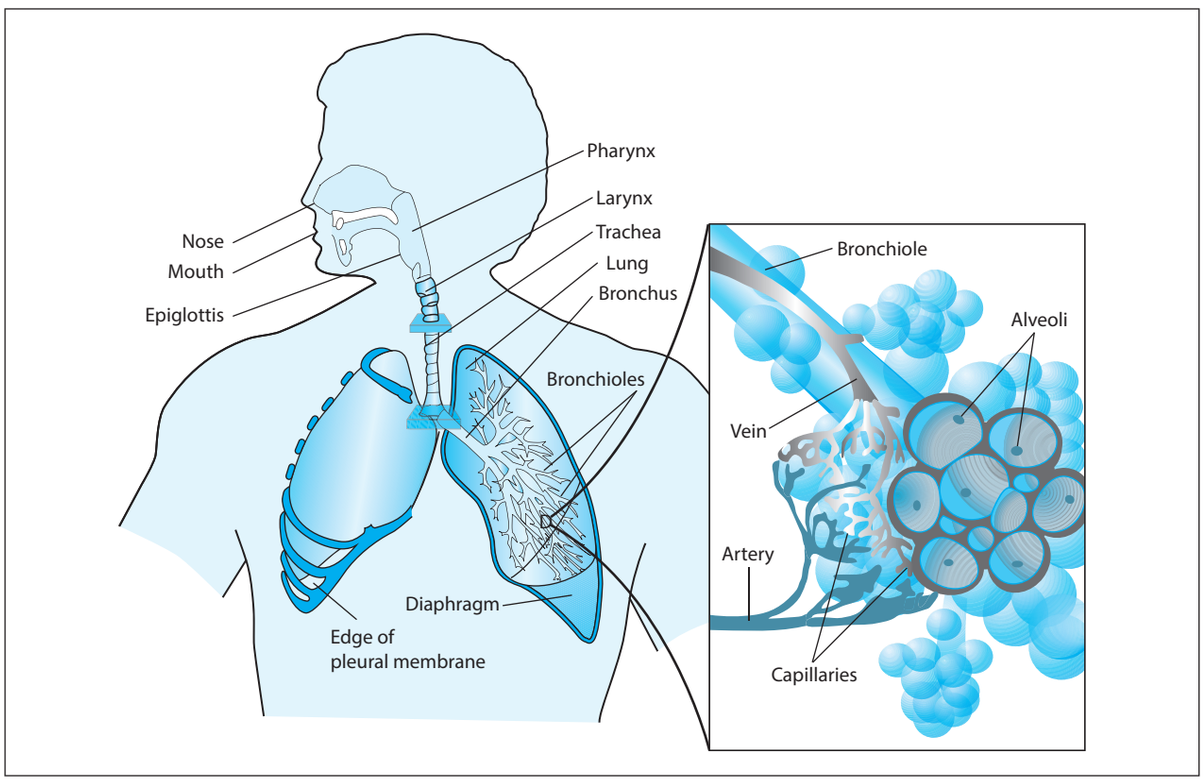

FIGURE 9-11 The respiratory system.

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Air is inhaled through the nose or mouth. Because the respiratory system is an open system, it is particularly vulnerable to infection. In the nose and pharynx (back of the throat), air is warmed to body temperature, moisturized so that gas exchange can occur, and filtered. Both areas are covered with a mucus membrane that helps prevent desiccation of the tissues and collects particles and microbes that may enter the system. The **nose** is particularly well-suited to filtration because it has cilia and hair to help trap substances that enter the respiratory system. Although filtration in the nose and pharynx does not catch all particles and microbes, it catches many of them. The nose has the additional function of olfaction.

Air that passes through the nose or mouth moves into the **pharynx**, where there are two passageways: the **esophagus** and the **larynx**. During breathing, air flows through the **glottis**, which is the opening of the larynx. The **larynx** is the voice box; it is made of cartilage and has vocal cords that vibrate, producing sound. Unless a person is swallowing, the esophagus is closed off and the glottis is open. However, if a person is swallowing, a small piece of cartilage called the **epiglottis** covers the glottis and stops food from entering the larynx.

As air flows through the larynx, it eventually makes its way into the trachea and the lower respiratory tract. The **trachea** is supported by C-shaped rings of cartilage. The interior surface of the trachea is covered with mucus and cilia to further trap any particles or microbes that may not have been caught in the nose or pharynx.

The trachea branches off toward the left and right **bronchi**. The two bronchi branch into smaller and smaller tubes called **bronchioles**. Smooth muscles surrounding the bronchioles can adjust their diameter to meet O_2 demands. The bronchioles terminate in tiny air sacs called the **alveoli**. The alveoli are numerous to provide a large amount of surface area for gas exchange. They are made of **simple squamous epithelium** that allows for easy gas exchange with the capillaries that surround them.

The **lungs** are a collection of resilient tissue, encompassing the bronchioles and alveoli. In humans, the right lung has three **lobes** of tissue, whereas the left lung has only two lobes. A fluid-filled **pleural membrane** surrounds each lung. A **surfactant fluid** produced by the tissues decreases surface tension in the lungs, which keeps the alveoli inflated, preventing them from collapsing. Without surfactant fluid to relieve surface tension, the lungs are unable to function.

Ventilation

Gas exchange within the lungs results from pressure gradients. To get air into the lungs, the volume of the chest cavity must increase to decrease pressure in the chest cavity. This allows air to flow from an area of more pressure (outside the body) to an area with less pressure (the chest cavity). This is the process of **inhalation** (or inspiration). It occurs when the **diaphragm**, the thin muscle that separates the thoracic cavity from the abdominal cavity, contracts and pushes down, as seen in Figure 9-12. The

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intercostal muscles of the rib cage also assist in inhalation by contracting to help move the rib cage up and out. When the diaphragm and intercostal muscles relax, the volume of the chest cavity decreases, which results in a higher level of pressure inside the chest cavity as compared to outside. This forces air to leave the lungs by the process of **exhalation** (expiration).

The control of **ventilation rate** is by the **medulla oblongata of the brain**. The diaphragm is innervated and neurally connected to the area of the medulla that controls breathing. The **inspiratory neurons** are active, causing contraction of the diaphragm, followed by a period of inactivity that allows for relaxation of the diaphragm and exhalation. In a relaxed state, the diaphragm is stimulated between 12 and 15 times per minute. During times of increased O_2 demand and excessive CO_2 production, this rate can increase significantly. Although it might be expected that O_2 levels are the primary influence on **breathing rate**, it turns out that the primary trigger is the CO_2 level, which is monitored by chemoreceptors located in the brain and in certain large blood vessels. As CO_2 levels increase, the pH decreases (due to carbonic acid), and the breathing rate increases to eliminate the excess CO_2. This, in turn, increases the O_2 levels.

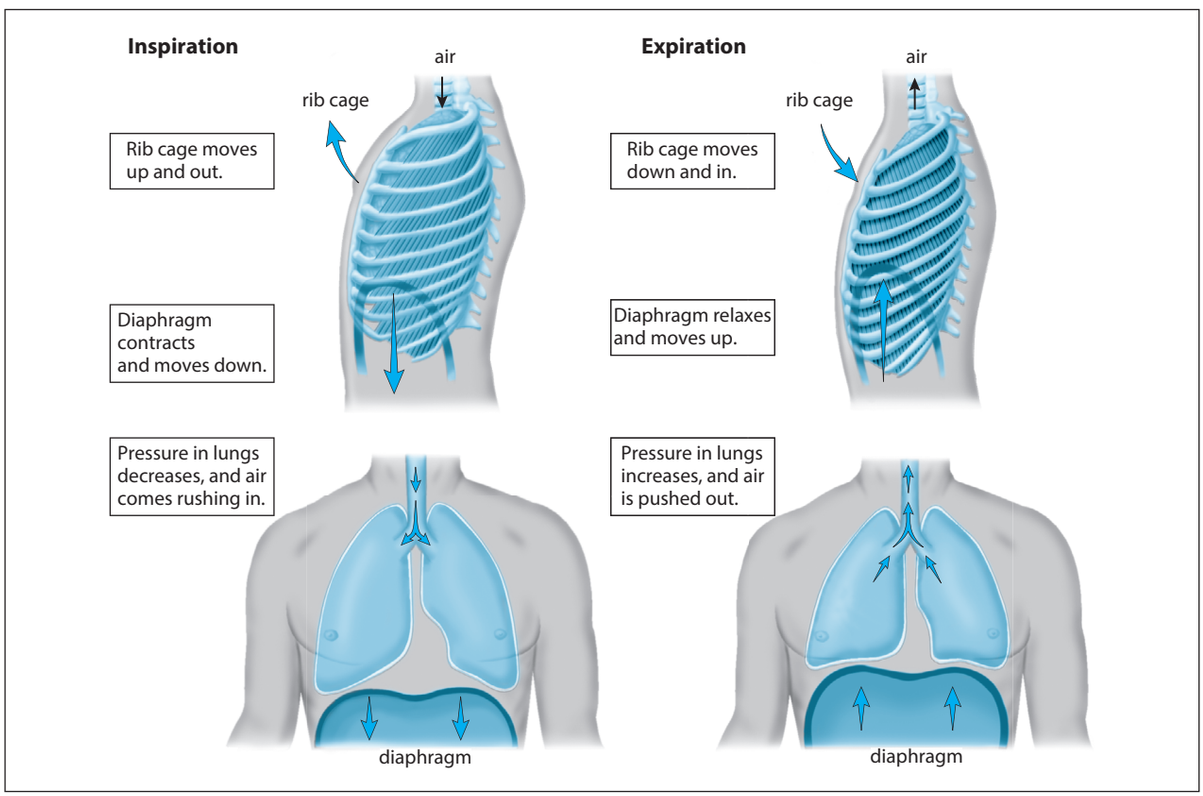

FIGURE 9-12 Ventilation. Contraction of the diaphragm allows for inspiration, whereas relaxation of the diaphragm allows for exhalation. *Source:* From Sylvia S. Mader, *Biology*, 8th ed., McGraw-Hill, 2004; reproduced with permission of The McGraw-Hill Companies.

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GAS EXCHANGE

The concentration of gases can be measured as **partial pressures**. After an inhalation, the amount of O_2 or partial pressure of O_2 in the alveoli is greater than the amount of O_2 or partial pressure in the capillaries surrounding the alveoli. Gases flow from an area of high concentration (partial pressure) to an area of low concentration (partial pressure), so O_2 moves from the alveoli into the capillaries and there binds to hemoglobin. Further, immediately following inhalation, CO_2 levels are low in the alveoli and high in the capillaries. **Diffusion** moves the CO_2 into the alveoli where it can be exhaled. At this point, the blood in the pulmonary capillaries is oxygenated and ready to move back to the left side of the heart via pulmonary veins.

The role of **CO_2 exchange** is important in the maintenance of **acid–base balance** within the body. When CO_2 interacts with water, it forms carbonic acid. The carbonic acid is converted to bicarbonate ions and hydrogen ions, as described with the circulatory system. The bicarbonate ions help buffer pH in the body. When the pH of the body becomes too acidic, the reaction can be reversed. The bicarbonate and hydrogen ions join together to produce carbonic acid, which is then converted to water and CO_2. The CO_2 is exhaled in order to adjust pH.

DIGESTIVE SYSTEM

The **digestive system** is designed to extract nutrients from food and eliminate wastes. The three primary components of the diet that require digestion are **carbohydrates**, **proteins**, and **fats**. The digestive system has the following functions: mechanical digestion of food achieved by chewing, chemical digestion of food achieved by assorted digestive enzymes, absorption of nutrients into the bloodstream, and the elimination of waste products. The **gastrointestinal tract**, seen in Figure 9-13, is set up as a series of modified tubes to keep food and digestive enzymes sequestered from the body.

Tissues of the Digestive System

The contents of the system need to be kept away from the rest of the body for two major reasons. First, any contact of the digestive enzymes with the rest of the body could actually result in the digestion of self tissues. Second, the digestive system is an open system where infectious organisms can enter. To make sure that the components of the digestive system are kept separate from the rest of the body, the digestive tubes are composed of four tissue layers as follows:

- **Mucosa layer**. It is a mucus membrane that actually comes in contact with food. It serves as a lubricant and provides protection from desiccation, abrasion, and digestive enzymes. The mucosa lacks blood vessels and nerve endings.
- **Submucosa layer**. It is below the mucosa. It contains blood vessels, lymphatic vessels, and nerve endings. Its primary function is to support the mucosa and to transport materials to the bloodstream.

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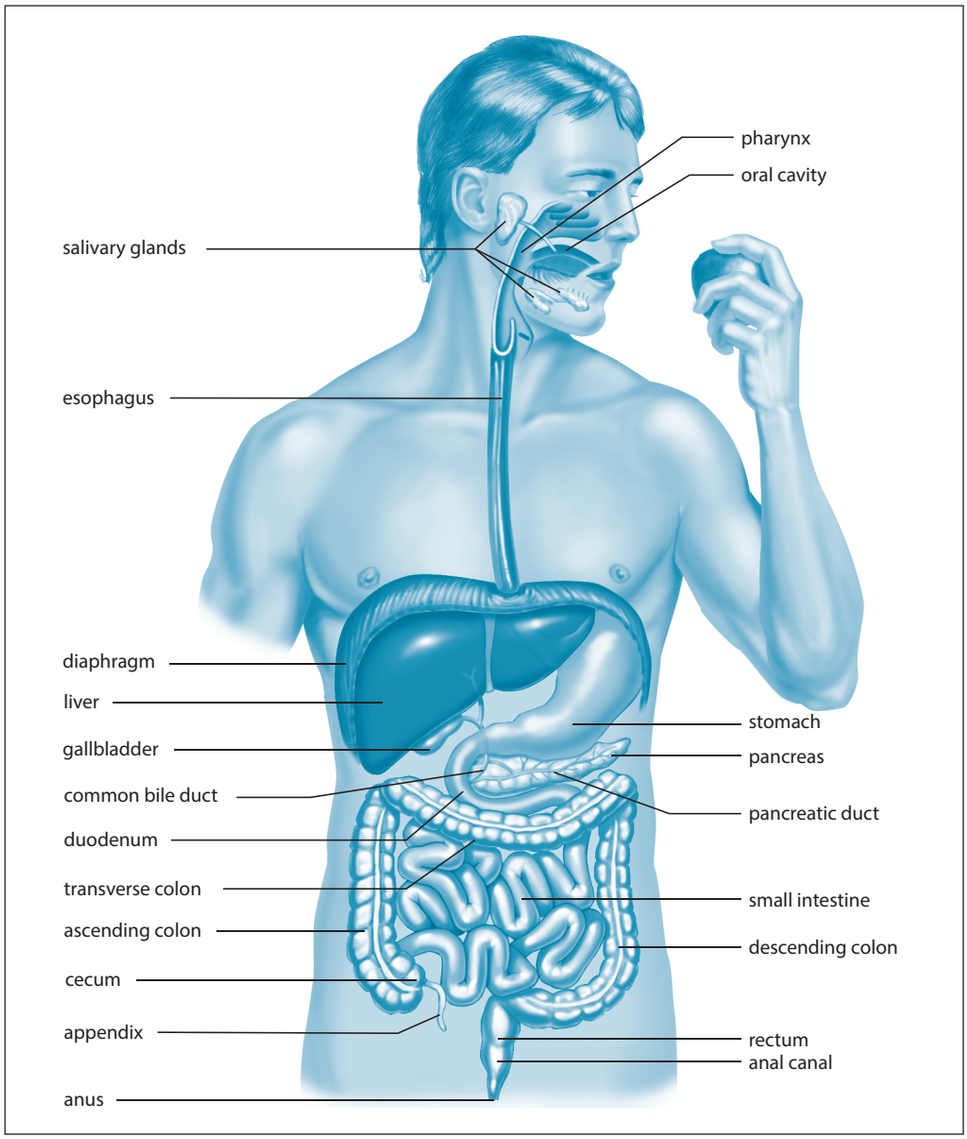

FIGURE 9-13 The digestive system. The digestive system includes the gastrointestinal tract as well as the accessory structures of the liver and pancreas. *Source:* From Sylvia S. Mader, *Biology*, 8th ed., McGraw-Hill, 2004; reproduced with permission of The McGraw-Hill Companies.

- **Muscularis layer**. It is composed of two layers of smooth muscle that run in opposing directions. The nerve endings in the submucosa serve to stimulate the muscularis layer to produce contractions that propel food through the system. The muscular contractions are termed **peristalsis**.
- **Serosa**. It is a thin connective tissue layer that is found on the surface of the digestive tubing. Its purpose is to reduce friction with other surfaces in contact with the gastrointestinal (GI) tract.

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Pathway of Food Through the Digestive Tract

Food enters the digestive tract at the oral cavity. From there, it moves to the esophagus and then the stomach. Small bits of the stomach contents are released to the small intestine. The small intestine completes digestion with assistance from secretions from the liver and pancreas, and is the site where nutrients are absorbed into the bloodstream. Finally, the waste products of digestion are solidified in the large intestine and are released.

ORAL CAVITY

As food is ingested and enters the **mouth**, three sets of salivary glands begin to secrete saliva. The **teeth** are responsible for mechanical digestion of food by breaking it into smaller pieces by chewing. As **saliva** mixes with the chewed food, chemical (enzymatic) digestion begins. In addition to its lubricating function, saliva contains the digestive enzyme **amylase**, which begins the chemical breakdown of carbohydrates such as starch. Because food does not stay in the mouth for long, amylase rarely gets to complete its job in the oral cavity. During chewing, the food is rolled into a **bolus** (small ball) by the tongue and is ready to be swallowed.

ESOPHAGUS

As food is ready to be swallowed, it must pass by the pharynx. Recall that the **pharynx** has two openings: one to the larynx and one to the **esophagus**. Normally, the esophagus is closed during breathing so that air passes through the larynx. When food touches the pharynx, a reflex action occurs that pushes the epiglottis over to cover the glottis of the larynx. This allows for the bolus to proceed down the esophagus. Once in the esophagus, muscular contractions will force the food toward the stomach by **peristalsis**.

STOMACH

The **stomach** is a relatively small, curved organ when empty, but is capable of great expansion when full of food due to the presence of many folds in the interior lining of the stomach. The stomach is unique in that it has a very acidic environment, and its secretions must be retained in the stomach. Tightly closing muscular sphincters guard the top and bottom of the stomach, making sure secretions stay in the stomach.

The **cardiac sphincter** opens to allow the bolus to enter the stomach. Once food is inside the stomach, it is mixed with gastric juice for the purpose of liquefying the food as well as initiating the chemical digestion of proteins. The hormone **gastrin** signals the gastric glands of the stomach to begin producing gastric juice as well as to start churning.

Gastric juice is composed of a mixture of **mucus** to protect the stomach lining from being digested; **pepsinogen**, which is an inactive form of the enzyme that digests protein; and **hydrochloric acid**, which is needed to activate the pepsinogen to its active

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form called **pepsin**. The hydrochloric acid secreted in the stomach provides an overall pH of 1 to 2, which is highly acidic. Normally a pH this low would denature enzymes, but pepsin is unusual in that it is inactive except at a low pH. The low pH of the stomach is also helpful in killing most, but not all, infectious agents that may have entered the digestive tract with food.

After food mixes with gastric juice, the resulting liquid is called **chyme**. The chyme leaves the stomach in small bursts as the **pyloric sphincter** opens. Depending on the size and nutritional content of the meal, it takes on average about 4 hours for the stomach to empty its contents into the small intestine. Strangely, the only items that are absorbed into the bloodstream directly from the stomach are alcohol and aspirin.

SMALL INTESTINE

The **small intestine** is a tube of approximately 6 meters in length. Its primary job is to complete the chemical digestion of food and to absorb the nutrients into the bloodstream. The small intestine relies on secretions from the liver and pancreas to complete chemical digestion. As the pyloric sphincter of the stomach opens, small amounts of chyme enter the top region of the small intestine, which is termed the **duodenum**. The acidity from gastric juice must be neutralized. This is achieved by the secretion of **sodium bicarbonate** from the pancreas into the small intestine. In addition to receiving secretions made from the pancreas, the duodenum also receives secretions from the liver. These secretions help with chemical digestion, which occurs in the middle region of the small intestine termed the **jejunum** and the lower end of the small intestine termed the **ileum**.

Liver and Gallbladder. The **liver** is composed of several lobes of tissue and is one of the larger organs in the body. The liver has numerous functions within the body. In the case of the digestive system, the liver produces **bile**, which is a fat emulsifier. Although bile is not an enzyme, it helps break fats into smaller pieces so they are more susceptible to digestion by enzymes secreted from the pancreas. Bile contains water, cholesterol, bile pigments, bile salts, and some ions. Bile from the liver is stored in the **gallbladder**, a small structure on the underside of the liver. As food enters the small intestine, the hormones secretin and cholecystokinin (CCK) signal for the release of bile to the small intestine via the common bile duct.

The liver has some additional functions within the digestive system. Following the absorption of nutrients in the small intestine, blood from the capillaries in the small intestine will travel directly to the liver via the hepatic portal vein. Once in the liver, the glucose levels of the blood will be regulated. When blood glucose levels increase, the liver will store the excess as glycogen under the influence of insulin. When blood sugar levels are low, the liver will break down glycogen to release glucose under the influence of glucagon. The liver will also package lipids in lipoproteins to allow them to travel throughout the body. The smooth endoplasmic reticulum within the liver cells

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produces enzymes to detoxify certain harmful substances. The liver also stores vitamins A, E, D, and K (the fat-soluble vitamins). After these functions occur in the liver, blood reenters general circulation.

Pancreas. The **pancreas** secretes pancreatic juice into the small intestine via the pancreatic duct. Although the pancreas has cells involved in endocrine functions (producing insulin and glucagon), it also has exocrine cells that produce pancreatic juice. Signaled by the hormones secretin and CCK, the pancreas secretes pancreatic juice when food enters the small intestine. Pancreatic juice contains the following substances:

- **Bicarbonate ions.** They act as a neutralizer of stomach acid.
- **Amylase.** It completes carbohydrate (starch) digestion that began in the oral cavity to release glucose.
- **Proteinase.** It completes protein digestion that was started in the stomach to release amino acids. There are three specific proteinases found in pancreatic juice: trypsin, chymotrypsin, and carboxypeptidase.
- **Lipase.** It breaks down fats to fatty acids and glycerol.
- **Nuclease.** It breaks down DNA and RNA to nucleotides.

Absorption of Nutrients. Once the bile and pancreatic juice are mixed with the contents of the small intestine, chemical digestion is nearly complete. Although the pancreatic enzymes are most essential to chemical digestion, a few additional enzymes are needed. These enzymes are made by the small intestine and include:

- **Maltase.** It breaks down the disaccharide maltose to glucose.
- **Sucrase.** It breaks down the disaccharide sucrose to glucose and fructose.
- **Lactase.** It breaks down the disaccharide lactose to glucose and galactose.
- **Aminopeptidase.** It breaks down small pieces of proteins to amino acids.

Once food has been exposed to the secretions of the pancreas, liver, and small intestine, chemical digestion is complete. Then the nutrients must be absorbed and the wastes eliminated. It can take anywhere from 3 to 10 hours for nutrients to be absorbed from the small intestine.

The small intestine has an internal anatomy with a tremendous surface area, making it well-suited for absorption, as seen in Figure 9-14. The **mucosa** in the small intestine is folded into **villi**, which form the brush border. The villi are then further folded into microscopic **microvilli**. Within each villus, there are capillaries and a **lacteal** (a lymphatic capillary). Nutrients such as glucose and other simple sugars, amino acids, vitamins, and minerals diffuse into the capillaries within each villus. From there they are carried into the blood circulation. The products of fat digestion take another route. The fat products are assembled into a triglyceride and packaged in a special coating, including cholesterol, which creates a **chylomicron**. These structures cannot diffuse into

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capillaries, so they enter the lacteals. The lymphatic fluids deliver the chylomicrons to the bloodstream at the **thoracic duct**, which is a merger between the two systems.

LARGE INTESTINE

Now that the nutrients have been absorbed into the bloodstream, the remnants of digestion have made their way to the **large intestine**. Now water must be reclaimed by the body to solidify the waste products. These waste products are stored by the large intestine and released at the appropriate time. In addition, the large intestine contains a large and diverse population of normal flora or harmless resident microbes, all of which are part of the microbiome. Members of the **microbiota** are responsible for the synthesis of certain vitamins that the body needs. Additionally, certain changes to the microbiome are linked to various diseased states within the body.

The large intestine has a much larger girth than the small intestine, but its length is reduced. The large intestine is about 1.5 meters long. There are four regions within the large intestine:

- **Cecum.** It is a small area where the large intestine connects with the small intestine on the right side of the body. There is an outgrowth of this area that constitutes the

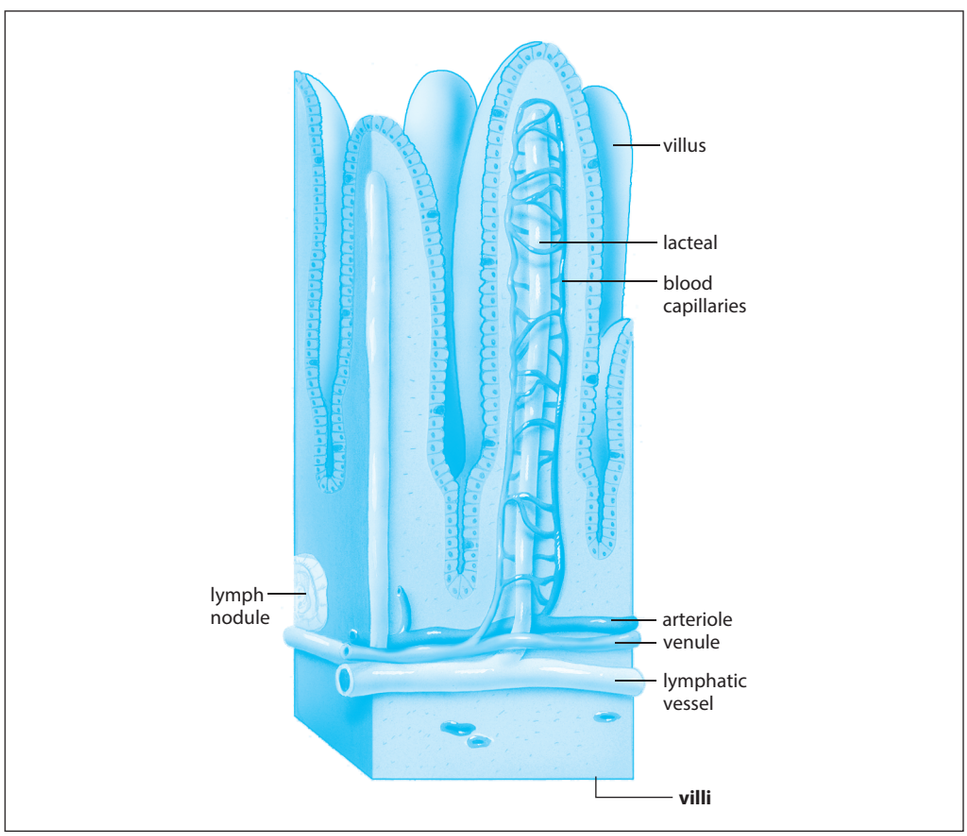

FIGURE 9-14 Absorption of nutrients. Nutrients are absorbed by villi, which are located in the small intestine. *Source:* From Sylvia S. Mader, *Biology*, 8th ed., McGraw-Hill, 2004; reproduced with permission of The McGraw-Hill Companies.

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appendix. The **appendix** has nothing to do with digestion, but it happens to be located within the digestive system. The appendix is a vestigial structure thought to play a noncrucial role in the lymphatic system.

- **Colon.** It constitutes the majority of the large intestine. The **ascending colon** moves up the right side, the **transverse colon** moves horizontally across the abdomen, and the **descending colon** runs down the left side of the body. The primary role of the colon is water absorption in order to solidify the feces. Vitamin absorption can also occur in the colon. It can take up to 24 hours for materials to pass through the colon.
- **Rectum.** It is the ultimate destination for feces in the large intestine. Stretching of this area stimulates nerves and initiates the defecation reflex.
- **Anal canal.** It receives the contents of the rectum for elimination. There are two sphincters regulating exit from the anal canal. The **first internal sphincter** operates involuntarily, and the **second external sphincter** is under voluntary control.

URINARY SYSTEM

The urinary system consists of two **kidneys** that produce urine, and supporting structures that store and eliminate urine from the body. The kidneys are the main excretory organs of the body; however, the skin can also act as an excretory organ. In addition to producing urine as a means of eliminating nitrogenous cellular waste products, the urinary system also regulates blood pressure by adjusting blood volume, adjusting blood pH, and regulating the osmotic concentrations of the blood.

Structures of the Urinary System

The two kidneys of the urinary system filter blood to produce urine. The **urine** moves toward the bladder via two **ureters**, which are tubes that connect each kidney to the bladder. Once urine moves into the **bladder**, it is stored until it eventually leaves the body through the **urethra**. The anatomy of the urethra is different in males and females. In males, the urethra is relatively long and is shared with the reproductive system so that sperm can move through it when appropriate. In females, the urethra is shorter, and it is only used for urine passage. The structures of the urinary system are shown in Figure 9-15.

Kidney Structure

The kidneys are located along the dorsal surface of the abdominal wall, above the waist, and are secured by several layers of connective tissue, including a layer of fat. Each kidney has an **adrenal gland** located on top of it. The outer region of the kidney is the **renal cortex**, the middle portion is the **renal medulla**, and the inner portion is the **renal pelvis**, as shown in Figure 9-16.

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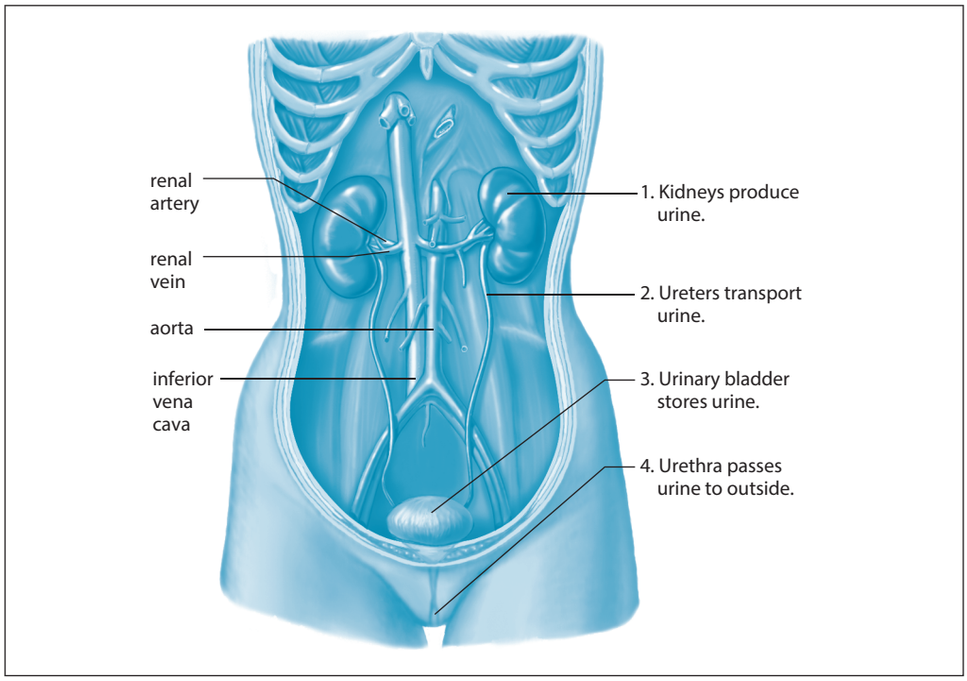

FIGURE 9-15 The urinary system. The kidneys produce urine, which is carried to the bladder by the ureters, where it is eliminated from the system. *Source:* From Sylvia S. Mader, *Biology*, 8th ed., McGraw-Hill, 2004; reproduced with permission of The McGraw-Hill Companies.

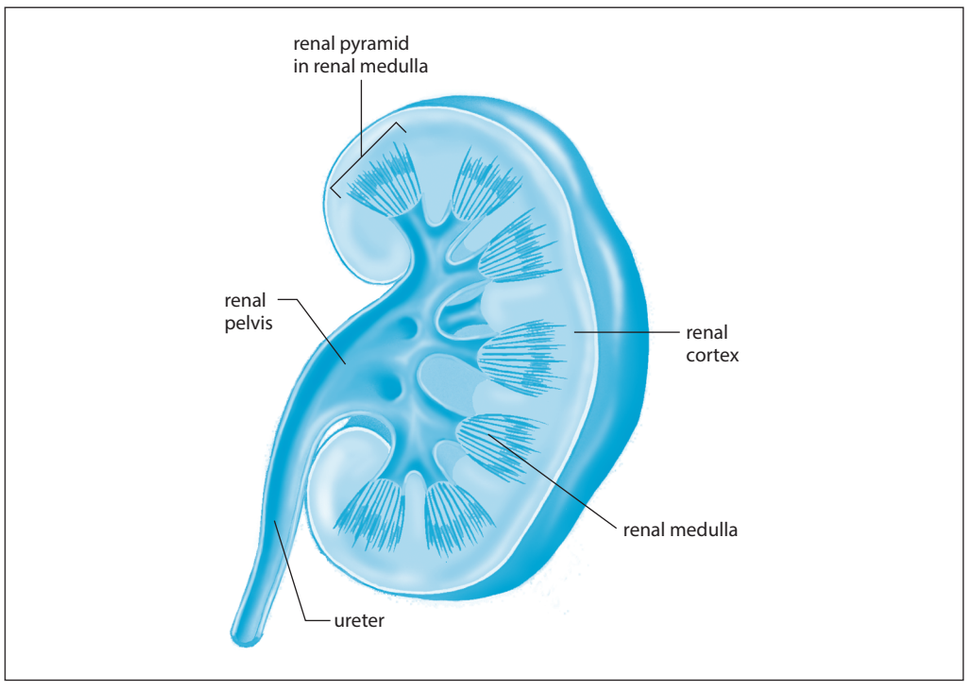

FIGURE 9-16 Kidney structure. Urine is produced in the nephrons of the kidney, which are found within the renal cortex and renal medulla. *Source:* From Sylvia S. Mader, *Biology*, 8th ed., McGraw-Hill, 2004; reproduced with permission of The McGraw-Hill Companies.

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The kidneys are responsible for filtering blood, so they have an excellent blood supply. **Renal arteries**, which branch off the aorta, carry blood into the kidneys, whereas the **renal veins** carry blood away from the kidneys toward the **inferior vena cava**. The indentation where the ureter, renal artery, and renal vein attach to each kidney is the **renal hilus**.

NEPHRON

Within the **renal medulla** of each kidney, there are triangular chunks of tissue called **renal pyramids**. Within these renal pyramids and extending into the **renal cortex** are about one million nephrons per kidney. The **nephrons**, seen in Figure 9-17, are microscopic tubules that are the basic functional units of the kidney and actually produce urine.

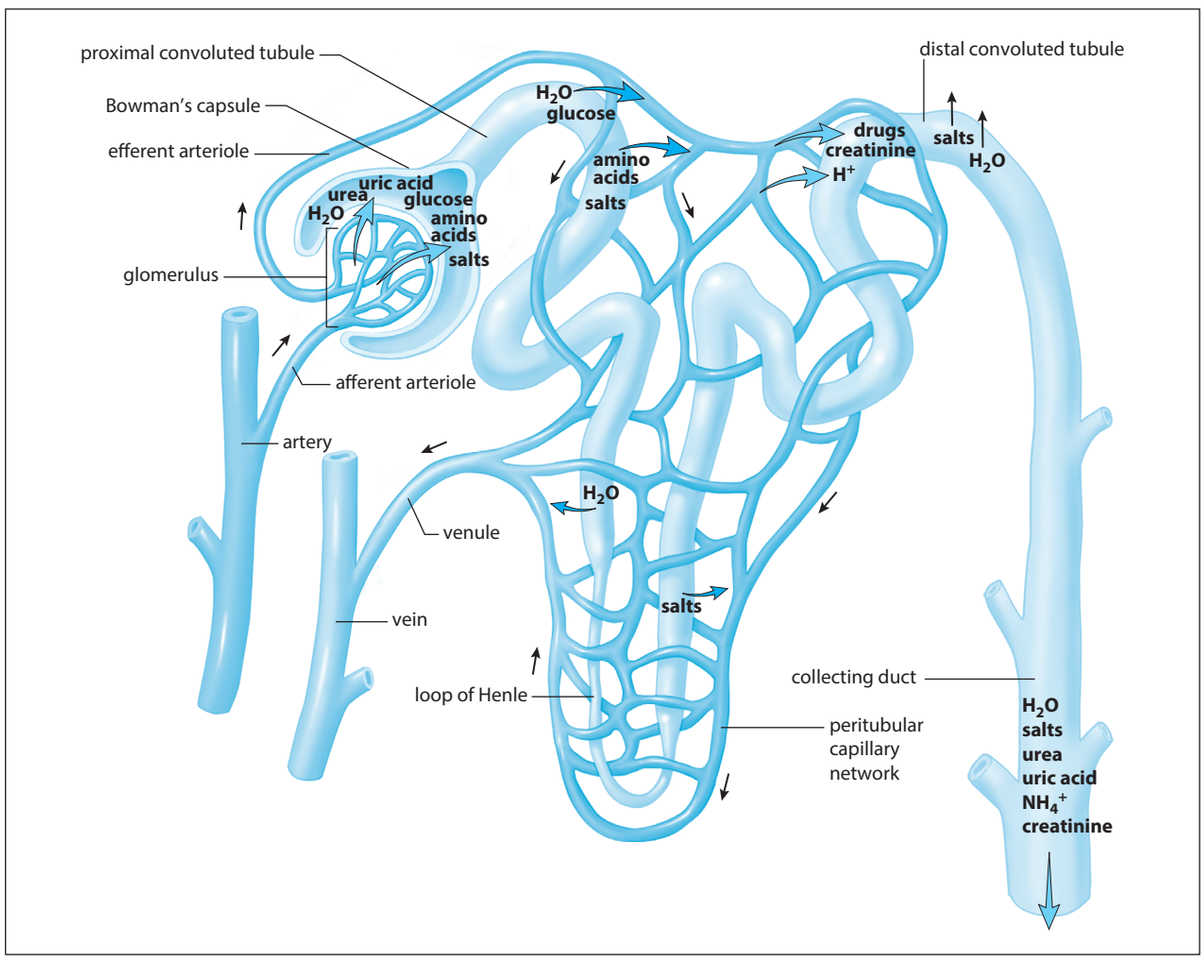

FIGURE 9-17 Nephron structure. Urine is produced as filtrate moves through the nephron. In reality, a nephron is twisted along itself, but for ease of viewing, the nephron shown here has been untwisted. *Source:* From Sylvia S. Mader, *Biology*, 8th ed., McGraw-Hill, 2004; reproduced with permission of The McGraw-Hill Companies.

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Each nephron is surrounded by a network of capillaries. Any items leaving the nephron are picked up by the capillaries and returned to the bloodstream. The regions of the nephron and their roles in the filtration of blood and production of urine are as follows:

- The **renal corpuscle** has two parts. The first is the **glomerulus**, which is a network of capillaries, and the second is the **Bowman's capsule**, which surrounds the glomerulus. There is no direct connection between the glomerulus and the Bowman's capsule; rather, there is a space between the two. **Afferent arterioles** carry blood into the glomerulus, where blood pressure pushes certain components of the blood into the Bowman's capsule. **Efferent arterioles** carry blood out of the glomerulus. Only blood components that are small in size enter the Bowman's capsule. This means that blood cells and plasma proteins should not enter the Bowman's capsule, whereas plasma components such as water, ions, small nutrients, nitrogenous wastes, gases, and others should enter the Bowman's capsule. The materials that enter the Bowman's capsule are referred to as **filtrate** and have approximately the same osmotic concentration as the plasma. Approximately 99 percent of filtrate that enters the nephron should be reabsorbed back into circulation. Any components remaining in the nephron once filtration and reabsorption are complete will be lost as urine and are much more concentrated than the plasma.
- The **proximal convoluted tubule** allows for the reabsorption of nutrients such as glucose and amino acids, water, salt, and ions. The majority of reabsorption occurs here.
- The **loop of Henle** also allows for reabsorption, primarily of salt (NaCl) and water by osmosis. A fairly complex countercurrent multiplier system is in effect in the loop of Henle. This area is a loop with a descending side and an ascending side that are located in close proximity to each other. Each limb of the loop has a different osmotic concentration. As salt is actively pumped out of the ascending limb, it creates a high osmotic pressure that draws water out of the descending limb via osmosis. Fresh filtrate then enters the loop of Henle, pushing the existing filtrate from the descending limb into the ascending limb. The process of pumping salt out of the ascending limb and the osmotic movement of water out of the descending limb is repeated several times.
- The **distal convoluted tubule** is where the fine-tuning of filtrate concentration begins. The activity of the distal convoluted tubule is regulated by hormones. The more water this section of the nephron reabsorbs, the more concentrated the urine becomes. The lower the urine volume, the higher the blood volume becomes.
- The **collecting duct** can be shared by several nephrons. The remaining urine empties into the collecting duct, where it moves toward the renal pelvis and ultimately into the ureters to be carried to the bladder. Hormones can be used in the collecting duct to allow for the reabsorption of more water, making the urine even more concentrated.

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Regulation of Blood Volume and Pressure. Specific hormones regulate the fine-tuning of filtrate concentration and reabsorption of water, which, in turn, affect blood volume and pressure and the acid–base balance of the blood.

If **antidiuretic hormone (ADH)** is present, more water is reabsorbed in the distal convoluted tubule and the collecting duct of the nephrons. This increases the concentration of urine and decreases urine volume. If **aldosterone** is present, more salt is reabsorbed from the distal convoluted tubule and collecting ducts. Water follows the movement of salt by osmosis. This results in an increased concentration of filtrate and a decrease in urine volume. Both ADH and aldosterone have the same effects on filtrate concentration. By increasing water reabsorption, blood volume has been increased. The increase in blood volume is one way to increase blood pressure.

The secretion of ADH and aldosterone is regulated by renin produced by the kidneys. **Renin** secretion is triggered by low blood pressure in the afferent arterioles. Renin converts a protein made by the liver called angiotensin I into angiotensin II. **Angiotensin II** then triggers release of ADH by the posterior pituitary gland and aldosterone by the adrenal cortex.

Diuretics are substances that increase urine volume. Alcohol qualifies as a diuretic because it interferes with the activity of ADH. Caffeine is also a diuretic because it interferes with salt reabsorption and aldosterone's function. Large amounts of alcohol or caffeine have a noticeable effect by increasing urine volume. This in turn decreases blood volume and pressure.

One last hormone that alters nephron function is **atrial natiuretic peptide** (ANP), which is secreted by the heart. When the heart stretches due to elevated blood pressure, ANP is released. ANP decreases water and salt reabsorption by the nephrons. This results in less concentrated urine, a higher urine volume, and a lower blood volume. The reduced blood volume means a decrease in blood pressure.

MAINTENANCE OF ACID–BASE BALANCE

As the kidneys filter blood, they also balance the pH of blood. Even a relatively minor change to blood pH can have drastic consequences, which is one of the reasons that kidney failure can be deadly. Luckily, dialysis methods are available to mimic normal kidney functions for patients whose kidneys do not work properly.

Recall that CO_2 interacts with water to produce **carbonic acid**. Carbonic acid can then dissociate into hydrogen ions and bicarbonate ions, both of which influence pH. The pH of blood can be adjusted by changing the amount of bicarbonate ions being reabsorbed and altering the amount of hydrogen ions being retained in the nephron. When the blood pH drops and becomes acidic, more bicarbonate ions return to circulation and hydrogen ions are released in urine, which gives urine an acidic pH.

PROPERTIES OF URINE

The substances remaining at the end of the collecting duct of the nephron constitute **urine**. Urine always contains water, ions (such as Ca^{++}, Cl^{-}, Na^{+}, and K^{+}), and

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nitrogenous wastes. Depending on the diet and function of other organs in the body, other components might be present in the urine. Because it was filtered directly from blood, the urine should be sterile. The presence of proteins, blood cells, or nutrients within the urine is considered abnormal.

The three primary nitrogenous wastes, all produced by cells, are as follows:

- **Urea.** As cells deaminate amino acids during protein metabolism, the resulting product is **ammonia**, which is highly toxic. The liver converts ammonia to a less toxic waste called **urea**. The kidneys will concentrate urea and release it via urine. Urea is the most abundant of nitrogenous waste products.
- **Uric acid.** During nucleic acid metabolism in the cell, uric acid is produced as a waste product.
- **Creatinine.** As muscle cells use creatine phosphate to produce ATP needed to fuel muscular contraction, creatinine is produced as a waste product.

Additional Functions of the Kidneys

In addition to their role in blood filtration and urine production, the kidneys have two additional jobs. First, the kidneys act to convert vitamin D from the diet into its active form that can be used by the cells. The kidneys are able to convert vitamin D to calcitriol, which helps the body absorb calcium and phosphorus. Second, the kidneys secrete the hormone **erythropoietin** (EPO), which is used to stimulate red blood cell production in the red bone marrow.

LYMPHATIC SYSTEM

The **lymphatic system** consists of a series of vessels running throughout the body, lymph, and lymphoid tissue as seen in Figure 9-18. The system serves to return fluids that were unclaimed at the capillary beds to the circulatory system, picks up chylomicrons from the digestive tract and returns them to circulation, transports proteins and large glycerides, and fights infection via leukocytes.

The vessels of the lymphatic system carry the fluid **lymph**, which is the same composition as plasma and interstitial fluid. Lymph moves through the vessels primarily due to the influence of muscular contractions that push lymph and valves that prevent the backflow of lymph.

The lymphoid tissues within the system are as follows:

- **Lymph nodes.** They are swellings along lymphatic vessels that contain macrophages for phagocytosis of pathogens and cancer cells and lymphocytes for immune defenses. The lymph is filtered through the nodes before moving on in the system. Clusters of lymph nodes exist in the neck, under the arms, and in the groin. Swelling of the lymph nodes is a sign of infection.

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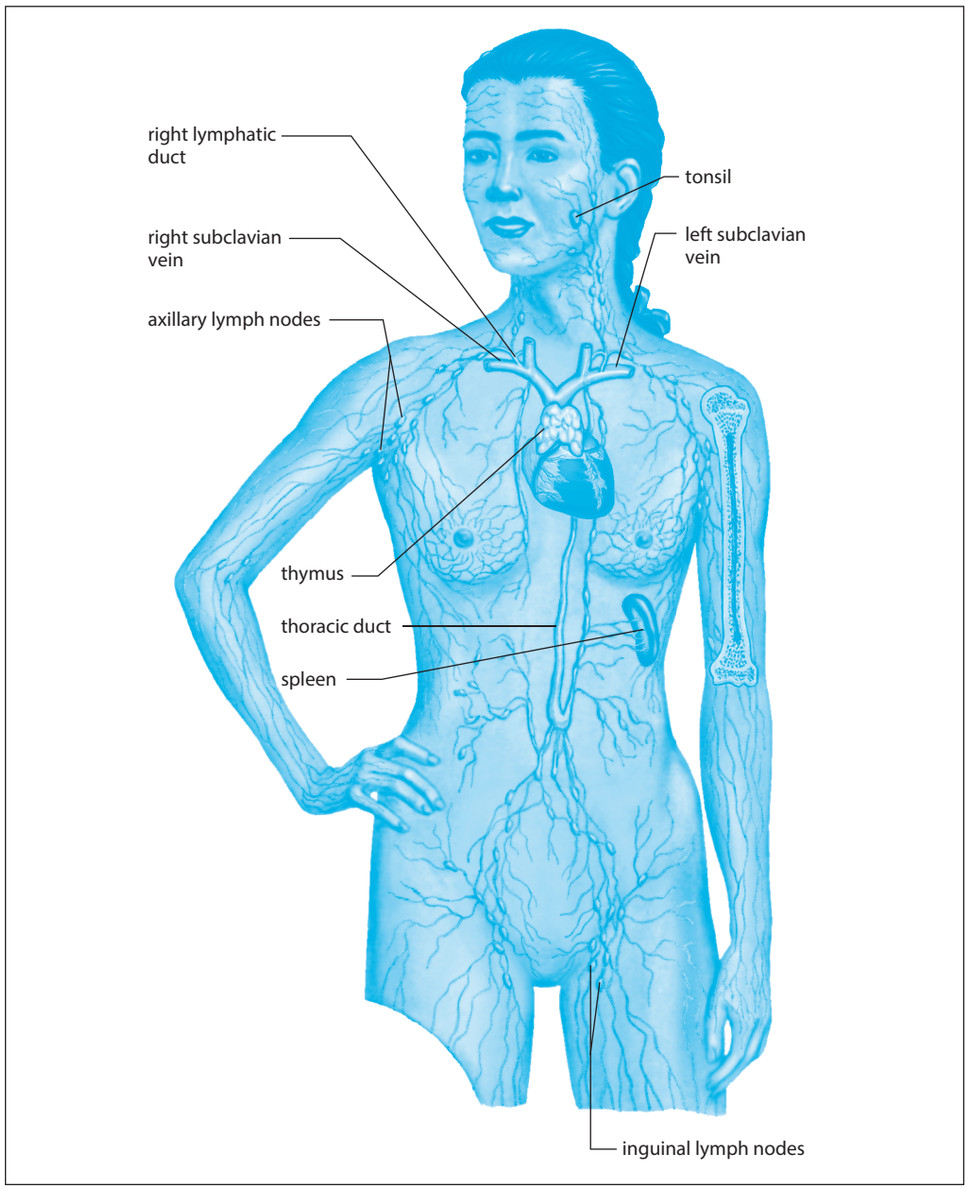

FIGURE 9-18 The lymphatic system is composed of vessels, lymph nodes, the tonsils, spleen, and thymus gland. *Source:* From Sylvia S. Mader, *Biology*, 8th ed., McGraw-Hill, 2004; reproduced with permission of The McGraw-Hill Companies.

- **Tonsils.** They resemble a lymph node in their ability to prevent infection by pathogenic organisms in the throat.
- **Peyer's patches.** They are clusters of lymphatic tissues in the small intestine that serve to prevent infectious organisms from crossing the intestinal wall into the abdomen.
- **Thymus gland.** It allows for the maturation of T cells, which are a form of lymphocytes needed for adaptive immune defenses.

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- **Spleen.** It is located on the left side of the body and acts as a blood filter. In addition, the spleen has an excellent blood supply and acts to destroy old red blood cells and platelets.

IMMUNE SYSTEM

The **immune system** exists anywhere **white blood cells** are found. This includes the blood, lymph, and within tissues of the body. The job of the immune system is to differentiate "self" cells from "non-self" (foreign cells) and to eliminate both foreign cells and abnormal self cells.

Immune defenses begin with nonspecific, or innate, responses that attempt to prevent foreign cells from entering the body and attack them if they do enter, and later, if needed, to move to specific, or adaptive, responses. An **innate immune defense** always works the same way, no matter what the offending invader, while **adaptive immune defenses** are activated and tailor-made to a specific invader.

Innate Defenses

Innate defenses come in several varieties. They are as follows:

- Physical and chemical barriers prevent foreign cells from entering the body. The skin is an example of a barrier that generally prevents infection. Mucous membranes provide another good barrier. Chemicals such as sweat, stomach acid, and lysozyme also generally prevent infection.
- Defensive leukocytes include macrophages (mature monocytes), polymorphonuclear neutrophils (PMNs), and dendritic cells, and are all capable of phagocytosis to destroy pathogens that may have entered the body. Eosinophils enzymatically destroy large pathogens such as parasitic worms that cannot be phagocytized. Finally, natural killer (NK) cells find self cells that have unusual membrane properties and destroy them. Cancerous cells are notorious for having altered cell membranes and are usually destroyed by NK cells.
- Defensive proteins are another category of innate defense. In the case of viral invaders, infected cells can secrete proteins called **interferons**. A virally infected cell releases these proteins as messengers to other cells that are yet to be infected. This limits the spread of the virus within the body. Interferons are not specific; they work against all types of viruses. The **complement system** is a series of multiple plasma proteins that are effective at killing bacteria by causing lysis of their cell membrane. The complement system also enhances phagocytosis within the area of invasion.
- When there is damage to tissues, the **inflammatory response** will initiate. It is characterized by redness (due to increased blood flow), heat (due to increased blood

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flow), swelling, and pain. Increased blood flow to the area is caused by the chemical histamine, which is secreted by basophils. This increased blood flow brings in other white blood cells, proteins, and other components needed to fight infection. Histamine makes capillaries more permeable than normal, and this, in turn, results in increased fluid in the area, which causes swelling. This swelling can put pressure on pain receptors, which causes the sensation of pain.

- When the body temperature is reset to a higher level by chemicals called pyrogens, **fever** is the result. Controlled fevers are beneficial as they increase metabolism and stimulate other immune defenses. When fevers get too high, they are dangerous and can cause the denaturing of critical enzymes needed to sustain life.

Adaptive Defenses

When innate defenses fail to control infection, adaptive defenses must be used. Because these are customized to the specific invader, they take at least a week to respond strongly to a new antigen. An antigen is a substance that elicits an immune response.

There are two types of adaptive defenses: **humoral immunity**, involving B lymphocytes, and **cellular immunity**, involving T lymphocytes. **Lymphocytes** are derived from stem cells in the red bone marrow. B cells complete their maturation in the bone marrow, while T cells mature in the thymus gland. Both types of cells are designed to ultimately destroy antigens, either directly or indirectly.

In humoral immunity, the B cells ultimately secrete antibodies to destroy foreign antigens. In cellular (or cell-mediated) immunity, T cells are used to directly destroy infected or cancerous cells. A specific variety of T cell known as the **helper T cell** is the key coordinator of both humoral and cellular responses.

HUMORAL IMMUNITY

Humoral immunity involves the production of specific antibody proteins from B cells that have been activated. Each B cell displays an antibody on its cell membrane, and each of the million or more B cells in the body has a different antibody on its membrane. The activation of a particular B cell by a specific antigen is based on shape recognition between the antibody on the B cell membrane and the antigen. The activation process is also dependent on cytokines from a helper T cell, specifically a T_H2 cell, which will be discussed in the next section.

The activation of a particular B cell causes proliferation of that B cell, leading to a population of plasma cells that actively secrete antibodies, and memory B cells that produce the same type of antibody. This is referred to as **clonal selection**, and it is the key event of the primary immune response, which leads to active immunity. It takes at least a week for this response to reach peak levels. Once antibodies are produced in

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large quantities by plasma cells, they circulate through blood, lymph, and tissues where they seek out their antigen and bind to it, forming a complex. Once an antibody binds to an antigen, the complex either is phagocytized or agglutinates and is later removed by phagocytic cells.

The primary immune response and active immunity can be achieved by natural exposure to an antigen or by vaccination. On secondary and subsequent exposures to the same antigen, the memory B cells that were created during the primary exposure can proliferate into plasma cells that produce antibodies, which provides a much faster response to the antigen. Although antibodies don't circulate for long once an antigen has been destroyed, memory B cells can last for years, if not forever.

Sometimes antibodies are passed from one person to another, which leads to passive immunity. This occurs during pregnancy, when maternal antibodies cross the placenta, and during breast-feeding. Breast milk contains antibodies that are transmitted to the newborn. **Passive immunity** can be induced by the injection of antibodies from one individual to another. Passive immunity is short-lived and declines within a few months.

Antibody Structure. An **antibody** consists of 4 protein chains bonded together. Two chains are identical heavy chains, and 2 chains are identical light chains. The structure of an antibody can be seen in Figure 9-19. Variable regions on the chains bind to the antigen, while constant regions on the chains assist in the destruction of the antigen.

There are five types of organizations of constant regions, which result in five different classes of antibodies (also called **immunoglobulins**): **IgG, IgM, IgA, IgD**, and **IgE**. The incredible diversity of antibodies produced by the immune system is based on a genetic recombination system that produces countless variable regions. The genes that produce the variable regions of antibodies are broken into segments that can be

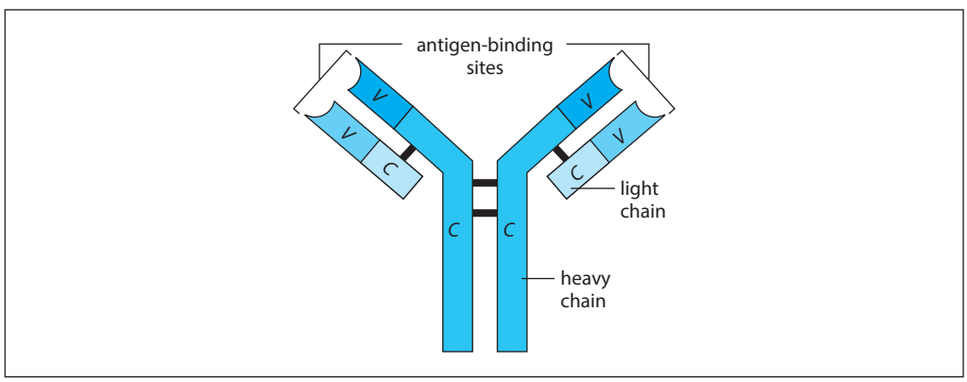

FIGURE 9-19 Antibody structure. Antibodies contain heavy chains and light chains. The variable regions of the antibody allow for antigen binding. *Source:* From Sylvia S. Mader, *Biology*, 8th ed., McGraw-Hill, 2004; reproduced with permission of The McGraw-Hill Companies.

arranged in variable orders during RNA splicing, which produce many variations of the variable region.

CELLULAR IMMUNITY

Cellular immunity is based on the actions of T cells, which come in several varieties. T cells have a cell membrane receptor that, like antibodies on the surface of B cells, recognizes the shape of one particular antigen. However, T cells cannot be directly activated by contact with the antigen.

T cells come in several varieties, two critical ones being **CD4⁺ helper T cells** (T_H0) and **CD8⁺ cytotoxic T cells** (T_C). The **T_H0 cells** are ultimately responsible for the activation of humoral and cellular immunity, but they must be presented with an antigen and appropriate cytokine signals in order to activate. Once activated, two populations are produced: T_H1 and T_H2.

The **T_H1 cells** primarily interact with macrophages or dendritic cells when the body is dealing with cancer, viral infection, or intracellular bacterial infections (which are rare). The T_H1 population secretes pro-inflammatory cytokines and activates cell-mediated immunity by producing a population of T_C cells and natural killer (NK) cells that have the ability to seek and destroy cells bearing the foreign antigen. As with plasma cell activation, this primary response takes at least a week to occur. Memory T cells are also produced. Once all cells bearing the foreign antigen have been completely destroyed, regulatory T cells are used to stop the response. Only memory T cells remain, which can be quickly activated to T_C cells on secondary and subsequent exposures to the same antigen.

T_H2 cells primarily interact with B cells and involve the activation of humoral immunity when the body is dealing with extracellular issues such as bacterial infection. T_H2 cells produce anti-inflammatory cytokines and activate plasma cells, which will eventually produce antibodies as described in the previous section.

IMMUNODEFICIENCY DISORDERS

A variety of immune system problems are characterized as **immunodeficiencies**. These disorders occur when the immune system is lacking one or more component of its adaptive defenses. For example, **severe combined immunodeficiency syndrome** (SCID) occurs when an individual is born without lymphocytes. This renders the person with no adaptive immune defenses and quickly causes death unless the individual is maintained in a sterile, isolated environment.

The **HIV virus** induces immunodeficiency in an individual. It selectively infects helper T cells. When the virus activates after a latent period, the helper T cells begin to die. Without them, B cell and cytotoxic T cell activation is not present. This leads to an inability to mount humoral and cellular responses to antigens. This leads to **acquired immunodeficiency syndrome** (AIDS), which can eventually cause death due to an overwhelmed immune system.

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REPRODUCTIVE SYSTEMS

The female and male **reproductive systems** have a common function of producing gametes for sexual reproduction in the form of egg cells in females and sperm cells in males, both of which are produced by the gonads. The process of gamete production via meiosis has already been discussed in Chapter 7. In addition to producing gametes, the female reproductive system has the additional need to be structured to accept sperm from the male system and allow for embryonic and fetal development.

Female Reproductive System

The functions of the female reproductive system are carried out in special structures under the influence of a complex system of hormones that regulate the development of egg cells (oogenesis), their release from the ovary (ovarian cycle), and the preparation of the woman's body for embryo implantation and development (menstrual cycle).

STRUCTURE

The female reproductive system is enclosed within the abdominal cavity and is open to the external environment. Although having an opening to the outside environment is necessary for reproduction and childbirth, it presents some unique challenges in terms of the ability of pathogens to enter the system.

The structures of the female reproductive system consist of two **ovaries**, where egg production occurs, and supporting structures, as shown in Figure 9-20. After an egg is released from an ovary, it is swept into the **fallopian tube** (oviduct) that is associated with that ovary. If sperm are present and they meet with the egg in the fallopian tube, fertilization occurs. The fallopian tubes merge into the **uterus**, which is composed of a muscular myometrium and a vascularized lining called the **endometrium**. If the egg has been fertilized, the embryo implants into the endometrium, where development will continue. If fertilization has not occurred, the egg is lost with the shedding of the endometrium, which occurs about every 28 days during menstruation. The **vagina** serves as an entry point for sperm to enter the system, an exit point for menstrual fluids, and the birth canal during childbirth. The pH of the vagina is acidic, which can discourage the growth of certain pathogens. The **cervix** regulates the opening of the uterus into the vagina and is normally very narrow.

The external genitalia of the female system are known as the **vulva**. The **labia** are folds of skin that surround the opening to the vagina and occur as an outer and inner pair. The **clitoris** is located under the anterior portion of the inner labia. The clitoris has multiple nerve endings and is associated with female sexual arousal.

The breast tissue contains **mammary glands**, which serve the primary purpose of producing milk for a newborn. The tissue that surrounds the glands is fibrous

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connective tissue. The mammary glands are under the control of several hormones, including **estrogen**, **progesterone**, **oxytocin**, and **prolactin**.

MENSTRUAL CYCLE

The female reproductive cycle lasts about 28 days on average. Characteristic changes occur within the uterus that occur during this time. These changes are referred to as the menstrual (or uterine) cycle.

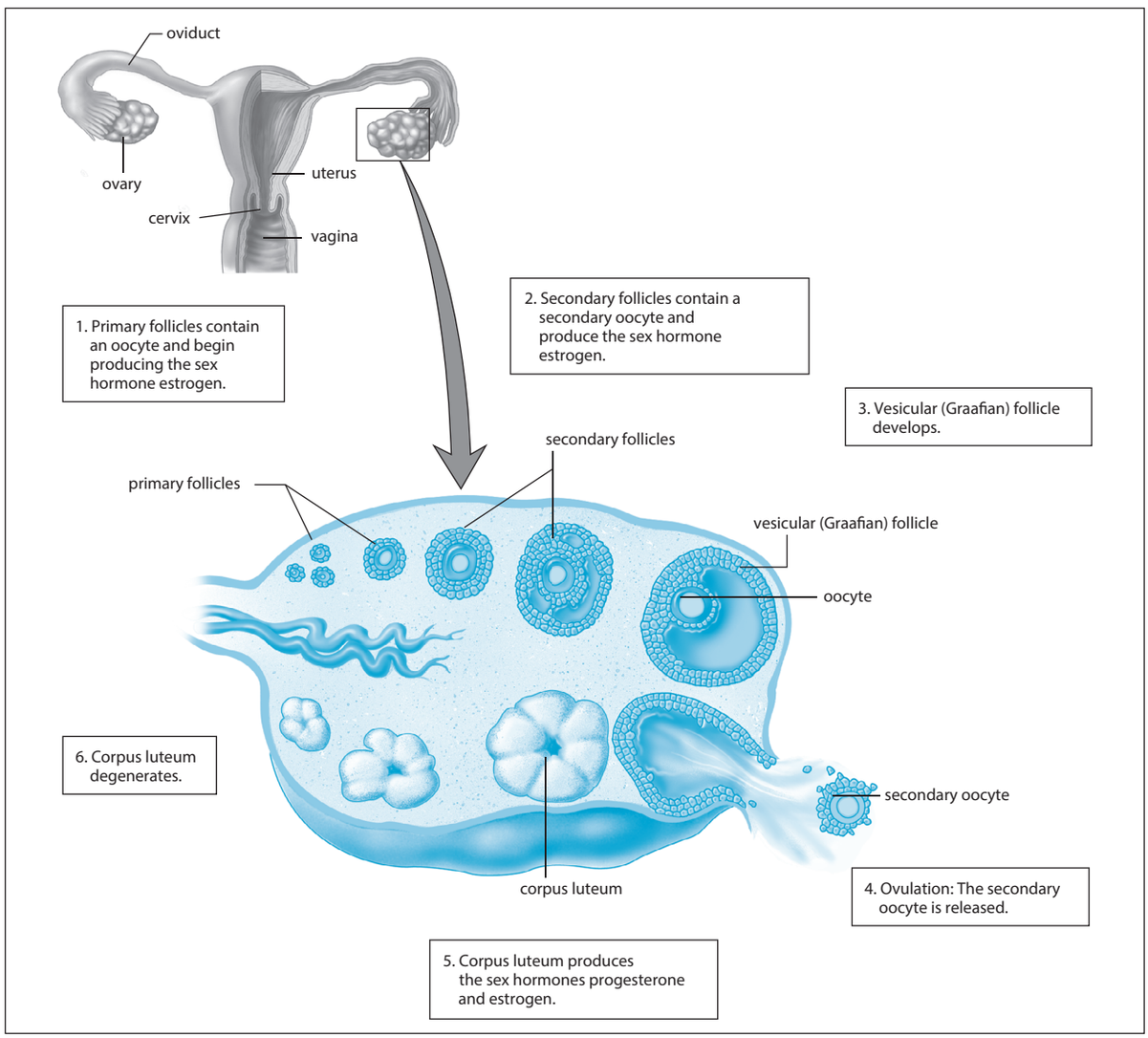

FIGURE 9-20 The female reproductive system. The ovaries release an egg into the fallopian tube during each reproductive cycle. Should the egg be fertilized, the resulting embryo implants in the uterus. *Source:* From Sylvia S. Mader, *Biology*, 8th ed., McGraw-Hill, 2004; reproduced with permission of The McGraw-Hill Companies.

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The menstrual cycle, which has three phases, is as follows:

- **Menses.** During the first 5 or so days of the cycle, the existing endometrium is lost via menstrual fluid as arteries serving the endometrium constrict, restricting the cells from O_2 and nutrient, resulting in tissue death.
- **The proliferative phase.** During the second week of the cycle, the primary event in the uterus is the proliferation of cells to replace the endometrium that was lost during menstruation.
- **The secretory phase.** During the last 2 weeks of the cycle, hormones are secreted to prepare the endometrium for implantation, if an embryo is present. As the 28th day of the cycle approaches, the endometrium deteriorates and menses will soon begin as the cycle restarts.

OVARIAN CYCLE

Eggs are produced through the ovarian cycle, whose timing must be carefully choreographed to the menstrual cycle, both of which can be seen in Figure 9-21. Like the menstrual cycle, the ovarian cycle also typically lasts 28 days.

The ovarian cycle consists of the following phases:

- **The pre-ovulatory phase.** This phase consists of the events prior to ovulation and lasts from days 1 to 13 of the cycle. This timing corresponds to menses and the proliferative phase of the menstrual cycle.
- **Ovulation.** The rupture of a follicle in the ovary and subsequent release of an egg to a fallopian tube constitutes ovulation. It typically occurs on day 14 of the cycle, although there is considerable individual variation.
- **The post-ovulatory phase.** During this phase, the egg may be fertilized. This part of the cycle typically lasts from days 15 to 28 and corresponds with the secretory phase of the menstrual cycle. Should fertilization occur, the embryo implants into the endometrium. If fertilization has not occurred, the menstrual cycle restarts, causing the egg to be lost.

Oogenesis. The events that lead to the maturation of an egg are termed **oogenesis** and are regulated through the ovarian cycle. Within the ovaries of a female, the process of **meiosis** has begun before she was ever born. This process results in the creation of primary follicles within the ovaries. A **follicle** consists of a potential egg cell surrounded by a shell of follicular cells to support the egg. The number of primary follicles is set at birth and is usually around 700,000. As the female is born and ages, many of these follicles die. By the time a female reaches puberty between ages 12 and 14, as few as 200,000 follicles remain. Although the number has drastically declined and continues to decline with age, there are still more than enough follicles to support the

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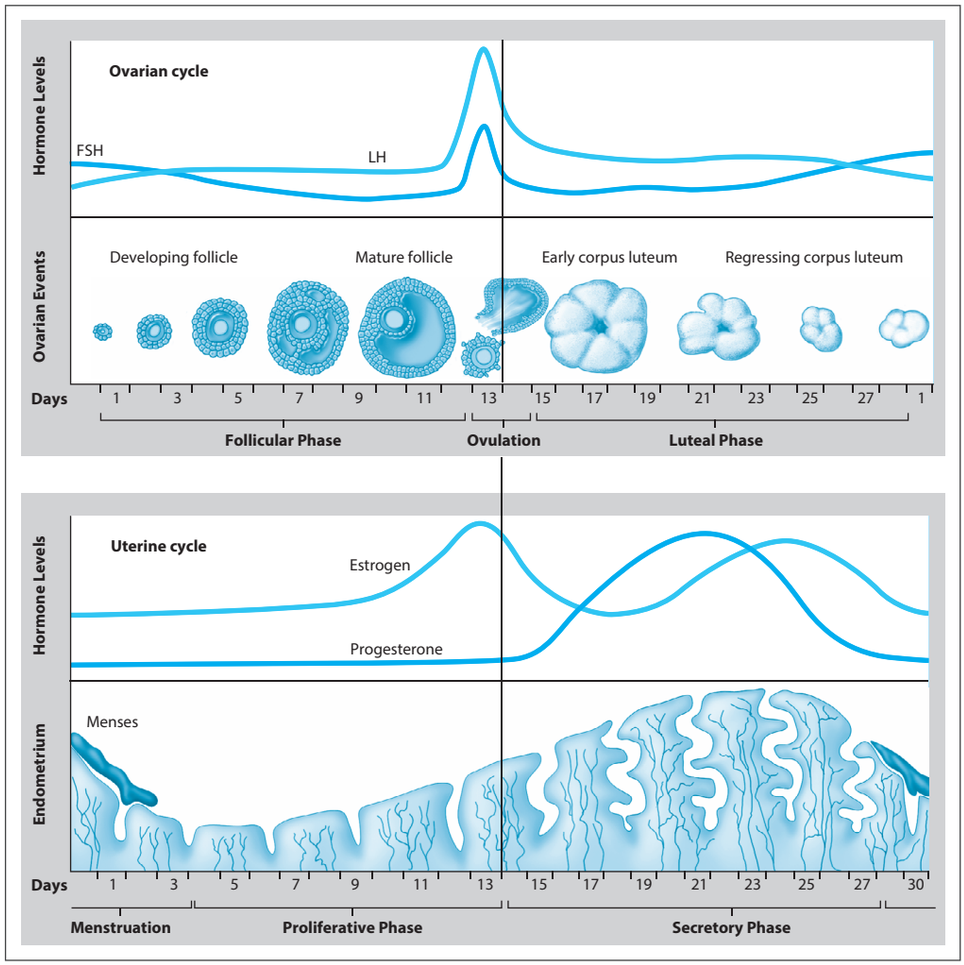

FIGURE 9-21 The female reproductive cycle. The control of the uterine cycle is achieved by estrogen and progesterone. The ovarian cycle is regulated primarily by follicle-stimulating hormone (FSH) and luteinizing hormone (LH). *Source:* From Sylvia S. Mader, *Biology*, 8th ed., McGraw-Hill, 2004; reproduced with permission of The McGraw-Hill Companies.

reproductive needs of a female, because only one egg is released every 28 days. Until puberty begins, these follicles stay in an arresting phase of meiosis.

After puberty, the **ovarian cycle** begins. During the pre-ovulatory phase, a few primary follicles resume meiosis and begin growing as primary oocytes. Starting at day 1 of the cycle, the **anterior pituitary gland** secretes **follicle-stimulating hormone (FSH)** and **luteinizing hormone (LH)**. Recall that the anterior pituitary is under the control of the hypothalamus. The **hypothalamus** produces **gonadotropin-releasing hormone (GnRH)**, which stimulates the release of FSH and LH. FSH causes the growth of several follicles, which begin to produce **estrogen**. The more the follicles grow, the more estrogen is produced. Estrogen levels are at their highest during the second week

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of the cycle, which corresponds to the rebuilding of the endometrium following menstruation.

During the second week of the cycle, the high levels of estrogen actually inhibit FSH such that no more follicles begin to grow on this cycle. As estrogen from the growing follicles continues to rise, there is a massive surge in LH. This surge causes the completion of the first round of meiosis, leading to the formation of a secondary oocyte and the rupture of the follicle within the ovary. This is **ovulation**, and it happens on day 14 of the cycle. The oocyte is released to the **fallopian tubes**, and the remnants of the follicle remain in the ovary.

If the oocyte is fertilized, **meiosis II** occurs, which results in a **mature egg (ovum)**. Only one mature egg is needed during ovulation, so the remaining cells produced during meiosis are termed **polar bodies**. They are much smaller than the egg and are degraded. If more than one egg is released on a given cycle, the potential exists for multiple fertilizations and multiple embryos, resulting in fraternal twins or triplets.

The remains of the follicle in the ovary continue secreting estrogen and become the **corpus luteum**, which also secretes **progesterone**. The estrogen and progesterone suppress FSH and LH so that no more eggs are released in this cycle. These hormones also keep the endometrium prepared to receive an embryo during the secretory phase (third and fourth weeks) of the menstrual cycle.

At the end of the fourth week of the cycle, if an **embryo** has not implanted into the endometrium, the cycle restarts. At this point, the corpus luteum degrades. Without the corpus luteum, the levels of estrogen and progesterone decline. The lack of these hormones, particularly the lack of progesterone, is the cause of menstruation, which can occur only when these levels are low. Furthermore, the lack of estrogen and progesterone allows the pituitary gland to begin secreting FSH and LH again to initiate a new cycle.

The ability to perform the ovarian cycle ends at **menopause**, when the ovaries are no longer sensitive to FSH and LH. The levels of estrogen and progesterone in the body decrease and the ovaries atrophy. This typically occurs between the ages of 45 and 55.

Because estrogen and progesterone have the ability to suppress the actions of FSH and LH, they are the hormones of choice for use in birth control methods such as pills, patches, injections, rings, or implants. The use of synthetic estrogen and/or synthetic progesterone can be used to manipulate the ovaries into bypassing ovulating since FSH and LH are suppressed.

Male Reproductive System

In contrast to the female system, the male reproductive system is not housed completely within the abdominal cavity and is a closed system, which can be seen in

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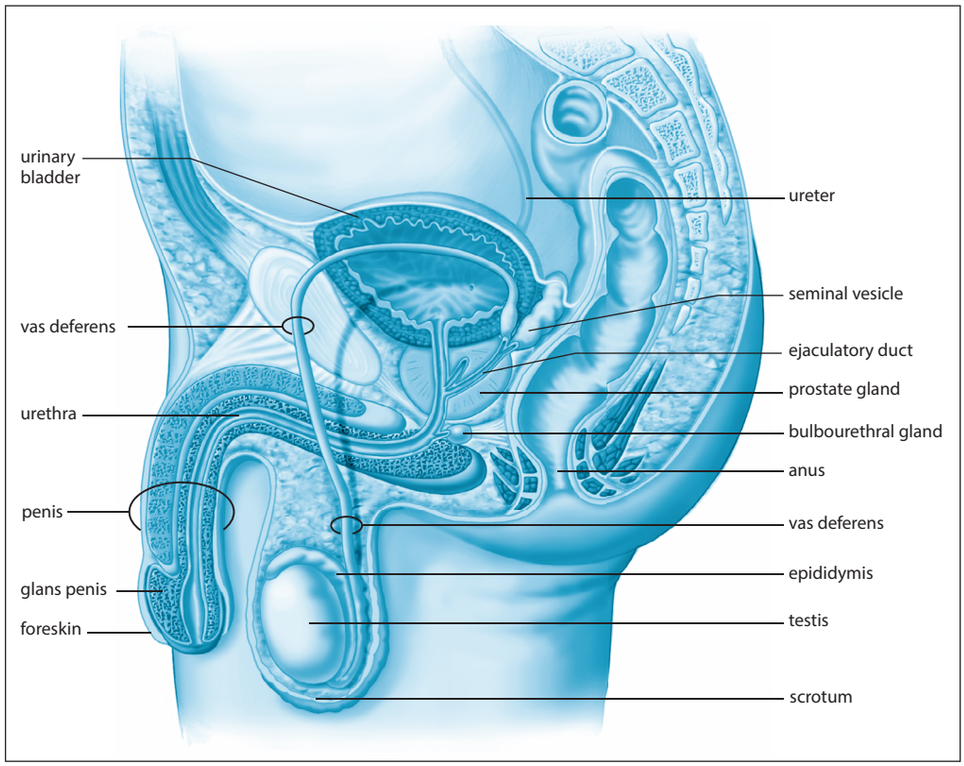

FIGURE 9-22 Sperm are produced in the testes of the male reproductive system. As sperm are released from the male system, secretions from a variety of glands are added to produce semen. *Source:* From Sylvia S. Mader, *Biology*, 8th ed., McGraw-Hill, 2004; reproduced with permission of The McGraw-Hill Companies.

Figure 9-22. The male gonads, or **testes**, produce **sperm**. The remaining reproductive structures serve as a means to transport sperm out of the body and into the female system.

Sperm begin their development in the **seminiferous tubules** of the testes, where they are nourished by **Sertoli cells**. The testes are housed in the **scrotum** outside of the abdominal cavity, where the temperature is a few degrees cooler than body temperature. Oddly enough, sperm require a temperature cooler than normal body temperature to become functional. As sperm develop in the testes, they move into the **epididymis** associated with each testis. Once in the epididymis, the sperm acquire motility and are stored.

When ejaculation occurs, the sperm must be moved toward the male urethra. The sperm enter the **vas deferens**, which are tubes that move up into the abdominal cavity. From there, the two vas deferens merge into the ejaculatory duct and into the urethra. Recall that the **urethra** is also used for urine passage. When sperm are moving through, the urethra is unavailable to the bladder. The urethra progresses through the length of the penis.

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Once in the urethra, three types of glands add their secretions to the sperm as they pass by. This creates **semen**, which is a mixture of sperm and secretions. The glands of the male reproductive system that provide secretions to semen are as follows:

- **Seminal vesicles.** They provide a fluid rich in nutrients to serve as an energy source for the sperm.
- **Prostate gland.** It wraps around the urethra and deposits a secretion that is alkaline to balance the acidic environment of the vagina.
- **Bulbourethral glands.** They secrete a fluid prior to ejaculation, which may serve to lubricate the urethra for sperm passage.

SPERMATOGENESIS

The process of **spermatogenesis** produces sperm through meiosis. Unlike meiosis in females that produces one egg and three polar bodies, meiosis in men results in the production of four sperm cells. While women need to release only one egg per reproductive cycle, men need millions of sperm per fertilization attempt. While the one egg produced in oogenesis is quite large, the sperm produced in spermatogenesis are quite small. This is because the egg cell must contain additional components needed to support embryonic development. Additional differences between spermatogenesis and oogenesis were presented in Chapter 7.

Spermatogenesis requires the hormonal influence of testosterone and begins at puberty. **Testosterone** is secreted during development to cause the development of male reproductive structures, but it is then halted until puberty. Diploid cells in the testes called **spermatogonia** differentiate into primary spermatocytes, which undergo **meiosis I**, producing two haploid secondary spermatocytes. The secondary spermatocytes undergo **meiosis II** to produce four mature sperm (spermatozoa). The spermatozoa then move to the **epididymis** to mature. The process takes between 2 and 3 months to complete.

Mature sperm structure can be seen in Figure 9-23. The **acrosome** contains digestive enzymes that are used to penetrate the egg, the **head** contains the nucleus that the sperm will contribute to the egg, and the **tail** is a flagellum that is propelled by ATP, which is produced by large numbers of mitochondria present in the sperm.

Some of the same hormones that are used in the female reproductive system are also used to regulate spermatogenesis. GnRH from the hypothalamus allows for the secretion of LH from the anterior pituitary. LH causes the production of testosterone by cells in the testes. The secretion of GnRH from the hypothalamus also results in the release of FSH from the anterior pituitary. While testosterone is needed to stimulate spermatogenesis, FSH is also needed to make the potential sperm cells sensitive to testosterone. The levels of testosterone regulate sperm production in a manner that resembles a thermostat.

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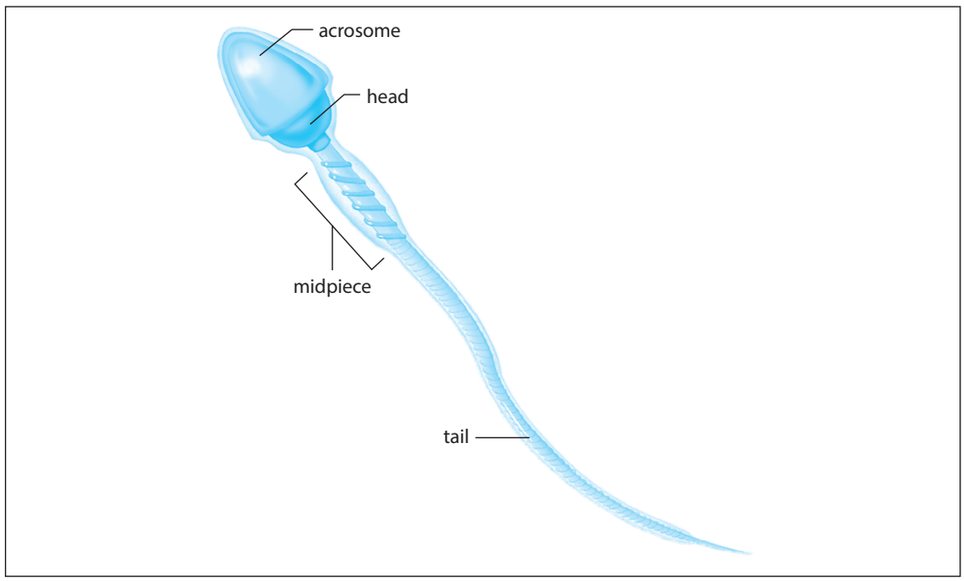

FIGURE 9-23 Sperm structure. The head of the sperm contains the nucleus, which is needed to fertilize an egg. *Source:* From Sylvia S. Mader, *Biology*, 8th ed., McGraw-Hill, 2004; reproduced with permission of The McGraw-Hill Companies.