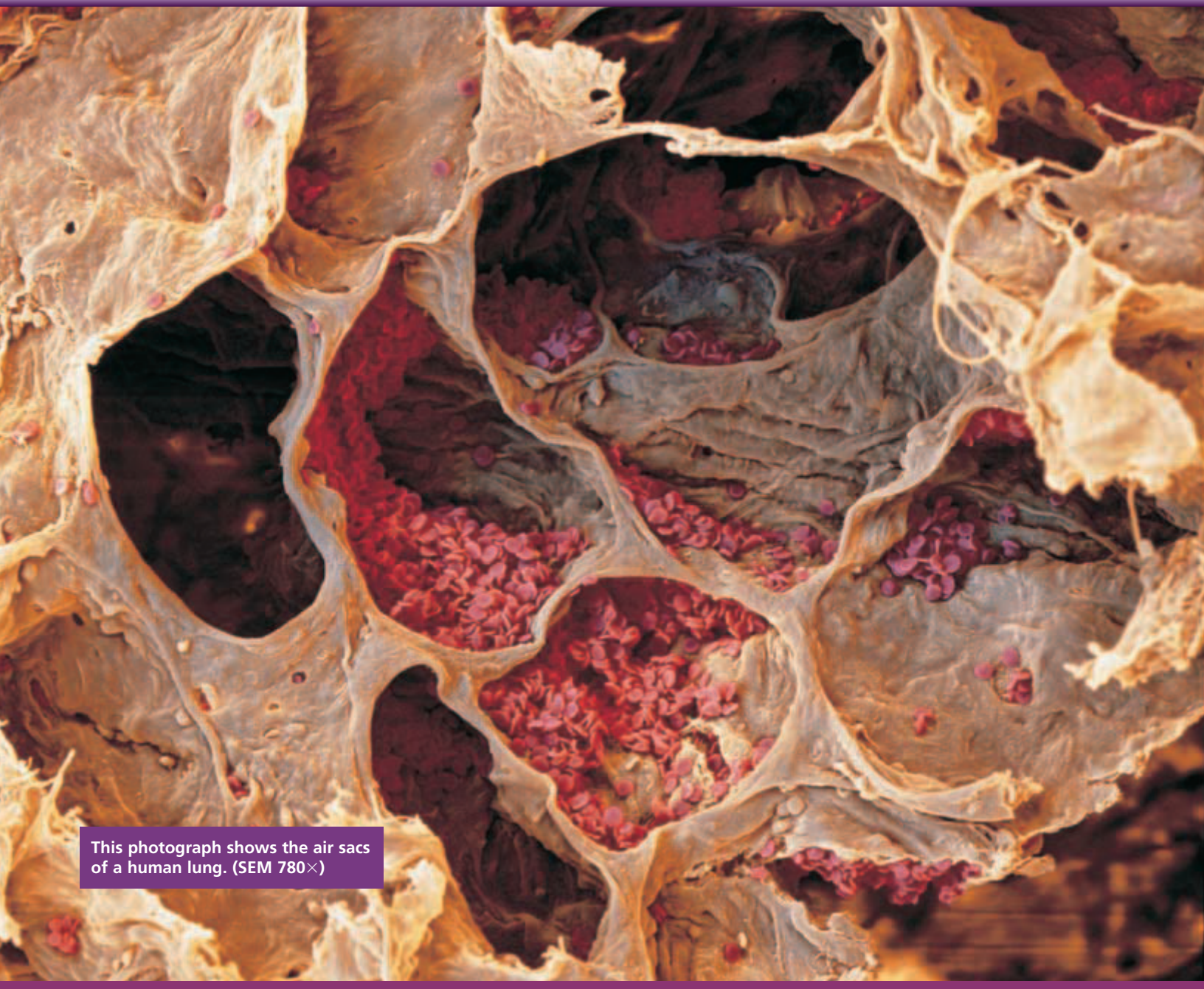
CHAPTER 46

CIRCULATORY AND RESPIRATORY SYSTEMS



This photograph shows the air sacs of a human lung. (SEM 780×)

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THE CIRCULATORY SYSTEM

Most of the cells in the human body are not in direct contact with the external environment. The circulatory system acts as a transport service for these cells. Two fluids move through the circulatory system: blood and lymph.

SECTION 1

OBJECTIVES

- **Describe** the structure and function of the human heart.
- **Trace** the flow of blood through the heart and body.
- **Distinguish** between arteries, veins, and capillaries in terms of their structure and function.
- **Distinguish** between pulmonary circulation and systemic circulation.
- **Summarize** the functions of the lymphatic system.

VOCABULARY

cardiovascular system
lymphatic system
atrium
ventricle
valve
aorta
sinoatrial node
atrioventricular node
pulse
artery
blood pressure
hypertension
capillary
vein
pulmonary circulation
systemic circulation
atherosclerosis
lymph

THE HEART

The blood, heart, and blood vessels form the **cardiovascular system.** The lymph, lymph nodes, and lymph vessels form the **lymphatic system.** The cardiovascular system and lymphatic system collectively make up the *circulatory system.* The circulatory system transports nutrients, hormones, and gases; gets rid of wastes; and helps maintain a constant body temperature.

The central organ of the cardiovascular system is the heart, the muscular organ that pumps blood through a network of blood vessels. The heart beats more than 2.5 billion times in an average life span. Yet this organ is slightly larger than a fist. The heart lies within the thoracic (chest) cavity, behind the sternum (breastbone) and between the two lungs. A tough, saclike membrane called the *pericardium* surrounds the heart and secretes a fluid that reduces friction as the heart beats.

Notice in Figure 46-1 that a *septum* (wall) vertically divides the heart into two sides. The right side pumps blood to the lungs, and the left side pumps blood to the other parts of the body. Each side of the heart is divided into an upper and lower chamber. Each upper chamber is called an **atrium,** and each lower chamber is called a **ventricle.**

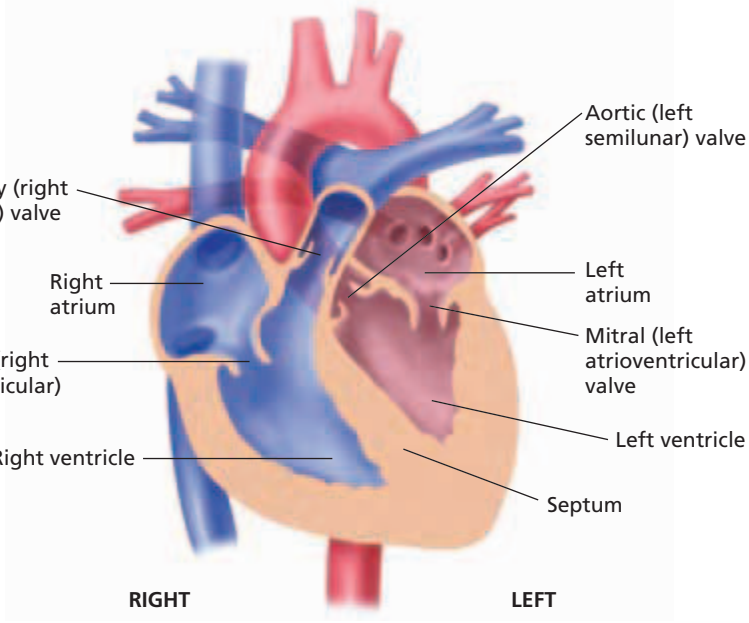

FIGURE 46-1
The septum prevents mixing of blood from the two sides of the heart, and the valves ensure that blood flows in only one direction.

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Quick Lab

Determining Heart Rate

Materials stopwatch or clock with second hand

Procedure

1. Have your partner find the pulse in your wrist and count your heartbeats for 15 seconds while you are seated. Calculate your resting heart rate in beats per minute.
2. Have your partner count your heartbeats for 15 seconds while you are standing. Calculate your heart rate in beats per minute.
3. Have your partner count your heartbeats for 15 seconds after you jog or march in place for 1 minute. Calculate your heart rate in beats per minute.

Analysis What causes your pulse? What causes the change in your heart rate in each situation?

Valves are flaps of tissue that open in only one direction. The *atrioventricular* (AY-tree-oh-ven-TRIH-kyuh-luhr) *valve* (AV valve) on the right side of the heart is called the *tricuspid valve*. The *mitral valve*, also called the *bicuspid valve,* is on the left. As the ventricles pump, blood pressure closes the AV valves to prevent blood from flowing backward into the atria. From the ventricles, blood is pumped out of the heart into large vessels. A *semilunar* (SEM-ee-LOON-uhr) *valve* (SL valve) separates the ventricles from these large vessels on each side of the heart. The SL valve on the right side is known as the *pulmonary valve*, and the SL valve on the left side is known as the *aortic valve*. The SL valves prevent blood from flowing back into the ventricles when the heart relaxes.

Circulation in the Heart

Refer to Figure 46-2 to trace the path of the blood as it circulates through the heart. Blood returning to the heart from parts of the body other than the lungs has a high concentration of carbon dioxide and a low concentration of oxygen. (1) Deoxygenated (O_2-poor) blood enters the right atrium.

(2) The right atrium sends deoxygenated blood into the right ventricle. (3) The muscles of the right ventricle contract and force the blood into the pulmonary arteries. (4) The pulmonary artery sends the blood to the lungs. In the lungs, the carbon dioxide diffuses out of the blood, and oxygen diffuses into the blood. (5) The oxygenated blood returns to the left atrium of the heart. Notice in Figure 46-2 that the flow of blood on the left side of the heart is illustrated with a red arrow representing oxygenated blood, which has a bright red color.

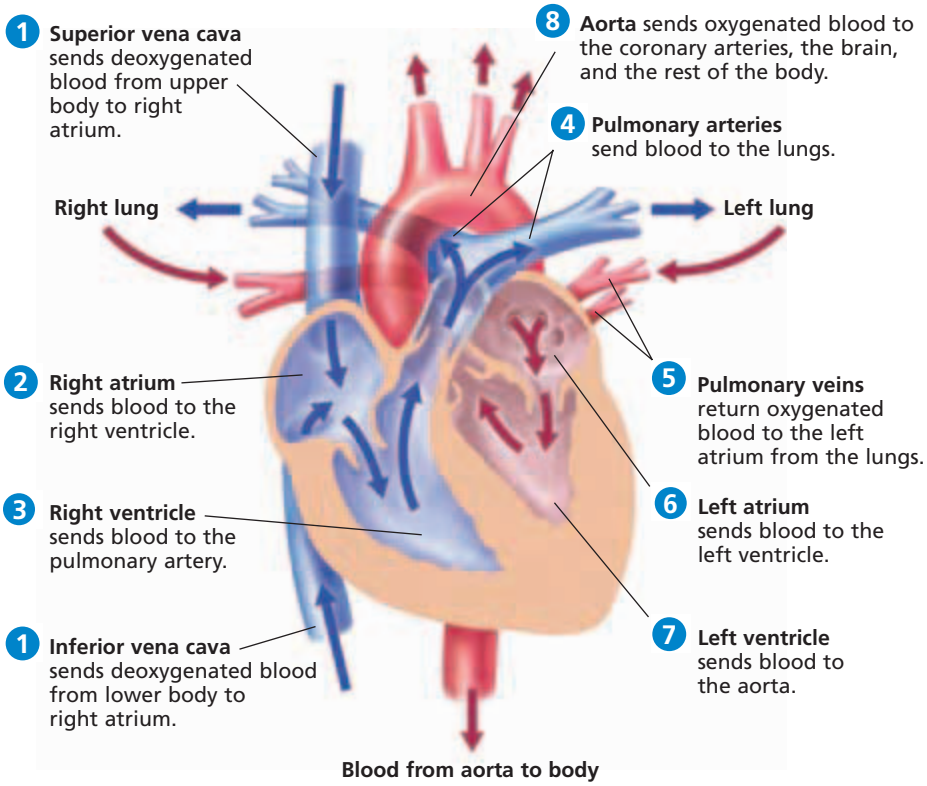

FIGURE 46-2

Trace the path of blood through the heart. Notice that illustrations of a heart are drawn as if the heart were in a person facing you. That is, the left side of the heart is shown on the right as you face the heart, and the right side of the heart is on the left as you face the heart.

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6 The oxygenated blood is then pumped into the left ventricle. 7 Contraction of the muscular walls of the left ventricle forces the blood into a large blood vessel called the **aorta.** 8 From the aorta, blood is transported to all parts of the body. The left ventricle is the thickest chamber of the heart because it has to do the most work to pump blood to all parts of the body.

Deoxygenated blood is commonly represented with the color blue. However, it is a misconception that deoxygenated blood is blue. When oxygen is attached to hemoglobin, the blood is bright red. Without oxygen, blood is dark red. The dark red blood in veins appears blue when it shows through the vein walls and skin.

Control of the Heartbeat

The heart consists of muscle cells that contract in waves. When the first group of cells are stimulated, they in turn stimulate neighboring cells. Those cells then stimulate more cells. This chain reaction continues until all the cells contract. The wave of activity spreads in such a way that the atria and the ventricles contract in a steady rhythm. The first group of heart-muscle cells that get stimulated lie in an area of the heart known as the sinoatrial node, shown in Figure 46-3.

The **sinoatrial** (SIEN-oh-AY-tree-uhl) **(SA) node** is a group of specialized heart-muscle cells located in the right atrium. These muscle cells spontaneously initiate their own electrical impulse and contract. The SA node is often called the *pacemaker* because it regulates the rate of contraction of the entire heart. The electrical impulse initiated by the SA node subsequently reaches another special area of the heart, known as the **atrioventricular (AV) node.** The AV node is located in the septum between the atria, as shown in Figure 46-3. The AV node relays the electrical impulse to the muscle cells that make up the ventricles. As a result, the ventricles contract a fraction of a second after the atria, completing one full heartbeat. In an average adult at rest, the heart beats about 70 times each minute.

A heartbeat has two phases. Phase one, called *systole* (SIS-tohl), occurs when the ventricles contract, closing the AV valves and opening the SL valves to pump blood into the two major vessels that exit the heart. Phase two, called *diastole* (DIE-a-stohl), occurs when the ventricles relax, allowing the back pressure of the blood to close the SL valves and opening the AV valves. The closing of these two heart valves results in the characteristic *lub dup* sound we call a heartbeat. If one of the valves fails to close properly, some blood may flow backward, creating a different sound, which is known as a heart murmur.

A person's **pulse** is a series of pressure waves within an artery caused by the contractions of the left ventricle. When the ventricle contracts, blood surges through the arteries, and the elastic walls in the vessels expand and stretch. The most common site for taking a pulse is at a radial artery, on the thumb side of each wrist. The average pulse rate ranges from 70 to 90 beats per minute for adults.

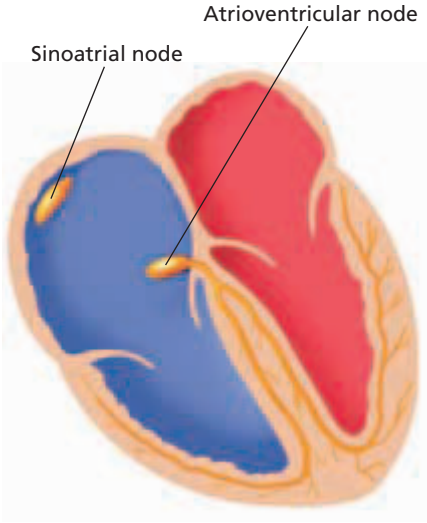

FIGURE 46-3

Two areas of specialized tissue, known as nodes, control the heartbeat. A person whose SA node is defective can have an operation to implant an artificial pacemaker. An artificial pacemaker can also help a defective AV node.

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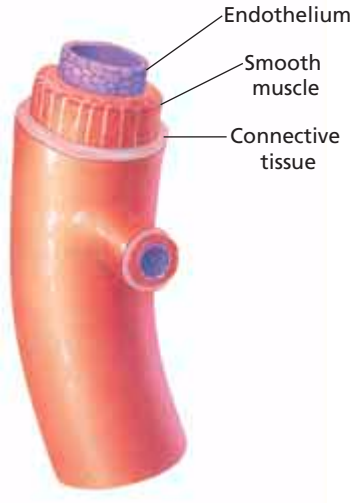


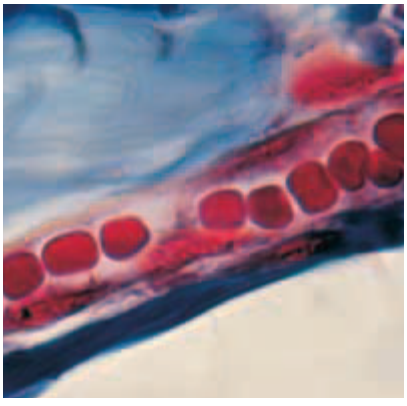
Artery
(carries blood away from the heart)

FIGURE 46-4

Notice the thick muscular layer of an artery. The layers of the artery wall are separated by elastic tissue. This tissue provides strength, preventing systolic pressure from bursting the artery.

FIGURE 46-5

The diameter of a capillary is so small that red blood cells must move single file through these vessels, as shown in this photograph (1,200×). All exchange of nutrients and waste between blood and cells occurs across the thin walls of the capillaries.



BLOOD VESSELS

The circulatory system is known as a closed system because the blood is contained within either the heart or the blood vessels at all times. This type of system differs from an open system, in which blood leaves the vessels and circulates within tissues throughout the organism's body. The blood vessels that are part of the closed circulatory system of humans form a vast network to help keep the blood flowing in one direction.

Arteries and Blood Pressure

The large, muscular vessels that carry blood away from the heart are called **arteries.** As shown in Figure 46-4, the thick walls of the arteries have three layers: an inner endothelial layer, a middle layer of smooth muscle, and an outer layer of connective tissue. This structure gives arteries a combination of strength and elasticity, which allows them to stretch as pressurized blood enters from the heart. You can feel this stretching of arteries—it is your pulse.

Contraction of the heart moves the blood through the arteries with great force. The force that blood exerts against the inside walls of a blood vessel is known as **blood pressure.** Blood pressure is highest in the two main arteries that leave the heart. It is usually measured in the artery that supplies blood to the arm. To measure blood pressure, a trained person inflates a cuff that is placed around a patient's arm, temporarily stopping the flow of blood through the artery. Connected to the cuff is a gauge containing a column of mercury (Hg) that rises as the pressure in the cuff increases. The trained person then releases the air in the cuff slowly while listening to the artery with a stethoscope and watching the column of mercury. The first sounds of blood passing through the artery indicates the *systolic pressure*, or the pressure of the blood when the ventricles contract. In a normal adult, the systolic pressure is about 120 mm of Hg for males and 110 mm of Hg for females. Continuing to release the air in the cuff, the trained person next listens for the disappearance of sound, which indicates a steady flow of blood through the artery in the arm. This indicates the *diastolic pressure*. In a normal adult, the diastolic pressure is about 80 mm of Hg for males and 70 mm of Hg for females.

High blood pressure, or **hypertension,** is a leading cause of death in many countries. Blood pressure that is higher than normal places a strain on the walls of the arteries and increases the chance that a vessel will burst.

Capillaries and Veins

Recall that when the left ventricle contracts, it forces blood into the aorta, the body's largest artery. From the aorta, blood travels through a network of smaller arteries, which in turn divide and form even smaller vessels, called *arterioles*. The arterioles branch into a network of tiny vessels, called **capillaries.** A capillary is shown in Figure 46-5.

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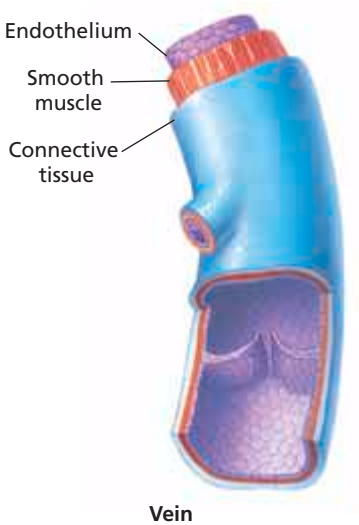
The network formed by capillaries is so extensive that all of the approximately 100 trillion cells in the body lie within about 125 µm of a capillary. This close association between capillaries and cells allows for rapid exchange of materials. Capillary walls are only one cell thick; gases and nutrients can diffuse through these thin walls. Wherever the concentration of oxygen or nutrients is higher in the blood than in the surrounding cells, the substance diffuses from the blood into the cells. Wherever the concentrations of carbon dioxide and wastes are higher in the cells than in the blood, these substances diffuse from the cells into the blood.

Blood flows through capillaries that merge to form larger vessels called *venules* (VEN-yoolz). Several venules in turn unite to form a **vein,** a large blood vessel that carries blood to the heart. Veins returning deoxygenated blood from the lower parts of the body merge to form the *inferior vena cava*. Veins returning deoxygenated blood from the upper parts of the body merge to form the *superior vena cava*. Refer back to Figure 46-2, and locate the inferior vena cava and the superior vena cava.

As you can see in Figure 46-6, although the walls of the veins are composed of three layers, like those of the arteries, they are thinner and less muscular. By the time blood reaches the veins, it is under much less pressure than it was in the arteries. With less pressure being exerted in the veins, the blood could flow backward and disrupt the pattern of circulation. To prevent that, valves in the veins help keep the blood flowing in one direction. Many veins pass through skeletal muscle. When these muscles contract, they are able to squeeze the blood through the veins. When these muscles relax, the valves can close, thus preventing the blood from flowing backward. Figure 46-6 shows the structure of a valve in a vein.



Vein
(returns blood to the heart)

FIGURE 46-6
Like an artery, a vein has three layers: the outer layer of connective tissue, the middle layer of smooth muscle, and the inner layer of endothelial tissue.

PATTERNS OF CIRCULATION

The English scientist William Harvey (1578–1657) first showed that the heart and the blood vessels form one continuous, closed system of circulation, as shown in Figure 46-7. He also reasoned that this system consists of two primary subsystems: **pulmonary circulation,** in which the blood travels between the heart and lungs, and **systemic circulation,** in which the blood travels between the heart and all other body tissues.

Pulmonary Circulation

Deoxygenated blood returning from all parts of the body except the lungs enters the right atrium, where it is then pumped into the right ventricle. When the right ventricle contracts, the deoxygenated blood is sent through the pulmonary artery to the lungs. The pulmonary artery is the only artery that carries deoxygenated blood. The pulmonary artery branches into two smaller arteries, with one artery going to each lung. These arteries branch into arterioles and then into capillaries in the lungs.

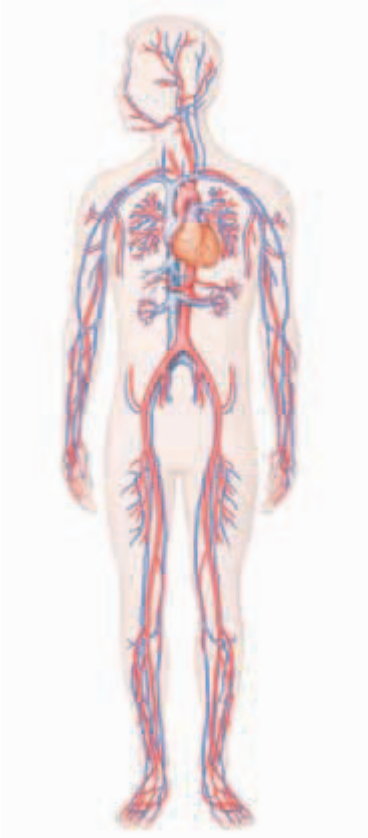


FIGURE 46-7
The cardiovascular system transports materials throughout the body and distributes heat.

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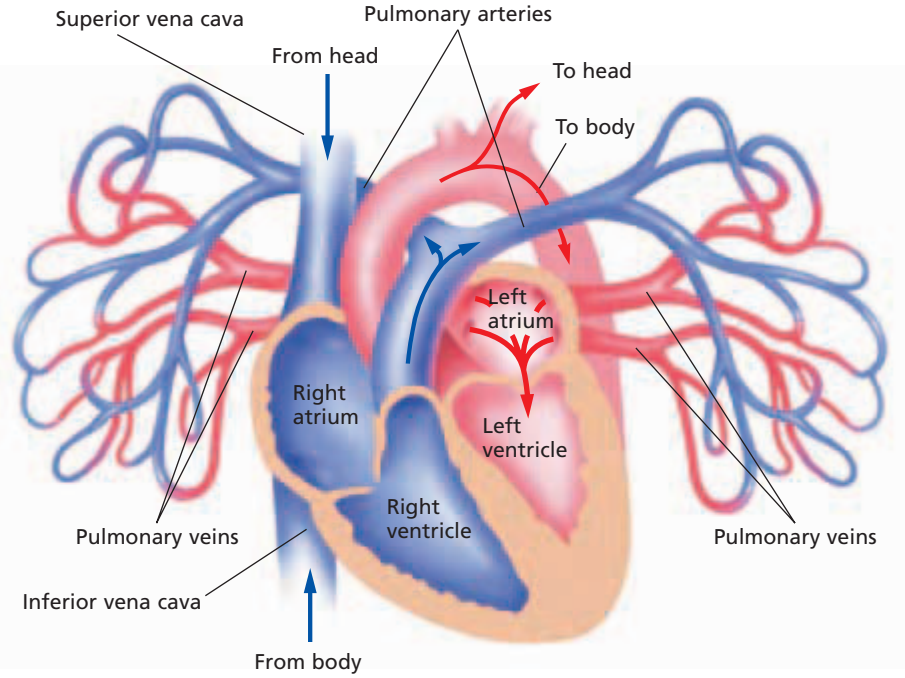
FIGURE 46-8

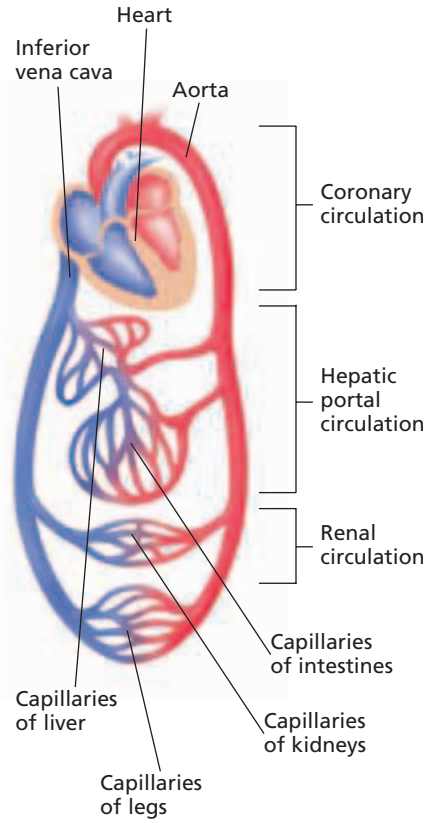
The pulmonary circulation between the heart and the lungs involves the pulmonary arteries and the pulmonary veins. Deoxygenated blood flows from the right side of the heart to the lungs. Oxygenated blood is returned to the left side of the heart from the lungs. This is the opposite of systemic and coronary blood flow, in which oxygen-rich blood flows from the heart and oxygen-poor blood is returned to the heart.



In the lungs, carbon dioxide diffuses out of the capillaries and oxygen diffuses into the capillaries. The oxygenated blood then flows into venules, which merge into the *pulmonary veins* that lead to the left atrium of the heart. From the left atrium, blood is pumped into the left ventricle and then to the body through the aorta. In Figure 46-8, trace the path blood takes as it passes through pulmonary circulation.

FIGURE 46-9

Notice three subsystems of systemic circulation. Other subsystems transport blood between the heart and the head, arms, and other organs.



Systemic Circulation

Systemic circulation is the movement of blood between the heart and all parts of the body except the lungs. Trace the path blood follows in systemic circulation in Figure 46-9. Notice that oxygenated blood is pumped out of the left ventricle and into the aorta. From the aorta, blood flows into other subsystems of systemic circulation.

Coronary circulation is the subsystem of systemic circulation that supplies blood to the heart itself. If blood flow in the *coronary arteries,* which supply blood to the heart, is reduced or cut off, muscle cells will die. This can happen when an artery is blocked by a blood clot or by **atherosclerosis** (ATH-uhr-oh-skler-OH-sis), a disease characterized by the buildup of fatty materials on the interior walls of the coronary arteries. Either type of blockage can lead to a *heart attack*.

Hepatic portal circulation is a subsystem of systemic circulation. Nutrients are picked up by capillaries in the small intestine and are transported by the blood to the liver. Excess nutrients are stored in the liver for future needs. The liver receives oxygenated blood from a large artery that branches from the aorta.

Renal circulation, another subsystem of systemic circulation, supplies blood to the kidneys. Nearly one-fourth of the blood that is pumped into the aorta by the left ventricle flows to the kidneys. The kidneys filter waste from the blood.

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LYMPHATIC SYSTEM

In addition to the cardiovascular system, the circulatory system also includes the lymphatic system. One function of the lymphatic system is to return fluids that have collected in the tissues to the bloodstream. Fluids diffuse through the capillary walls just as oxygen and nutrients do. Some of these fluids pass into cells, some return to the capillaries, and some remain in the intercellular spaces.

Excess fluid in the tissues moves into the tiny vessels of the lymphatic system; this fluid is called **lymph.** Lymph vessels merge to form larger vessels. The lymph vessels are similar in structure to capillaries, and the larger lymph vessels are similar in structure to veins. However, an important difference exists between blood vessels and lymph vessels. Blood vessels form a complete circuit so that blood passes from the heart to all parts of the body and then back again to the heart. In contrast, lymph vessels form a one-way system that returns fluids collected in the tissues back to the bloodstream. In addition, the lymphatic system has no pump. Like the blood in veins, lymph must be moved through the vessels by the squeezing of skeletal muscles. Like veins, the larger lymph vessels have valves to prevent the fluid from moving backward.

Notice in Figure 46-10 that lymph vessels form a vast network that extends throughout the body. The lymph that travels in these vessels is a transparent yellowish fluid, much like the liquid part of the blood. As the lymph travels through these vessels on its way to the heart, it passes through small organs known as lymph nodes. Notice in Figure 46-10 that lymph nodes are like beads on a string. These nodes filter the lymph as it passes, trapping foreign particles, microorganisms, and other tissue debris. Lymph nodes also store *lymphocytes*, white blood cells that are specialized to fight disease. When a person has an infection, the nodes may become inflamed, swollen, and tender because of the increased number of lymphocytes.

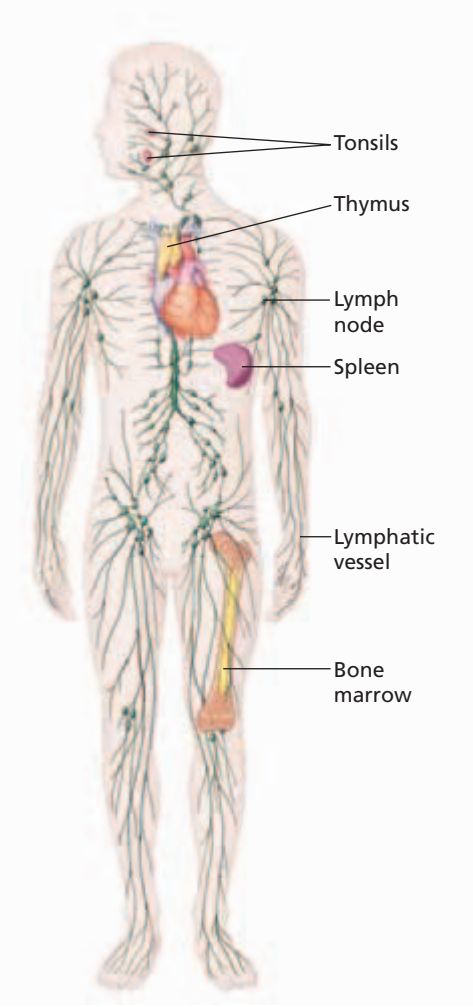

FIGURE 46-10
Like the cardiovascular system, the lymphatic system forms a vast network. Concentrated in certain regions of this network are lymph nodes that contain some of the disease-fighting cells of the immune system.

SECTION 1 REVIEW

1. Describe the structure of the heart.
2. Outline the path that blood follows through the heart and body, starting at the superior vena cava.
3. Describe the process by which the heartbeat is regulated.
4. How are the structures of arteries, veins, and capillaries related to their function?
5. Compare oxygenation levels in pulmonary circulation and systemic circulation.
6. Explain how the lymphatic system works with the cardiovascular system.

CRITICAL THINKING

7. **Analyzing Information** Some babies are born with a hole in the septum between the two atria. Based on what you know about blood flow through the heart, explain why this condition would be harmful to the baby.
8. **Forming Reasoned Opinions** In which blood vessels would you expect to find the lowest average blood pressure? Explain your answer.
9. **Applying Information** A man's arm is cut by a piece of glass. Blood comes out of the wound in rapid spurts. Which type of vessel was cut?

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SECTION 2

OBJECTIVES

- **List** the components of blood.
- **Distinguish** between red blood cells, white blood cells, and platelets in terms of their structure and function.
- **Summarize** the process of blood clotting.
- **Explain** what determines the compatibility of blood types for transfusion.

VOCABULARY

plasma
red blood cell (erythrocyte)
hemoglobin
white blood cell (leukocyte)
phagocyte
antibody
platelet
fibrin
blood type
antigen
Rh factor

BLOOD

Blood is a liquid connective tissue. The two main functions of the blood are to transport nutrients and oxygen to the cells and to carry carbon dioxide and other waste materials away from the cells. Blood also transfers heat to the body surface and plays a major role in defending the body against disease.

COMPOSITION OF BLOOD

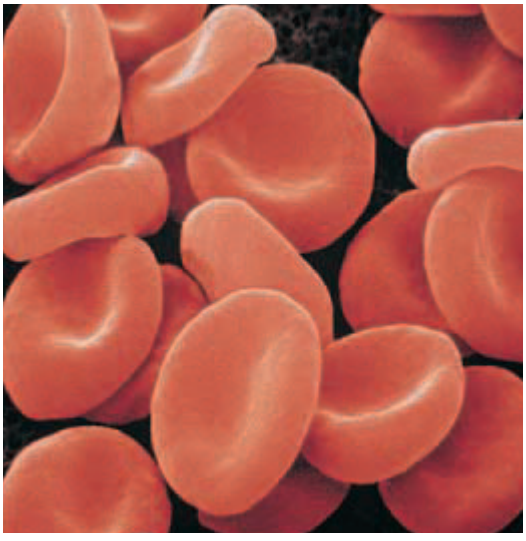
Blood is composed of a liquid medium and blood solids (formed elements). Formed elements include red blood cells, white blood cells, and platelets. The liquid makes up about 55 percent of the blood, and formed elements make up the remaining 45 percent. A healthy adult has about 4 to 5 L of blood in his or her body.

Plasma

Plasma, the liquid medium, is a sticky, straw-colored fluid that is about 90 percent water and includes metabolites, nutrients, wastes, salts, and proteins. Cells receive nourishment from dissolved substances carried in the plasma. These substances, which may include vitamins, minerals, amino acids, and glucose, are absorbed from the digestive system and transported to the cells. Plasma also carries hormones and brings wastes from the cells to the kidneys or the lungs to be removed from the body.

A variety of proteins are carried in the plasma. The plasma proteins have various functions. Some of the proteins in the plasma are essential for the formation of blood clots. Another protein, called albumin, plays an important role in the regulation of osmotic pressure between plasma and blood cells and between plasma and tissues. Other proteins, called antibodies, help the body fight disease.

FIGURE 46-11
Notice that a mature red blood cell (RBC) is disk-shaped and is concave on both sides. A red blood cell is little more than a cell membrane filled with hemoglobin. How is this structure related to its function?



Red Blood Cells

Red blood cells, or **erythrocytes** (uh-RITH-ruh-siets), shown in Figure 46-11, transport oxygen to cells in all parts of the body. Red blood cells are formed in the red marrow of bones. Immature red blood cells synthesize large amounts of an iron-containing protein called **hemoglobin.** Hemoglobin is the molecule that actually transports oxygen and, to a lesser degree, carbon dioxide. During the formation of a red blood cell, its cell nucleus and organelles disintegrate. The mature red blood cell is little more than a membrane containing hemoglobin.

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Because red blood cells lack nuclei, they cannot divide and they have a limited survival period, usually 120 to 130 days. Of the more than 30 trillion red blood cells circulating throughout the body at one time, 2 million disintegrate every second. To replace them, new ones form at the same rate in the red marrow of bones. Some parts of the disintegrated red blood cells are recycled. For example, the iron portion of the hemoglobin molecule is carried in the blood to the marrow, where it is reused in new red blood cells.

White Blood Cells

White blood cells, or **leukocytes** (LOO-kuh-siets), help defend the body against disease. They are formed in the red marrow, but some must travel to lymph nodes, tonsils, the thymus, or the spleen to mature. White blood cells are larger than red blood cells and significantly less plentiful. Each cubic millimeter of blood normally contains about 4 million red blood cells and 7,000 white blood cells. White blood cells can squeeze their way through openings in the walls of blood vessels and into the intercellular fluid. In that way, white blood cells can reach the site of infection and help destroy invading microorganisms.

Word Roots and Origins

leukocyte

from the Greek *leuco*, meaning "white," and *cyte*, meaning "cell"

Notice in Figure 46-12 that a white blood cell has a very different structure from that of a red blood cell. For instance, a white blood cell may be irregularly shaped and may have a rough outer surface. There are other differences between red blood cells and white blood cells as well. In contrast with the short-lived red blood cells, white blood cells may function for years. And while there is only one type of red blood cell, there are several types of white blood cells.

The white blood cell shown in Figure 46-12 is the type of white blood cell known as a **phagocyte** (FA-guh-siet). Phagocytes are cells that engulf invading microorganisms. Locate the microorganisms that are being engulfed by the phagocyte in Figure 46-12. Another type of white blood cell produces **antibodies.** Antibodies are proteins that help destroy substances, such as bacteria and viruses, that enter the body and can cause disease. When a person has an infection, the number of white blood cells can double.

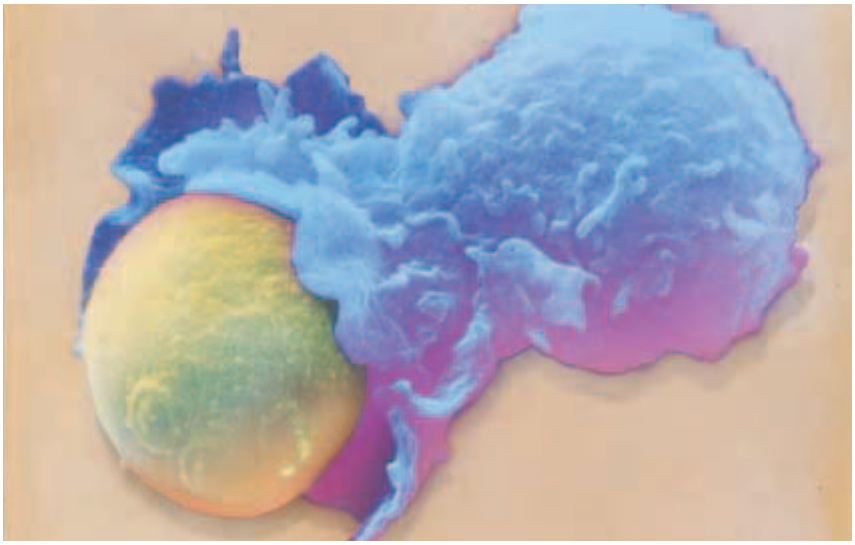

FIGURE 46-12
Some white blood cells, like the phagocyte shown in blue, engulf and destroy invading microorganisms.

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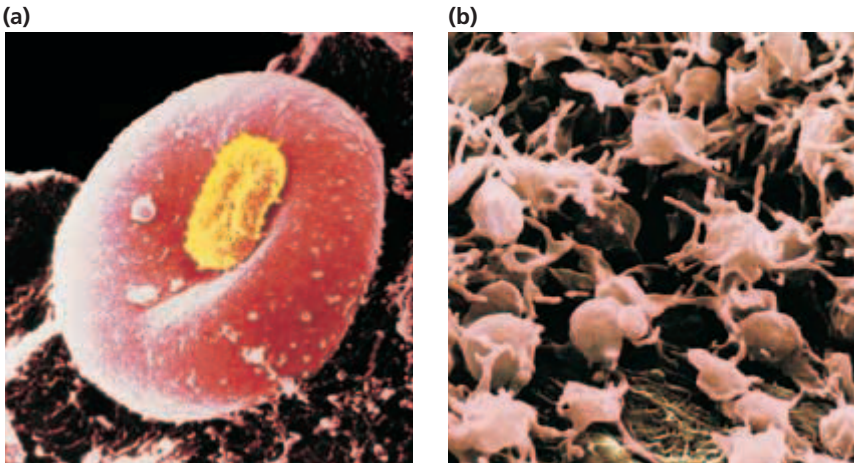
FIGURE 46-13

Inactive platelets, such as the yellow object shown in (a), derive their name from the fact that they look like little plates. Platelets are colorless and contain chemicals that are involved in the clotting process. (b) The platelets change shape during the clotting process. When activated, the platelets settle and spread on the substrate.



Eco Connection

Vampire Bats Help Save Stroke Victims

Vampire bats have an anticoagulant in their saliva that prevents blood clotting when it flows from a wound. In 1995, this enzyme was isolated and named *Draculin*.

Researchers have developed a clot-dissolving agent called *Desmodus rotundus salivary plasminogen activator* (DSPA), which is based on the salivary enzyme Draculin. DSPA targets and destroys fibrin. The current treatment must be given within three hours of the onset of a stroke (a sudden loss of consciousness or paralysis that occurs when the blood flow to the brain is interrupted). Otherwise, brain-cell death and brain damage may occur. According to research, DSPA could be a safe treatment for longer periods of time and appears to have no detrimental effect on brain cells.

Platelets

Platelets are essential to the formation of a blood clot. A blood clot is a mass of interwoven fibers and blood cells that prevents excess loss of blood from a wound. Platelets are not whole cells. They are fragments of very large cells that were formed in the bone marrow. As you can see in Figure 46-13a, platelets get their name from their platelike structure. Platelets lack a nucleus and have a life span of 7 to 12 days. A cubic micrometer of blood may contain as many as half a million platelets.

When a blood vessel tears or rips, platelets congregate at the damaged site, sticking together and forming a small plug. The vessel constricts, slowing blood flow to the area. Then, special clotting factors are released from the platelets and the damaged tissue. These factors begin a series of chemical reactions that occur at the site of the bleeding. The last step in this series brings about the production of a protein called **fibrin.** Fibrin molecules consist of long, sticky chains. As you can see in Figure 46-14, these chains form a net that traps red blood cells, and the mass of fibrin and red blood cells hardens into a clot, or scab.

Hemophilia is a disorder caused by the absence of one or more of the proteins required for blood clotting. When a person with hemophilia is injured, bleeding continues for much longer than it would in a person without hemophilia. Large cuts or internal injuries can be life threatening. Today, people with hemophilia are treated with injections of the missing clotting factors.

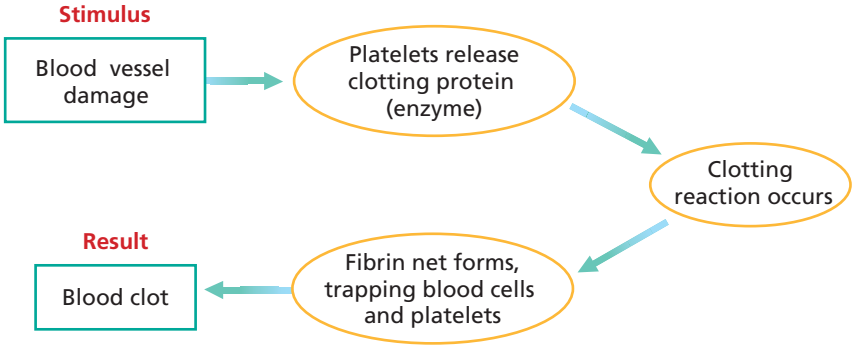


FIGURE 46-14

The release of enzymes from platelets at the site of a damaged blood vessel initiates a "clotting cascade."

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BLOOD TYPES

Blood type is determined by the type of antigen present on the surface of the red blood cells. An **antigen** is a substance that stimulates an immune response. Antigens that are normally present in a person's body provoke no response. However, when foreign antigens enter the body, cells respond by producing antibodies. In fact, the word *antigen* is an abbreviation for "antibody-generating substance."

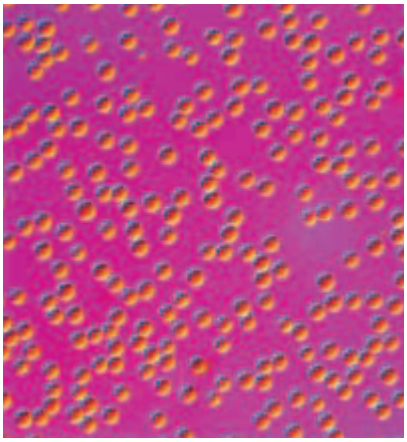
In the early 1900s, Karl Landsteiner used blood taken from his laboratory workers and made observations similar to those you see in Figure 46-15. He noticed that mixing blood samples from two people sometimes resulted in the cells clumping together, or *agglutinating*. When samples of two different blood types are mixed together, reactions occur between the antigens on the red blood cells and the antibodies in the plasma, causing the cells to agglutinate. When samples of the same blood type are mixed, no reaction occurs, and the blood cells do not agglutinate.

Landsteiner's observations led to the classification of human blood by blood types. Three of the most important human antigens are called A, B, and Rh. The A-B-O system of blood typing, described below, is based on the A and B antigens.

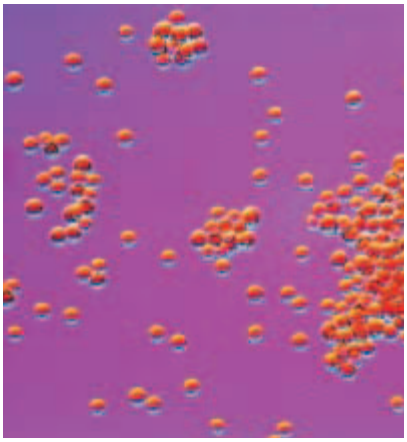
A-B-O System

The A-B-O system is a means of classifying blood by the antigens located on the surface of the red blood cells and the antibodies circulating in the plasma. As shown in Table 46-1, an individual's red blood cells may carry an A antigen, a B antigen, both A and B antigens, or no antigen at all. These antigen patterns are called blood types A, B, AB, and O, respectively.

Notice in Table 46-1 that an individual with type A blood also has anti-B antibodies against type B blood. If type B blood is given to a recipient with type A blood, the recipient's anti-B antibodies will react with the B antigens on the donated red blood cells and the blood will agglutinate. In addition, the donor's type B blood has anti-A antibodies. Their presence will compound the antigen-antibody reaction. The result will be agglutinated blood that will block the flow of blood through the vessels. For this reason, transfusion recipients must receive blood that is compatible with their own.



(a)



(b)

FIGURE 46-15

Notice that there is no agglutination of red blood cells in the slide in (a), where blood samples from two people with the same blood type were mixed. Compare this with the slide in (b), where blood samples from two people with different blood types were mixed.

TABLE 46-1 *Blood Types, Antigens, and Antibodies*

Blood types	Antigen on the red blood cells	Antibodies in the plasma	Can get blood from	Can give blood to
A	A	anti-B	O, A	A, AB
B	B	anti-A	O, B	B, AB
AB	A and B	none	A, B, AB, O	AB
O	none	anti-A, anti-B	O	A, B, AB, O

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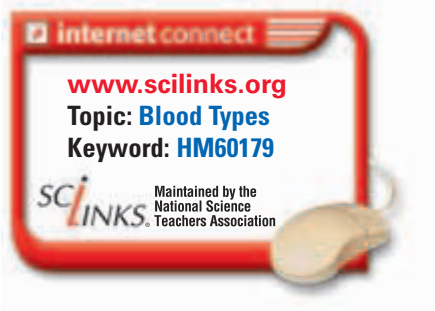

People who have type AB blood are *universal recipients.* They can receive A, B, AB, or O blood because they do not have anti-A or anti-B antibodies. People who have type O blood are *universal donors.* They can donate blood to people who have A, B, AB, or O blood because the blood cells of people who have type O blood do not have A or B antigens.

Rh System

An antigen that is sometimes present on the surface of red blood cells is the **Rh factor,** named after the rhesus monkey in which it was first discovered. Eighty-five percent of the United States' population is Rh-positive (Rh^+), meaning that Rh antigens are present. People who do not have Rh antigens are called Rh-negative (Rh^-).

If an Rh^- person receives a transfusion of blood that has Rh^+ antigens, antibodies may react with the antigen and agglutination will occur. The most serious problem with Rh incompatibility occurs during pregnancy. If the mother is Rh^- and the father is Rh^+, the child may inherit the dominant Rh^+ allele from the father. During delivery, a small amount of the fetus's Rh^+ blood may reach the mother's bloodstream. If this happens, the mother will develop antibodies to the Rh factor. If a second Rh^+ child is conceived later, the mother's antibodies can cross the placenta and attack the blood of the fetus. This condition is called *erythroblastosis fetalis.* The fetus may die as a result of this condition, or if the child is born alive, he or she may need an immediate transfusion of Rh^+ blood.

To prevent this condition, an Rh^- mother of an Rh^+ child can be given antibodies to destroy any Rh^+ cells that have entered her bloodstream from the fetus. The mother is, in effect, immunized against the Rh antigen before her immune system has a chance to develop its own antibodies. The antibody treatment prevents Rh sensitization in Rh^- women only if their bodies have not already produced Rh antibodies. If an Rh^- mother has not yet been sensitized, she receives the antibody treatment in the 28th week of pregnancy and again immediately after delivery.

SECTION 2 REVIEW

1. Identify the four main components of blood.
2. Explain how the structure of red blood cells, white blood cells, and platelets relates to the function of these cells.
3. Identify the stages and structures involved in the clotting process.
4. What factors determine the compatibility of blood types for transfusion?
5. Which blood types, in terms of the A-B-O and Rh antigens, can be donated to somebody with type AB^- blood?

CRITICAL THINKING

6. **Analyzing Information** Hemophilia is a disorder in which there is a failure in one of the steps of clot formation. What might be some advantages and disadvantages of this disorder?
7. **Evaluating Results** A patient's blood has an elevated count of leukocytes. What does this most likely indicate?
8. **Relating Concepts** Explain why a pregnant woman should know her blood type and the blood type of her baby's father.

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MILESTONES IN Blood Transfusions

Timeline

1628 William Harvey describes the circulation of blood.

1667 Jean-Baptiste Denis successfully transfuses blood from a lamb to a human.

1818 First human-to-human blood transfusion.

1901 Karl Landsteiner determined three of four blood types (A, B, and O).

1914 Blood is stored for the first time.

1937 Bernard Fantus formed the first blood bank.

1939 Charles Drew set up collection centers for blood to fill World War II needs.

1950 Carl Walter and W.P. Murphy, Jr. introduced the plastic bag to collect blood.

1985 Blood is screened for HIV and other diseases.

Every three seconds someone needs a blood transfusion—blood, plasma, or saline is introduced into the body. Blood and blood products are used to treat accident and burn victims, cancer patients, and patients undergoing surgeries and medical treatments. The development of safe blood transfusion techniques was an important achievement in modern medicine.

In 1665, Richard Lower, an English physician, transferred blood between two dogs. Jean-Baptiste Denis, a French physician and astrologer, transfused blood from a lamb to a human in 1667. The first successful human-to-human blood transfusions were performed in 1818 by James Blundell, a British physician, but these were followed by many failures.

In 1901, Austrian-born American physiologist Karl Landsteiner determined the first three blood types—A, B, and O—and that incompatible types will clot. This discovery explained why the outcome of transfusions had been so unpredictable in the past. For his work, Landsteiner received the Nobel Prize in medicine or physiology in 1930.

During World War I, scientists began to study how to preserve and transport blood for wounded soldiers. They found that the addition of sodium citrate prevented clotting, making the storage of blood possible for the first time.

In 1937, Bernard Fantus, a physician, established the first nonprofit blood bank at Cook County Hospital in Chicago. The next year, Charles Drew, a medical doctor, found that blood plasma (the liquid component of blood) could substitute for whole blood in emergency situations.

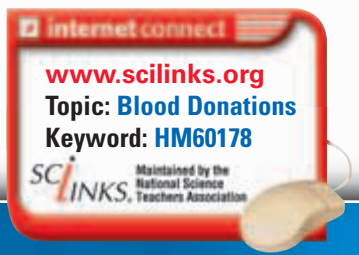
Germany's attack on France in 1940 created a great need for blood. Based on Drew's findings, the United States began to provide liquid plasma and whole blood for France. Working with the National Research Council and the American Red Cross, Drew set up blood collection centers.

Early in the 1980s, some transfused blood was found to carry the human immunodeficiency virus (HIV), the virus that causes acquired immune deficiency syndrome (AIDS). Since 1985, careful screening for HIV, hepatitis, and other diseases has almost entirely removed the risk of receiving contaminated blood.

Today, many people bank their own blood for later use in surgery. Blood can also be collected during surgery and returned to the patient later. The AIDS epidemic has triggered a race to create artificial blood. Several companies have begun testing blood substitutes from chemically treated animal blood and outdated human blood.

Review

1. What type of patients can benefit from blood transfusions?
2. **Critical Thinking** How might safe blood transfusion techniques affect you?
3. **Critical Thinking** Use the Web site below to research the latest progress on creating artificial blood. Write a short report to describe your findings.



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SECTION 3

OBJECTIVES

- **Differentiate** external respiration from internal respiration.
- **Trace** the path of air from the atmosphere to the bloodstream.
- **Describe** how gases are exchanged in the lungs and transported in the bloodstream.
- **Summarize** the skeletal and muscular changes that occur during breathing.
- **Describe** how the rate of breathing is controlled.

VOCABULARY

respiratory system
external respiration
internal respiration
lung
pharynx
epiglottis
trachea
larynx
bronchus
bronchiole
alveolus
inspiration
diaphragm
expiration

THE RESPIRATORY SYSTEM

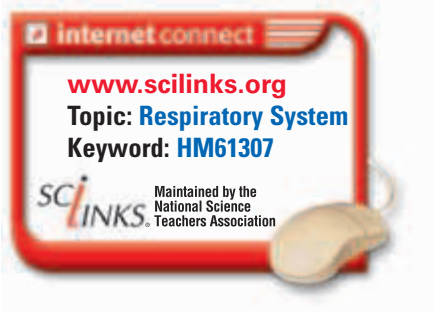
The blood transports oxygen from the lungs to cells and carries carbon dioxide from the cells to the lungs. It is the function of the ***respiratory system*** *to exchange gases with the cardiovascular system.*

RESPIRATION

The respiratory system involves both external respiration and internal respiration. **External respiration** is the exchange of gases between the atmosphere and the blood. **Internal respiration** is the exchange of gases between the blood and the cells of the body. Once oxygen is in the cells, the cells use it to break down glucose and make ATP by the process of aerobic respiration. Without oxygen, the body could not obtain enough energy from food to survive. Excess carbon dioxide produced as a waste product of aerobic respiration is toxic to cells and is removed from the cells by internal respiration.

THE LUNGS

The **lungs** are the site of gas exchange between the atmosphere and the blood. Notice in Figure 46-16 that the right lung has three divisions, or lobes. It is slightly heavier than the two-lobed left lung. The lungs are located inside the *thoracic cavity*, bounded by the rib cage and the diaphragm. Lining the entire cavity and covering the lungs are *pleura*, membranes that secrete a slippery fluid that decreases friction from the movement of the lungs during breathing.



The Path of Air

Refer to Figure 46-16 to trace the path air follows from the atmosphere to the capillaries in the lungs. External respiration begins at the mouth and at the nose. Air filters through the small hairs of the nose and passes into the nasal cavity, located above the roof of the mouth. In the nasal cavity, mucous membranes warm and moisten the air, which helps prevent damage to the delicate tissues that form the respiratory system. The walls of the nasal cavity are also lined with cilia. These cilia trap particles that are inhaled and are eventually swept into the throat, where they are swallowed.

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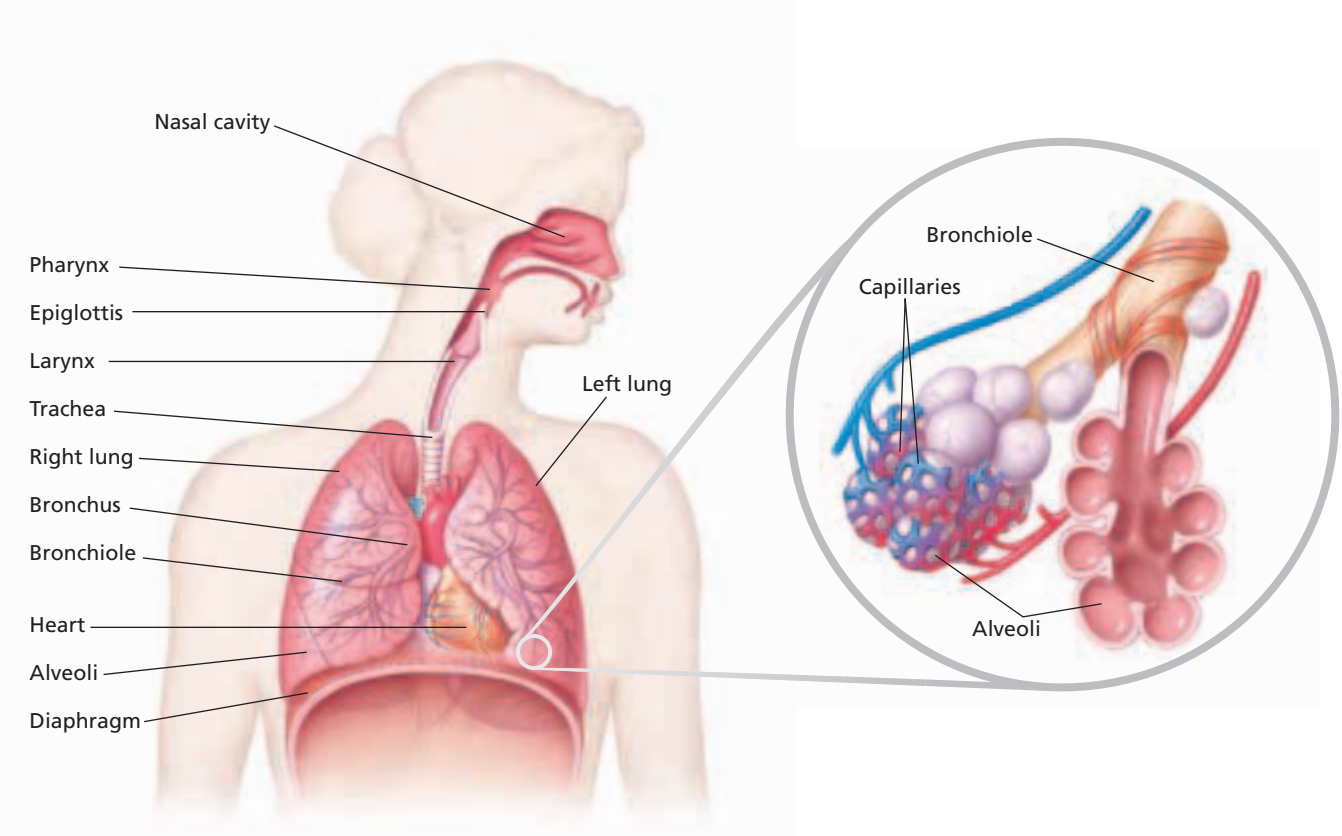

FIGURE 46-16

Trace the passage of air from the atmosphere to the lungs. Oxygen in the air finally reaches the alveoli, the functional units of the respiratory system. All exchange of gases between the respiratory system and the cardiovascular system occurs in the alveoli.

The moistened, filtered air then moves into the throat, or **pharynx** (FER-inks), a tube at the back of the nasal cavities and the mouth. The pharynx contains passageways for both food and air. When food is swallowed, a flap of cartilage, called the **epiglottis,** presses down and covers the opening to the air passage. When air is being taken in, the epiglottis is in an upright position, allowing air to pass into a cartilaginous tube called the windpipe, or **trachea** (TRAY-kee-uh). The trachea is about 10 to 12 cm long and has walls lined with ciliated cells that trap inhaled particles. The cilia sweep the particles and mucus away from the lungs toward the throat.

At the upper end of the trachea is the voicebox, or **larynx** (LER-inks). Sounds are produced when air is forced past two ligaments—the *vocal cords*—that stretch across the larynx. The pitch and volume of the sound produced varies with the amount of tension on the vocal cords and on the amount of air being forced past them.

The trachea then branches into two **bronchi** (BRAHN-kie) (singular, bronchus), each of which leads to a lung. The walls of the bronchi consist of smooth muscle and cartilage and are lined with cilia and mucus. Within the lungs, the bronchi branch into smaller and smaller tubes. The smallest of these tubes are known as **bronchioles,** which are also lined with cilia and mucus. Eventually the bronchioles end in clusters of tiny air sacs called **alveoli** (al-VEE-oh-LIE) (singular, alveolus). A network of capillaries surrounds each alveolus, as you can see in the detailed view shown in Figure 46-16. All exchange of gases in the lungs occurs in the alveoli. To facilitate this exchange, the surface area of the lungs is enormous. A healthy lung contains nearly 300 million alveoli and has a total surface area of about 70 m^2—about 40 times the surface area of the skin.

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GAS EXCHANGE AND TRANSPORT

In the lungs, gases are exchanged between the alveoli and the blood in the capillaries. Oxygen (O_2) to be transported throughout the body moves into the bloodstream, and carbon dioxide (CO_2) to be eliminated from the body moves into the alveoli.

Gas Exchange in the Lungs

Figure 46-17 illustrates the direction in which oxygen and carbon dioxide move in the alveoli. When air moves into the lungs, the oxygen in the air crosses the thin alveolar membranes as well as the capillary walls and dissolves in the blood. Carbon dioxide moves in the opposite direction, crossing the capillary walls and thin alveolar membranes and entering the alveoli.

Air moving into the alveoli is rich in oxygen and contains little carbon dioxide. In contrast, blood in the capillaries surrounding the alveoli is low in oxygen and contains high levels of carbon dioxide. Substances diffuse from an area of higher concentration to an area of lower concentration. Consequently, oxygen diffuses from the alveoli into the blood, and carbon dioxide diffuses from the blood into the alveoli. The enormous surface area of the alveoli increases the rate of diffusion of these two gases.

Transport of Oxygen

When oxygen diffuses into the blood, only a small amount remains dissolved in the plasma. Most of the oxygen—95 to 98 percent—moves into the red blood cells, where it combines with hemoglobin, an iron-containing protein. Each hemoglobin molecule contains four iron atoms. Each iron atom can bind to one oxygen molecule. Thus, one hemoglobin molecule can carry up to four molecules of oxygen. There are about 250 million hemoglobin molecules in each red blood cell. When oxygenated blood reaches body tissues, the oxygen concentration is higher in the blood than in the body tissues. Thus, oxygen is released from hemoglobin and diffuses out of the capillaries and into surrounding cells.

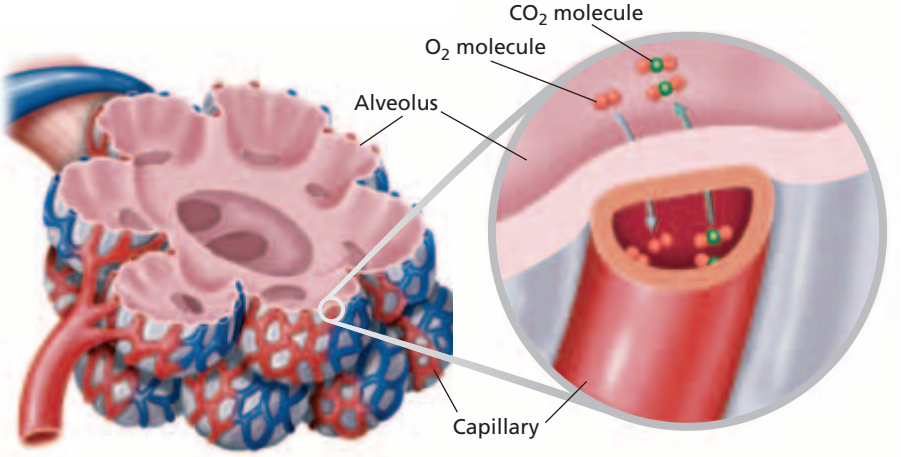

FIGURE 46-17
Because of concentration gradients, oxygen and carbon dioxide diffuse across the alveoli and capillary walls.

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Transport of Carbon Dioxide

Because the concentration of carbon dioxide (CO_2) is higher in the cells, it diffuses out of the cells and into the blood. Only about 7 percent of the carbon dioxide dissolves in the plasma. Approximately 23 percent binds to hemoglobin. The remaining 70 percent is carried in the blood as bicarbonate ions (HCO_3^-). As shown in the equation below, CO_2 reacts with water in the plasma to form carbonic acid (H_2CO_3). In turn, the carbonic acid disassociates into bicarbonate ions and hydrogen ions (H^+):

$$H_2O + CO_2 \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + H^+$$

Thus, most of the CO_2 travels in the blood as bicarbonate ions. When the blood reaches the lungs, the reactions are reversed:

$$HCO_3^- + H^+ \rightleftharpoons H_2CO_3 \rightleftharpoons H_2O + CO_2$$

Bicarbonate ions combine with hydrogen ions to form carbonic acid, which in turn forms carbon dioxide and water. The carbon dioxide diffuses out of the capillaries into the alveoli and is exhaled into the atmosphere.

MECHANISM OF BREATHING

Breathing is the process of moving air into and out of the lungs. **Inspiration,** shown in Figure 46-18, is the process of taking air into the lungs. When you take a deep breath, your chest expands as muscles contract to move the ribs up and outward. At the same time, your **diaphragm,** a large skeletal muscle that separates the thoracic cavity from the abdominal cavity, flattens and pushes down on the abdomen. Muscles in the abdominal wall in turn relax. This action provides room for the flattened diaphragm.

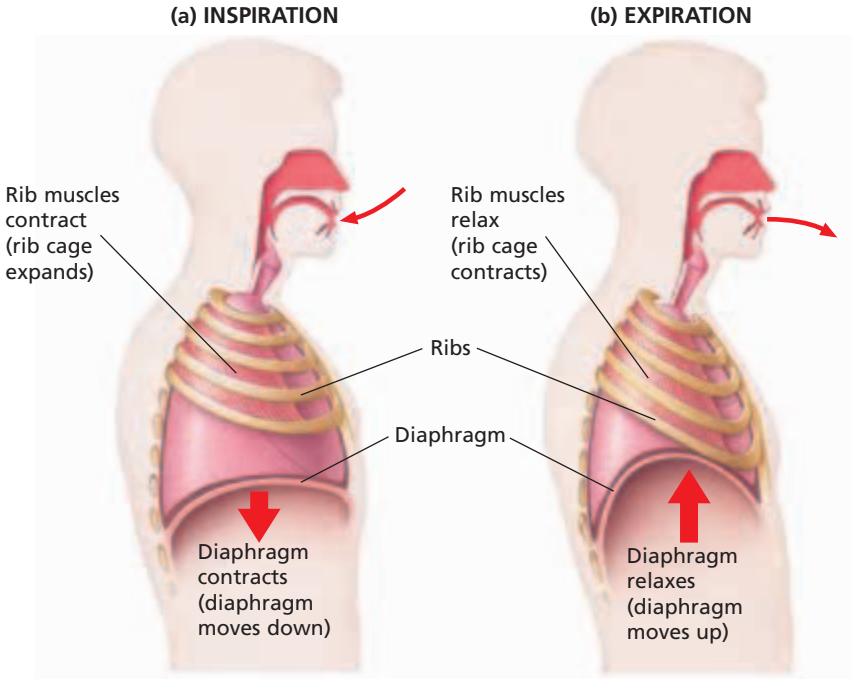

FIGURE 46-18

The diaphragm, a large skeletal muscle that separates the thoracic cavity from the abdominal cavity, and the muscles between the ribs control the movement of the thoracic cavity during breathing. If these muscles were paralyzed, then inspiration and expiration would not occur.

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When the diaphragm flattens and the ribs are lifted up and out, the volume of the lungs increases. An increased volume reduces the air pressure within the lungs. At this point, the air pressure inside the lungs is lower than the air pressure outside the body. As a result, air from the atmosphere moves into the lungs.

During **expiration,** the process of releasing air from the lungs, the reverse movements take place, as shown in Figure 46-18. As the diaphragm and rib muscles relax, the elastic tissues of the lungs recoil, deflating the lungs. The volume of the lungs decreases. Because the volume is smaller, the air pressure inside the cavity becomes greater than the air pressure outside the body. This pressure difference forces air out of the lungs until the pressures are again equal.

Word Roots and Origins

expiration

from the Latin *expir*, which means "to breathe out"

Regulation of Breathing

The rate at which oxygen is used depends on the activity of the cells. The greater their activity, the more oxygen they need and the faster the body needs to breathe. The slower their activity, the slower the body needs to breathe. Both rate and depth of breathing change in order to provide oxygen and eliminate carbon dioxide.

The rate of breathing is controlled by the brain and brain stem, which monitors the concentration of carbon dioxide in the blood. As activity increases, high levels of carbon dioxide in the blood stimulate nerve cells in the brain. The brain stem in turn stimulates the diaphragm to increase the breathing rate and depth. When the carbon dioxide concentration in the blood returns to lower levels, the sensors in the brain send a message to the respiratory muscles to return to a slower breathing rate. All this is controlled subconsciously by control centers in the brain. However, a person can temporarily override the respiratory control system at any time, holding his or her breath until losing consciousness. Then the brain stem takes control, and normal breathing resumes. This mechanism allows humans to swim underwater for short periods and to sleep without concern for breathing.

SECTION 3 REVIEW

1. How does internal respiration differ from external respiration?
2. Outline the path of oxygen from the atmosphere to the bloodstream.
3. Explain the process of gas exchange in the lungs.
4. Differentiate between oxygen transport and carbon dioxide transport in the bloodstream.
5. Sequence the skeletal and muscular changes that take place when a person inhales.
6. What factors regulate the rate of breathing?

CRITICAL THINKING

7. **Relating Concepts** Predict the effect that increasing altitude would have on blood-oxygen saturation.
8. **Applying Information** Why does a single-celled organism not need a respiratory system?
9. **Predicting Results** Normally, arterial blood is about 98 percent saturated with oxygen. What are two conditions that could result in lower oxygen saturation?

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CHAPTER HIGHLIGHTS

SECTION 1 The Circulatory System

- The human circulatory system is made up of the cardiovascular system and the lymphatic system.
- The heart is a muscular organ that pumps blood through an intricate network of blood vessels.
- Blood flows from the body into the heart, which then pumps blood to the lungs. After oxygenation, blood returns to the heart, which pumps blood to the rest of the body.
- Arteries carry blood away from the heart. Materials are exchanged at the capillaries. Veins contain valves and carry blood back to the heart.
- In pulmonary circulation, blood travels between the heart and lungs. In systemic circulation, blood travels between the heart and all other body tissues.
- The lymphatic system returns lymph, fluid that has collected in the tissues, to the bloodstream.

Vocabulary

cardiovascular system (p. 933)
lymphatic system (p. 933)
atrium (p. 933)
ventricle (p. 933)
valve (p. 934)
aorta (p. 935)
sinoatrial node (p. 935)
atrioventricular node (p. 935)
pulse (p. 935)
artery (p. 936)
blood pressure (p. 936)
hypertension (p. 936)
capillary (p. 936)
vein (p. 937)
pulmonary circulation (p. 937)
systemic circulation (p. 937)
atherosclerosis (p. 938)
lymph (p. 939)

SECTION 2 Blood

- Blood is composed of plasma (water, metabolites, wastes, salts, and proteins), red blood cells, white blood cells, and platelets.
- Red blood cells transport oxygen. White blood cells help defend the body against disease. Platelets are essential to the formation of a blood clot.
- Blood clotting occurs when platelets release a clotting protein, which causes a clotting reaction to occur. A fibrin net forms, trapping blood cells and platelets.
- Human blood can be grouped into four types—A, B, AB, and O—based on proteins on the surface of red blood cells. Another antigen called *Rh factor,* is sometimes present on red blood cells.

Vocabulary

plasma (p. 940)
red blood cell (erythrocyte) (p. 940)
hemoglobin (p. 940)
white blood cell (leukocyte) (p. 941)
phagocyte (p. 941)
antibody (p. 941)
platelet (p. 942)
fibrin (p. 942)
blood type (p. 943)
antigen (p. 943)
Rh factor (p. 943)

SECTION 3 The Respiratory System

- External respiration is the exchange of gases between the atmosphere and the blood. Internal respiration is the exchange of gases between the blood and the cells of the body.
- The lungs are the site of gas exchange between the atmosphere and the blood.
- Air enters through the mouth or nose, passes through the pharynx, larynx, trachea, bronchi and bronchioles and into alveoli. A network of capillaries surrounds each alveolus. All exchange of gases in the lungs occurs at the alveoli.
- Most oxygen is carried attached to hemoglobin. Some carbon dioxide is carried bound to hemoglobin. A small amount is dissolved in plasma. Most carbon dioxide is carried as bicarbonate ions.
- During inspiration, the diaphragm and rib muscles contract, the thoracic cavity expands, and air is pulled into the lungs. During expiration, the diaphragm and rib muscles relax, the thoracic cavity contracts, and air is forced out of the lungs.
- The rate of breathing is controlled by nerve centers in the brain that monitor the level of carbon dioxide in the blood.

Vocabulary

respiratory system (p. 946)
external respiration (p. 946)
internal respiration (p. 946)
lung (p. 946)
pharynx (p. 947)
epiglottis (p. 947)
trachea (p. 947)
larynx (p. 947)
bronchus (p. 947)
bronchiole (p. 947)
alveolus (p. 947)
inspiration (p. 949)
diaphragm (p. 949)
expiration (p. 950)

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CHAPTER REVIEW

USING VOCABULARY

1. Distinguish between *systolic pressure* and *diastolic pressure.*
2. Choose the term that does not belong in the following group: *erythrocyte, hemoglobin, leukocyte,* and *platelet.* Explain why it does not belong.
3. For each pair of terms, explain the relationship between the terms.
   a. *atrioventricular valve* and *semilunar valve*
   b. *artery* and *vein*
   c. *expiration* and *inspiration*
4. **Word Roots and Origins** The word *phagocyte* is derived from the Greek word *phagein,* which means "to eat." The suffix *cyte* means "cell." Using this information, explain why the term *phagocyte* is a good name for the biological process that the term describes.

UNDERSTANDING KEY CONCEPTS

5. **Identify** the parts of the human heart, and describe the function of each part.
6. **Outline** the route that blood takes through the heart, lungs, and body.
7. **Relate** the structure of arteries, veins, and capillaries to the function of each.
8. **Compare** the pulmonary arteries and the aorta.
9. **Compare** the pulmonary veins and the inferior vena cava.
10. **Summarize** the roles of the lymphatic system.
11. **Discuss** the function of each of the components of blood.
12. **Identify** the structure that red blood cells lack that limits their life span.
13. **Describe** three differences between white blood cells and red blood cells.
14. **Sequence** the process of blood-clot formation that occurs after a vessel is injured.
15. **Explain** the A-B-O blood-typing system.
16. **Identify** the role of the Rh factor in determining blood compatibility for transfusion.
17. **Compare** external respiration with internal respiration.
18. **Sequence** the path oxygen travels from the environment into the blood.
19. **Compare** the transport and exchange of oxygen and carbon dioxide.
20. **Describe** the movement of the diaphragm and the rib muscles during inspiration and expiration.
21. **Name** the factor that stimulates the brain stem to increase the breathing rate.
22.  **CONCEPT MAPPING** Use the following terms to create a concept map that shows the relationship between the cardiovascular, lymphatic, and respiratory systems: *artery, capillary, vein, lymphatic system, pulmonary circulation, systemic circulation, atrium, ventricle, aorta,* and *vena cava.*

CRITICAL THINKING

23. **Inferring Relationships** A person with anemia can have too few red blood cells or low hemoglobin levels. The most common symptom is a lack of energy. Why would anemia cause this symptom?
24. **Applying Information** Explain how the lymphatic system moves lymph through the body without the aid of a pumping organ like that of the cardiovascular system.
25. **Analyzing Concepts** One function of the cardiovascular system is to help maintain a uniform body temperature. Explain how the constant circulation of blood throughout the body can accomplish this task.
26. **Interpreting Graphics** Copy the blood-type table below on a sheet of paper. Fill in the missing information for each type.

TABLE 1 *Blood Type*

Blood type	Antigen on the red blood cell	Antibodies in plasma	Can receive blood from	Can donate blood to
A		B	O, A	A, AB
B	B		O, B	B, AB
AB	A, B	Neither A nor B	O, A, B, AB	
O	Neither A nor B	A, B		O, A, B, AB

27. **Calculating Data** Calculate the number of times a person's heart will beat if the person lives 75 years. Assume that the average heart beats 70 times per minute.
28. **Recognizing Relationships** Assuming that the heart of an overweight person beats an additional 10 times per minute, explain why being overweight can put additional strain on the heart.

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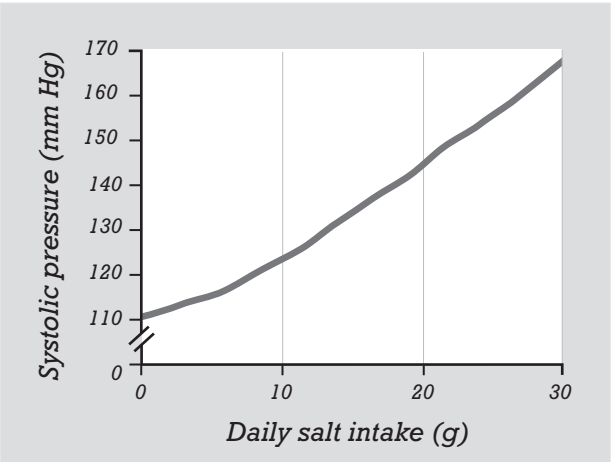
Standardized Test Preparation

DIRECTIONS: Choose the letter of the answer choice that best answers the question.

1. In what direction does blood move during ventricular systole?
   - **A.** from the atria to the veins
   - **B.** from the ventricles to the atria
   - **C.** from the atria to the ventricles
   - **D.** from the ventricles to the arteries
2. What is the function of the lymphatic system?
   - **F.** It opens two-way vessels.
   - **G.** It helps the body fight infections.
   - **H.** It interacts with the respiratory system.
   - **J.** It transports intercellular fluid away from the heart.
3. Fibrin is a protein that does which of the following?
   - **A.** transports oxygen
   - **B.** helps form a blood clot
   - **C.** destroys invading microorganisms
   - **D.** stimulates the production of antibodies

INTERPRETING GRAPHICS: The graph below shows how systolic pressure is affected by salt intake. Use the graph to answer the question that follows.

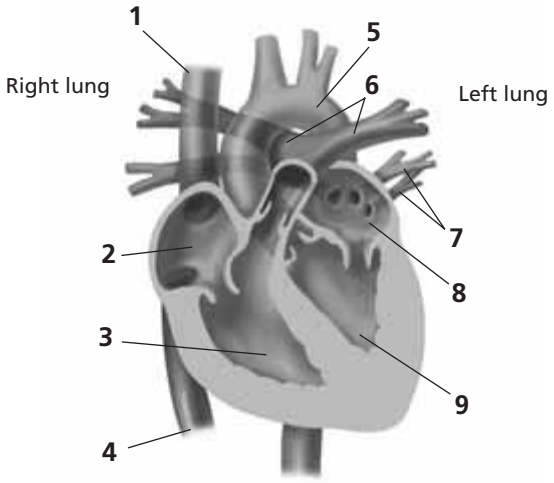


4. What is the relationship between salt intake and blood pressure?
   - **F.** As salt intake increases, blood pressure increases.
   - **G.** As salt intake increases, blood pressure decreases.
   - **H.** Salt intake of 20 g per day results in stable blood pressure.
   - **J.** Salt intake of 30 g per day results in stable blood pressure.

DIRECTIONS: Complete the following analogy.

5. superior vena cava : deoxygenated blood :: pulmonary veins :
   - **A.** type A blood
   - **B.** type B blood
   - **C.** oxygenated blood
   - **D.** deoxygenated blood

INTERPRETING GRAPHICS: The model below shows a cross section of the heart. Use the model to answer the question that follows.



6. Which numbers point to vessels that bring blood into the heart?
   - **F.** 1, 4, and 7
   - **G.** 1, 5, and 6
   - **H.** 4, 5, and 6
   - **J.** 5 and 6 only

SHORT RESPONSE

Even a small increase or decrease in blood volume has an effect on blood pressure. When an accident victim suffers significant blood loss, the person is transfused with plasma rather than whole blood.

Why is plasma effective in meeting the immediate threat to life?

EXTENDED RESPONSE

Polio is a disease that paralyzes muscles by affecting the nerves that make the muscles move.

Part A List muscles involved in breathing.

Part B Explain how polio might affect breathing.

Test TIP Slow, deep breathing helps a person relax. If you suffer from test anxiety, focus on your breathing in order to calm down.

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Measuring Lung Volumes and CO_2 Production

OBJECTIVES

- Use indirect measurement to determine lung capacity.
- Determine the effect of exercise on breathing rate and CO_2 production.

PROCESS SKILLS

- measuring
- hypothesizing
- collecting data
- analyzing data
- experimenting

MATERIALS

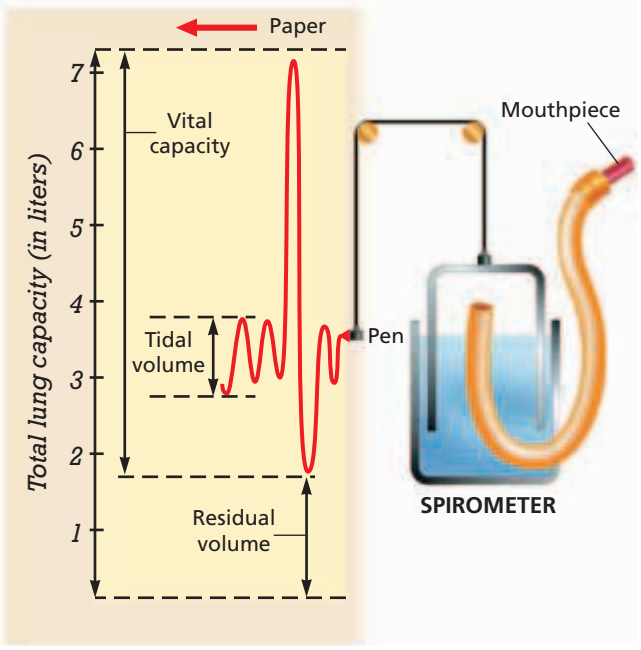
- safety goggles
- lab apron
- disposable gloves
- 1 L bromothymol indicator solution
- drinking straws
- 100 mL Erlenmeyer flasks, 2 per group
- 100 mL graduated cylinders
- marker
- plastic wrap
- spirometer
- stopwatch or clock with second hand

Background

1. A spirometer is an instrument used to measure the volume of air a person can breathe.
2. Compare the diagram of a spirometer on the right with the spirometer you will be using to complete this investigation. The marking pen creates a line that can be compared with the scale on the left side to measure liters of air.
3. Tidal volume is the volume of air inhaled or exhaled during a normal breath.
4. Lung capacity is the total volume of air that the lungs can hold. Total lung capacity is 5 to 6 L. What factors might increase or reduce lung capacity?
5. Expiratory reserve volume is the amount of air that can be forcefully exhaled after a normal exhalation.
6. Vital capacity is the maximum amount of air that can be inhaled or exhaled.
7. Carbon dioxide is soluble in water. You can determine the relative amount of CO_2 in your breath by using an indicator to react with the CO_2. Higher CO_2 levels will react with the indicator solution faster.

PART A Tidal Volume, Expiratory Volume, and Vital Capacity

1. Make a data table in your notebook like the one shown on the next page (Part A Lung Volumes).
2. Place a clean mouthpiece in the end of the spirometer. CAUTION **Many diseases are spread by body fluids, such as saliva. Do NOT share a mouthpiece with anyone.** Inhale a normal breath. Hold your nose, then exhale a normal breath into the spirometer. Record your data in the table.
3. Measure your expiratory reserve volume by first breathing a normal breath and exhaling normally. Then put the spirometer tube to your mouth as you forcefully exhale whatever air is left in your lungs. Be sure to force out as much air as possible. Record your data in the table.



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PART A *Lung Volumes*

	Average for young adult males	Average for young adult females	Average for athletes	Your readings
Tidal volume	**500 mL**			
Expiratory reserve volume	**100 mL**			
Vital capacity	**4,600 mL**			

4. The table includes values for young adult males. The average volumes for young adult females are 20–25 percent lower than those of males. Calculate the average volumes for young adult females. Athletes can have volumes that are 30–40 percent greater than the average for their gender. Calculate the average volumes for athletes.
5. Dispose of your mouthpiece in the designated waste container.

PART B Breathing Rate and CO_2 Production

6. Discuss with your partners the use of bromothymol blue as an indicator of CO_2. Develop a hypothesis that describes a relationship between air volume exhaled during rest or exercise and the volume of CO_2 exhaled.
7. Make a data table in your notebook like the one on this page, titled "Part B CO_2 Production".
8. Label two flasks as 1 and 2.
9. CAUTION **Wear safety goggles at all times during this procedure. If you get the indicator solution on your skin or clothing, wash it off at the sink while calling to your teacher. If you get the indicator solution in your eyes, immediately flush it out at the eyewash station while calling to your teacher.**
10. Add 100 mL of indicator solution to each flask. Cover the mouth of each flask with plastic wrap.
11. Remove the plastic wrap from flask 1. Begin the stopwatch. Blow gently through one straw into flask 1 until the solution turns a yellowish color, exhaling slowly so that the solution does not bubble up. CAUTION **Be careful not to inhale the solution or get it in your mouth.** Stop the stopwatch.
12. Record in your data table the time in seconds that it took to see a color change in flask 1.
13. Exercise by jogging in place or doing jumping jacks for 2 min. Begin the stopwatch immediately. Blow gently through a new straw into flask 2 until the solution becomes the same yellowish color as the solution in flask 1. Stop the stopwatch.
14. In your data table, record the amount of time in seconds that it took to get the same yellow color in flask 2 as you got in flask 1.
15. Calculate the difference in the amount of time it took to see a color change in the two flasks. What can you infer about the amount of CO_2 you exhaled before and after exercise?
16. Clean up your materials. Pour the solutions down the sink, and rinse the sink thoroughly with water. Wash your hands before leaving the lab.

Analysis and Conclusions

1. How did your tidal volume compare with that of your classmates?
2. What are the independent and dependent variables in Part B? How did you vary the independent variable and measure changes in the dependent variable?
3. Why were the flasks covered with plastic wrap?
4. Do your data support your hypothesis from Part B? Explain your answers.
5. How do you know whether you produced more carbon dioxide before or after you exercised?
6. What were some of the possible sources of error in your experiment?

PART B *CO_2 Production*

Time for color change in flask 1	
Time for color change in flask 2	
Difference in time between flask 1 and flask 2	

Further Inquiry

Design an experiment to determine whether exercise affects heart rate in the same way it affects breathing rate and tidal volume.

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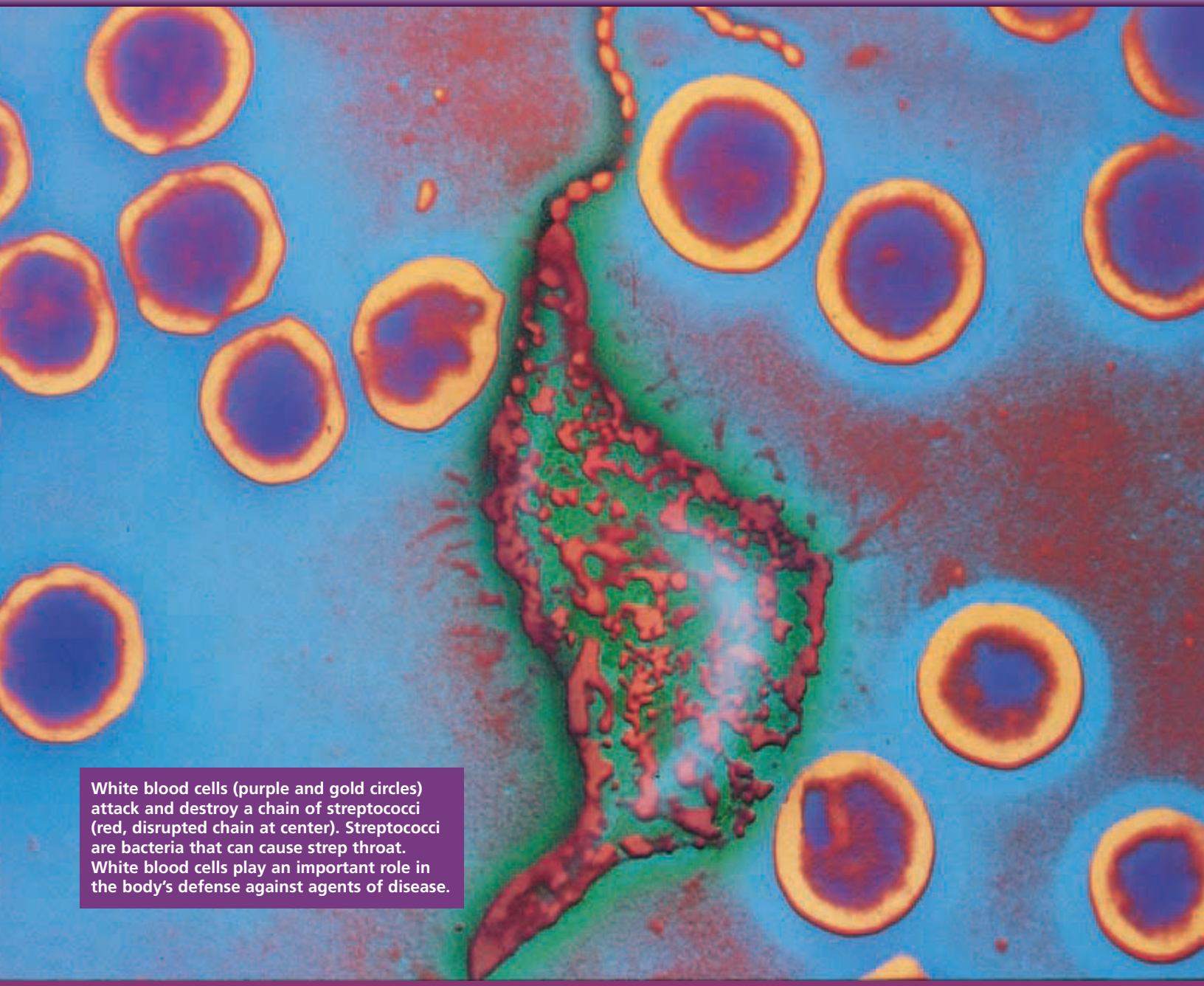
CHAPTER 47

THE BODY'S DEFENSE SYSTEMS



White blood cells (purple and gold circles) attack and destroy a chain of streptococci (red, disrupted chain at center). Streptococci are bacteria that can cause strep throat. White blood cells play an important role in the body's defense against agents of disease.

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SECTION 1

NONSPECIFIC DEFENSES

When a type of virus called a rhinovirus enters the human body, it can cause the common cold. Diseases, such as colds, that are caused by agents that have invaded the body are called ***infectious diseases.*** *This section explains how the human body identifies the agents that cause infectious diseases and defends itself against these agents.*

OBJECTIVES

- **Summarize** Koch's postulates for identifying a disease-causing agent.
- **Describe** how the skin and mucous membranes protect the body against pathogens.
- **Describe** the steps of the inflammatory response.
- **Analyze** the roles of white blood cells in fighting pathogens.
- **Explain** the functions of fever and proteins in fighting pathogens.

VOCABULARY

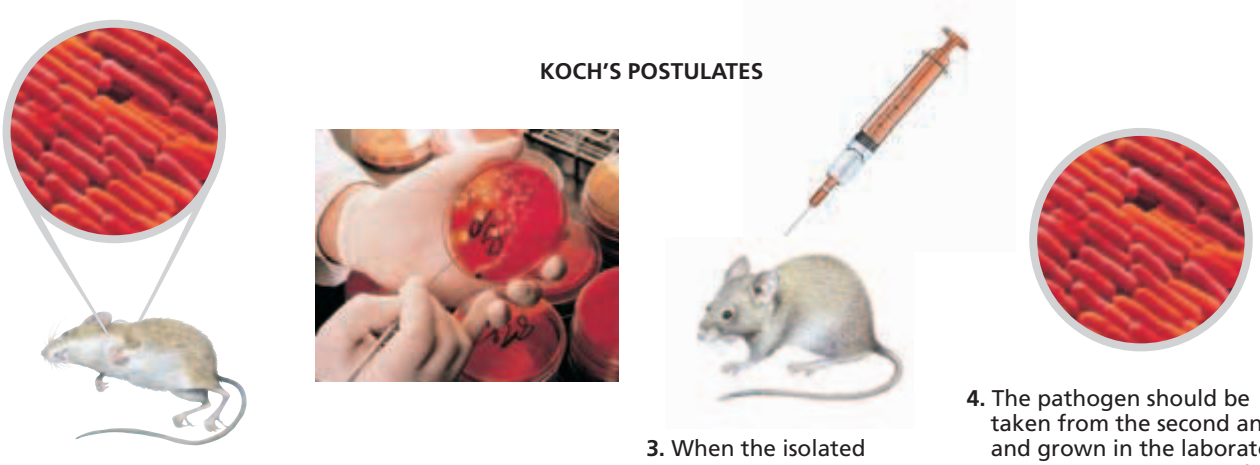
infectious disease
pathogen
Koch's postulates
mucous membrane
inflammatory response
histamine
phagocyte
neutrophil
macrophage
natural killer cell
complement system
interferon

IDENTIFYING PATHOGENS

A **pathogen** is any agent that causes disease. Robert Koch (KAWHK) (1843–1910), a German doctor, was the first person to establish a step-by-step procedure for identifying the particular pathogen that causes an infectious disease. In the 1870s, Koch studied anthrax, a disease of cattle that can spread to people. Koch observed that cattle with the illness had swarms of bacteria in their blood. He hypothesized that these bacteria caused anthrax.

To test his hypothesis, Koch isolated rod-shaped bacteria from a cow with anthrax and grew colonies of the bacteria to be sure he had isolated a single species. Then, he injected healthy cows with these bacteria. The cows developed anthrax. Koch found that the blood of these cows contained the same rod-shaped bacteria as the first cow. Furthermore, healthy cows that he had not injected lacked this type of bacteria. Koch concluded that the isolated species of bacterium causes anthrax. Through these studies, he developed **Koch's postulates,** which are "rules" for determining the cause of a disease. Figure 47-1 illustrates these postulates.

FIGURE 47-1
By applying the four principles of Koch's postulates, scientists can identify the pathogen that causes an infectious disease.



1. The pathogen must be present in an animal that has the disease and absent in healthy animals.

2. The pathogen must be isolated from the sick animal and grown in a laboratory.

3. When the isolated pathogen is injected into a healthy animal, the animal must develop the disease.

4. The pathogen should be taken from the second animal and grown in the laboratory. The pathogen cultured from the second animal should be the same as the pathogen cultured from the first animal.

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TABLE 47-1 *Pathogens Responsible for Some Human Diseases*

Disease	Pathogen	Method of transmission
Botulism	*Clostridium botulinum* (bacterium)	contaminated food
Lyme disease	*Borrelia burgdorferi* (bacterium)	tick bites
AIDS	HIV (human immunodeficiency virus)	sexual contact, contaminated needles, contact with contaminated fluids from a mother to a fetus or infant
Severe acute respiratory syndrome (SARS)	coronavirus (virus)	person-to-person contact, indirect contact through pathogens in air or on objects (from coughs or sneezes)
Amebic dysentery	*Entamoeba histolytica* (protist)	contaminated food and water
Athlete's foot	*Tinea* (fungus)	contact with contaminated surfaces, person-to-person contact
Head lice	Lice (invertebrate parasite)	person-to-person contact, sharing personal items

Scientists have used Koch's postulates to identify thousands of pathogens. Many human diseases are caused by bacteria, viruses, protists, fungi, and invertebrates. Pathogens can spread to humans in five main ways—through air, food, water, person-to-person contact, and the bites of animals. Table 47-1 lists examples of pathogens that cause different human diseases and the means by which each is commonly transmitted.

FIGURE 47-2

The passages of the respiratory system are lined with cells that are covered with beating cilia (purplish strands). Pathogens (bluish circles) that become trapped in mucus secreted by these cells are swept upward, away from the lungs. (5,325×)

FIRST LINE OF DEFENSE: BARRIERS

The body's nonspecific defenses help protect the body against any pathogen, regardless of the pathogen's identity. Nonspecific defenses include the skin and mucous membranes. **Mucous** (MYOO-kuhs) **membranes** are epithelial tissues that protect the interior surfaces of the body that may be exposed to pathogens.

Most pathogens must enter the body to cause disease. The skin serves as a physical barrier to pathogens. Any break in the skin may allow pathogens to enter the body. In addition, the skin also releases sweat, oils, and waxes. These substances contain chemicals that are toxic to many pathogens. For example, sweat contains *lysozyme,* an enzyme that destroys some bacteria.

Mucous membranes serve as a barrier and secrete *mucus,* a sticky fluid that traps pathogens. Mucous membranes line the respiratory and digestive systems, the urethra, and the vagina. The passages of the respiratory tract are lined with cells that are covered with beating cilia, as shown in Figure 47-2. These cilia sweep mucus and pathogens up to the pharynx, where they are swallowed. Most swallowed pathogens are destroyed in the stomach by acids.

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SECOND LINE OF DEFENSE: NONSPECIFIC IMMUNITY

If a pathogen gets past the skin and the mucous membranes, there is a second line of nonspecific defense inside the body—nonspecific immunity. Nonspecific immunity includes the inflammatory response, the temperature response, and proteins. Like the barriers of the first line of defense, these second-line defenses are nonspecific—they work the same way against any pathogen.

Inflammatory Response

Any pathogen that gets past the skin or mucous membranes will stimulate the **inflammatory response,** a series of events that suppress infection and speed recovery. An example is shown in Figure 47-3. When cells are damaged, whether through a cut on the skin or invasion by pathogens, some of the damaged cells release histamine (HIS-tuh-MEEN), as described in step 1. **Histamine** is a substance that increases blood flow to the injured area and increases the permeability of surrounding capillaries. The changes caused by histamine result in redness, swelling, warmth, and pain. If blood vessels have been damaged, platelets begin the blood-clotting process, sealing off surrounding tissues and stopping pathogens from entering the rest of the body.

White blood cells fight pathogens that have entered the body. In step 2, fluids and white blood cells called *phagocytes* pass through the capillary walls to the injured area. **Phagocytes** ingest and destroy pathogens and foreign matter, as shown in step 3. Phagocytes and some other types of white blood cells are attracted to the site of injury by histamine.

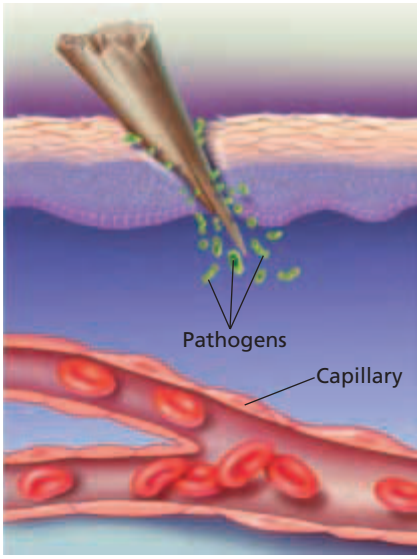
Eco Connection

Agriculture and Human Diseases

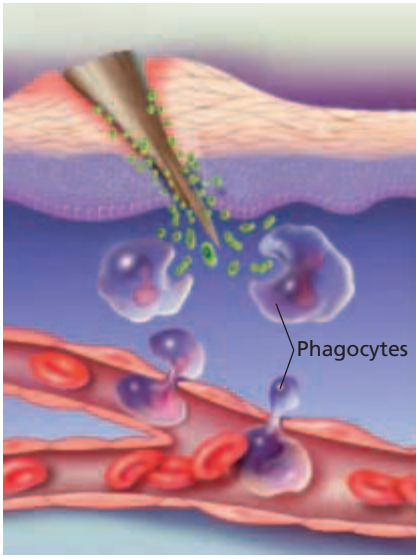
The beginning of farming and herding about 10,000 years ago changed the nature of human diseases. When humans began to keep herds of domesticated animals, such as cattle and sheep, humans were exposed to the pathogens that infect these animals. Some of these pathogens then began infecting humans. Measles, tuberculosis, smallpox, and flu are among the diseases that may have been transmitted to humans from domesticated animals.

FIGURE 47-3

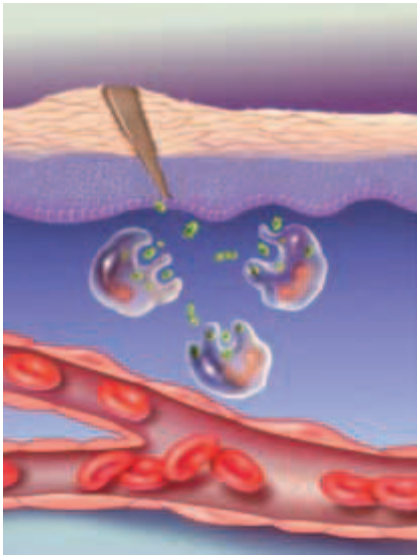
Injury to cells triggers an inflammatory response.



1 An injury may allow pathogens to get past the barrier of the skin. Injured cells release chemical messengers, such as histamine.



2 Nearby capillaries respond by swelling and leaking fluid. Phagocytes pass through capillary walls and attack the pathogens.



3 Phagocytes destroy the pathogens, and the injury begins to heal.

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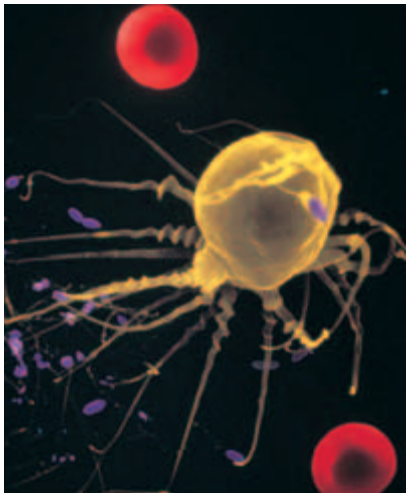

FIGURE 47-4

This macrophage (shown in yellow) is using cytoplasmic extensions to capture bacteria (shown in purple). (SEM 17,400×)

The **neutrophil** (NOO-troh-fil) is the most abundant type of phagocyte in the body. Neutrophils circulate through blood vessels, and they can squeeze through capillary walls to reach the infection site. Once there, neutrophils ingest pathogens they encounter. Another type of phagocyte is the **macrophage** (MAK-roh-FAYJ), shown in Figure 47-4. Macrophages engulf pathogens and cellular debris. Some are stationed in body tissues, waiting for pathogens, while others seek out pathogens.

Natural killer cells are large white blood cells that attack pathogen-infected cells—not the pathogens themselves. Natural killer cells are effective at killing cancer cells and virus-infected cells. A natural killer cell pierces the cell membrane of its target cell, allowing water to rush in and causing the cell to burst.

Temperature Response

When the body begins to fight pathogens, body temperature may increase several degrees. A rise in body temperature above the normal 37°C (98.6°F) is called a *fever.* Fever is a symptom of illness that shows the body is responding to an infection. Some pathogens trigger fever, as do chemicals released by macrophages. A moderate fever may slow bacterial and viral growth and promote white blood cell activity. However, very high fever is dangerous because extreme heat can destroy important cellular proteins. Temperatures greater than 39°C (103°F) can be dangerous, and those greater than 41°C (105°F) can lead to death.

Word Roots and Origins

macrophage

from the Greek *makros,* meaning "large," and *phagein,* meaning "to eat"

Proteins

Proteins also provide nonspecific defenses. About 20 different proteins make up the **complement system.** Complement proteins circulate in the blood and become active when they encounter certain pathogens. Some of these proteins form a ring-shaped structure that punctures the membranes of infected cells, causing the cells to die. Another nonspecific defense is **interferon,** a protein released by cells infected with viruses. Interferon causes nearby cells to make a protein that helps them resist viral infection.

SECTION 1 REVIEW

1. Explain how Koch tested his hypothesis about the cause of anthrax.
2. How does the body's first line of defense function?
3. What role does greater permeability of capillaries play in the inflammatory response?
4. How do natural killer cells differ from macrophages?
5. What is the role of interferon?

CRITICAL THINKING

6. **Analyzing Information** Scientists can't always apply all of Koch's postulates to determine the cause of a disease. Explain why.
7. **Forming Reasoned Opinions** Should a fever always be treated? Why or why not?
8. **Inferring Relationships** Explain how cold symptoms show that the body is using both lines of nonspecific defenses to fight pathogens.

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SECTION 2

SPECIFIC DEFENSES: THE IMMUNE SYSTEM

Although the nonspecific defenses usually keep pathogens from harming the body, a pathogen sometimes breaks through. In response, the body begins its third line of defense—a response aimed specifically at the pathogen.

OBJECTIVES

- **Identify** and describe the parts of the immune system.
- **Explain** how the immune system recognizes pathogens.
- **Compare** the actions of T cells and B cells in the immune response.
- **Relate** vaccination to immunity.
- **Distinguish** between allergy, asthma, and autoimmune disease.

VOCABULARY

immune system
lymphocyte
thymus
spleen
B cell
T cell
antigen
immune response
helper T cell
cell-mediated immune response
cytotoxic T cell
humoral immune response
plasma cell
antibody
memory cell
immunity
vaccination
allergy
asthma
autoimmune disease

THE IMMUNE SYSTEM

The **immune system,** the cells and tissues that recognize and attack foreign substances in the body, provides the body's specific defenses. The immune system fights pathogens and helps to stop the growth and spread of cancers. The immune system is made up of several tissues and white blood cells. The components of the immune system, shown in Figure 47-5, are found throughout the body. The tissues include the bone marrow, thymus, lymph nodes, spleen, tonsils, and adenoids. The white blood cells of the immune system are called **lymphocytes** (LIM-foh-sietz).

Each part of the immune system plays a special role in defending the body against pathogens. *Bone marrow,* the soft material found inside long bones, such as the femur, makes the billions of new lymphocytes needed by the body every day. The **thymus,** a gland located above the heart, helps produce a special kind of lymphocyte.

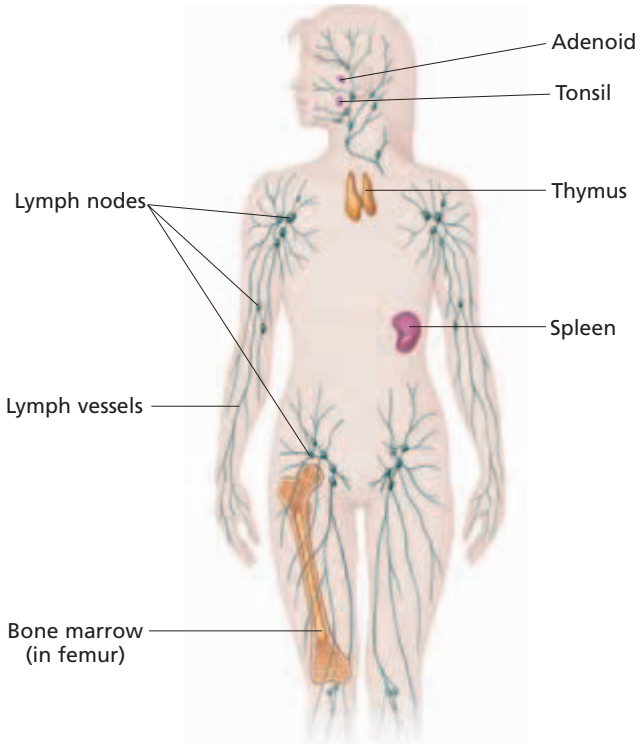

FIGURE 47-5
The cells and tissues of the immune system recognize and attack foreign substances in the body.

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Lymph nodes, located throughout the body along the vessels of the lymphatic system, contain lymphocytes. (Recall that the lymphatic system gathers and filters the fluid, called *lymph,* that leaks from the circulatory system.) Lymph nodes collect pathogens from the lymph and expose them to lymphocytes. The **spleen,** the largest lymphatic organ in the body, stores healthy blood cells, breaks down aging red blood cells, and helps develop lymphocytes and other types of white blood cells. The spleen also collects pathogens from the blood, and the lymphocytes in the spleen attack these trapped pathogens. The *adenoids* and *tonsils* are masses of lymph tissue found in the nose and throat.

There are two types of lymphocytes: B cells and T cells. **B cells** are made in the bone marrow and complete their development there. **T cells** are also made in the bone marrow but complete their development only after traveling to the thymus.

Word Roots and Origins

antigen

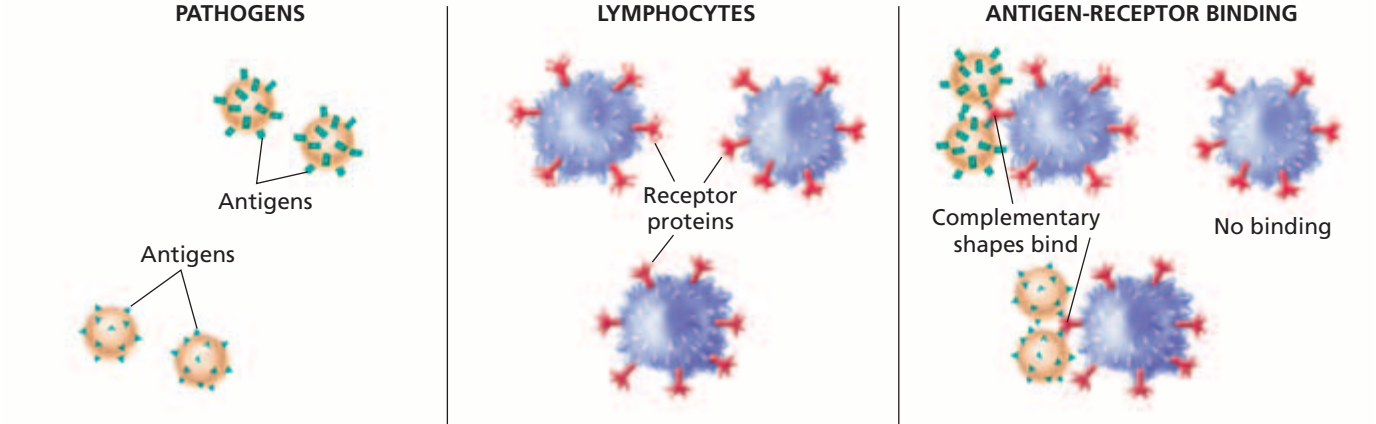
from the Greek *anti,* meaning "against," and *gen,* meaning "producing"

RECOGNIZING PATHOGENS

Lymphocytes can provide specific defenses because they recognize foreign invaders. An **antigen** (AN-tuh-juhn) is any substance that the immune system can recognize and react with. Antigens, as shown in Figure 47-6a, cause lymphocytes to react. A wide variety of substances can be antigens, including pathogens or parts of pathogens, bacterial toxins, insect venom, and pollen. In addition, almost any molecule that is not a natural part of an individual's body, such as that from transplanted tissue or transfused blood of an incompatible type, can act as a foreign antigen. When lymphocytes recognize an antigen, they bind to the antigen to start a specific attack. The reaction of the body against an antigen is known as an **immune response.**

FIGURE 47-6

(a) Antigens are found on a pathogen's surface. (b) The receptor proteins on the surface of lymphocytes (such as B cells, shown here) have a complex, three-dimensional structure. (c) The receptors can bind to antigens that have a complementary shape.



(a) Many pathogens are covered with molecules that function as antigens and cause lymphocytes to react.

(b) A lymphocyte has receptor proteins all over its surface. Note the different shapes of receptor proteins on the different lymphocytes. All of the receptor proteins on an individual lymphocyte are the same unique shape.

(c) The receptor proteins on each lymphocyte bind to antigens with complementary shapes. If a lymphocyte does not have a complementary receptor protein, it will not bind to an antigen (upper right).

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How do lymphocytes identify antigens? A lymphocyte has unique receptor proteins all over the surface of its cell membrane, as shown in Figure 47-6b. These receptor proteins recognize and bind to antigens that match their three-dimensional shape, as shown in Figure 47-6c. The surface of a bacterial cell, for instance, can be covered with many different kinds of molecules, each of which can function as an antigen and cause lymphocytes to react. All of the receptors on an individual lymphocyte are the same shape or type and thus bind to the same type of antigens.

The body can defend itself against an enormous number of different pathogens, because the immune system makes billions of different kinds of lymphocytes. Each kind of lymphocyte carries unique receptors. The specificity of the immune response is due to the specificity of the antigen receptors on the lymphocytes. For example, when a cold virus enters the body, lymphocytes with receptors that match the antigens of that cold virus respond. Lymphocytes with other kinds of receptors, such as those that bind to a flu virus, do not respond.

IMMUNE RESPONSE

An immune response is a two-part assault on a pathogen. Both parts, the cell-mediated immune response and the humoral immune response, occur at the same time and require a specialized lymphocyte called a **helper T cell.** Steps ❶, ❷, and ❸ of Figure 47-7 on the next page show how an immune response is initiated. The first step occurs when a macrophage engulfs a pathogen. The macrophage then displays fragments of the pathogen's antigens on the surface of its own cell membrane. When the macrophage binds to a helper T cell with a receptor matching this antigen, the macrophage releases a cytokine called *interleukin-1* (in-tuhr-LOO-kin). *Cytokines* are proteins that can affect the behavior of other immune cells. The release of interleukin-1 by the macrophage activates more helper T cells, which then release a second cytokine, interleukin-2.

Word Roots and Origins

cytokine

from the Greek *kytos,* meaning "hollow vessel" or "cell," and *kinesis,* meaning "movement"

Cell-Mediated Immune Response

More than one type of T cell carries out the **cell-mediated immune response.** Interleukin-2 stimulates the further production of helper T cells. The increase in helper T cells produces an increase in interleukin-2, which allows T cells to divide even faster. Interleukin-2 is also responsible for stimulating the production of **cytotoxic** (siet-oh-TAHKS-ik) **T cells** (sometimes called killer T cells), which recognize and destroy cells that have been infected by the pathogen. Invaded cells are recognizable because they usually have some of the pathogen's antigens on their surface, as shown in Figure 47-7. The cytotoxic T cells produced have receptors that match the antigen. Cytotoxic T cells usually kill by making a hole in the cell membrane of their target. Cytotoxic T cells can also kill cancer cells and attack parasites and foreign tissues.

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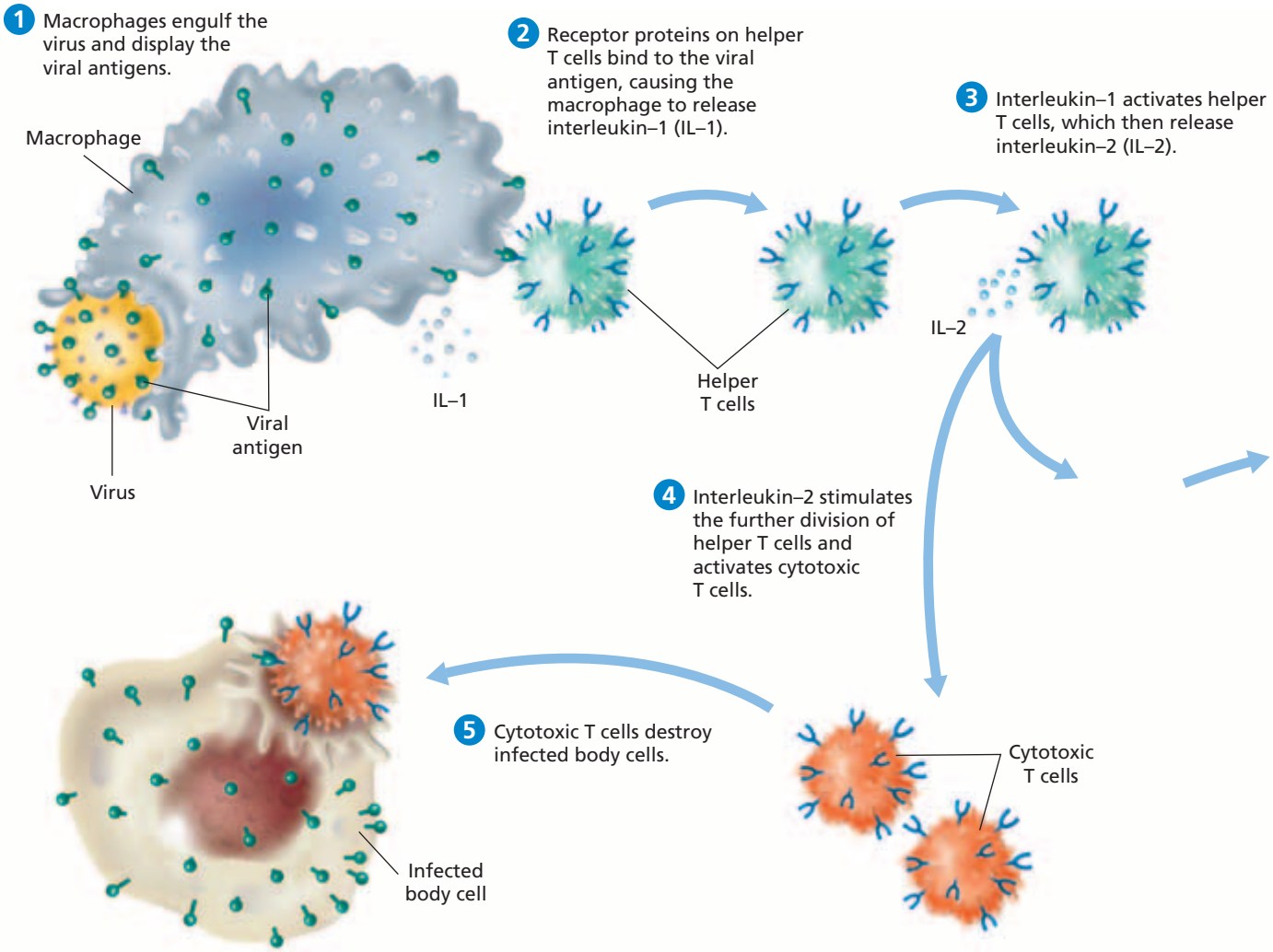

FIGURE 47-7

The immune response is a two-part assault on a pathogen: the cell-mediated immune response and the humoral immune response. Both responses occur at the same time and are triggered when a macrophage engulfs a pathogen, thus activating helper T cells (steps 1 through 3). The cell-mediated immune response is shown in steps 4 and 5, and the humoral immune response is shown in steps 6 through 9 on the next page.

One other type of T cell that plays a part in cell-mediated immunity is *suppressor T cells*. Suppressor T cells are not well understood but are thought to help shut down the immune response after the pathogen has been cleared from the body. The cell-mediated immune response is shown in steps 4 and 5 in Figure 47-7 above.

Humoral Immune Response

The **humoral** (HYOO-muhr-uhl) **immune response** involves the action of B cells and occurs at the same time the cell-mediated immune response occurs. Like the cell-mediated immune response, the humoral immune response is triggered when macrophages engulf pathogens, stimulating helper T cells. The release of interleukin-2 stimulates B cells that have receptors that are complementary to the antigen to divide and change into plasma cells. **Plasma cells** are highly specialized cells that make defensive proteins called *antibodies* that are released into the blood. An **antibody** binds to a specific antigen or inactivates or destroys toxins. Antibodies are Y-shaped molecules. The two arms of each Y are identical, and each arm has a receptor that can attach to a specific antigen. A plasma cell can make up to 30,000 antibody molecules per second.

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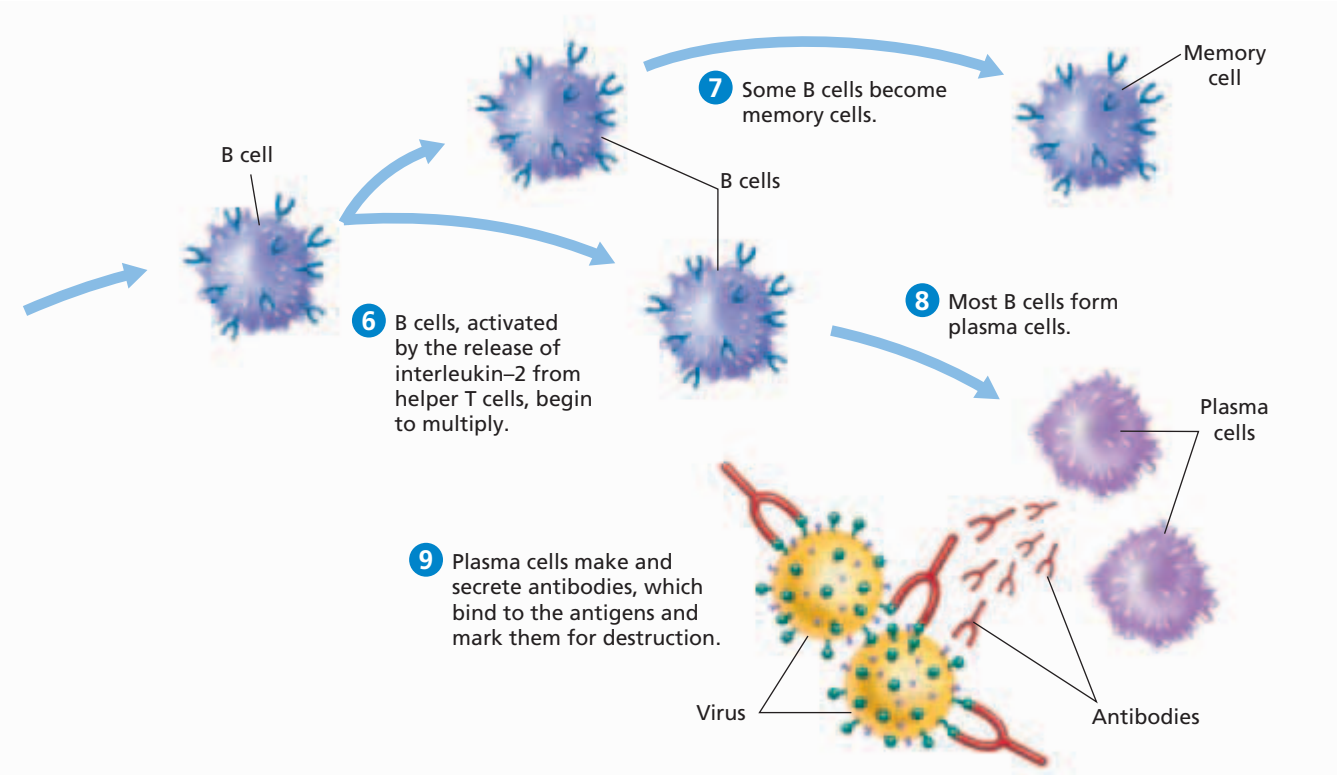

Antibodies bind to pathogens but do not destroy them directly. Instead, antibodies either inactivate the pathogen or cause its destruction by the nonspecific defenses. For example, by attaching to the surface proteins of a virus, antibodies prevent the virus from entering a cell, thereby blocking its reproduction. Antibodies also cause pathogens to clump together, which helps macrophages to engulf the pathogens. Antigen-antibody binding also activates the complement system. The complement proteins can then create holes in the membranes of the pathogen's cells, causing them to burst. The humoral immune response is shown in steps 6 through 9 in Figure 47-7 above.

Primary and Secondary Immune Responses

Although the immune response stops once the body has overcome an infection, some memory cells remain in the body. **Memory cells** are lymphocytes that will not respond the first time that they meet with an antigen or an invading cell but will recognize and attack that antigen or invading cell during later infections.

Memory cells are the body's long-term protection against reinfection by a pathogen. Memory cells often remain effective throughout an individual's life. Because of memory cells, a person will get most diseases only once. When exposed to a pathogen a second time, memory cells immediately recognize it and begin to divide rapidly. They eliminate the pathogen before it can produce serious illness.

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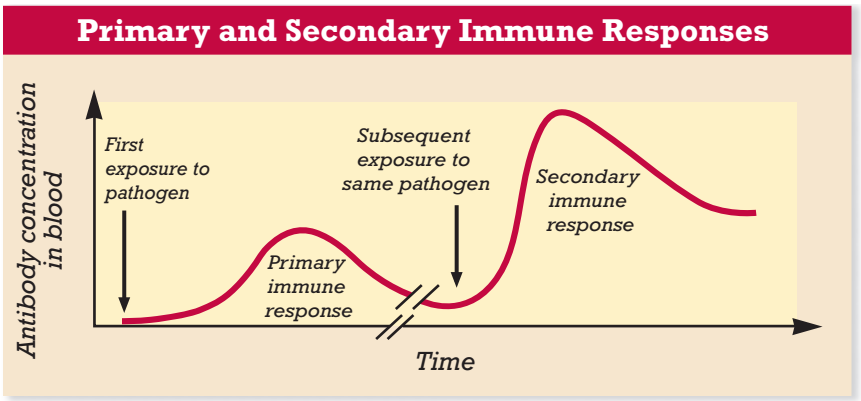
(a)



(b)

FIGURE 47-8

(a) Vaccinations take advantage of the production of memory cells and the secondary immune response. (b) Compare the production of antibodies during the primary and secondary immune responses that are shown on the graph.

The first time the body encounters an antigen, the immune response is called a *primary immune response*. The response of memory cells to a later infection by the same pathogen is called a *secondary immune response*. The secondary immune response is much faster and more powerful, producing many more antibodies, as shown in the graph above. Recall that memory cells protect only against pathogens already encountered. Colds and flu are an exception, because rhinoviruses and flu viruses mutate at a high rate. Therefore, these viruses are always presenting new antigens.

IMMUNITY AND VACCINATION

Immunity is the ability to resist an infectious disease. A person who is resistant to a pathogen is said to be immune to it. One way for the body to gain immunity to a pathogen is to be infected by it, undergo a primary immune response, and survive the disease it causes. Another, safer way is through **vaccination** (vak-suh-NAY-shuhn), the introduction of antigens into the body to cause immunity. Vaccination usually involves an injection of a vaccine under the skin, as shown in Figure 47-8a.

Vaccines

A *vaccine* is a solution that contains a dead or weakened pathogen or material from a pathogen. However, the antigens are still present, so the body produces a primary immune response to the antigens in the vaccine. The memory cells that remain after the primary immune response can provide a quick secondary immune response if the antigen ever enters the body again.

Some of the diseases that have been controlled through the use of vaccines are polio, measles, mumps, tetanus, and diphtheria. An intensive worldwide vaccination campaign has eliminated smallpox. Sometimes, the protection provided by vaccines wears off over time. So, doctors recommend *booster shots* to restore immunity against some diseases, such as tetanus and polio.

Quick Lab

Organizing the Immune Response

Materials paper, pencil

Procedure Create a diagram or a flowchart that outlines the steps involved in an immune response. Label the cells and the steps.

Analysis What are helper T cells? How is a cell-mediated response different from a humoral response?

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MILESTONES IN Vaccine Development

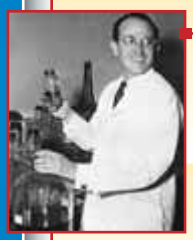
Timeline

Before 1700 Asian physicians use variolation.

1796 Jenner uses cowpox to immunize against smallpox.

1885 Pasteur treats rabies with vaccination.

1940s Vaccines for diphtheria, pertussis, tetanus, and smallpox are used routinely.

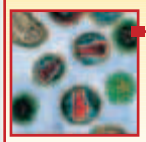


1955 An injectable polio vaccine is introduced by Jonas Salk.

1964 A vaccine for measles is released.

1967 A mumps vaccine is introduced.

1986 Recombinant vaccines are developed.



1990s and later Researchers seek an effective vaccine for HIV and other pathogens.

Centuries ago, Asian physicians sought to understand immunity by exposing healthy people to material from the sores of smallpox victims. This technique, called variolation, *had limited success but a huge historical impact. In the early 1700s, a British woman saw the technique being used in Turkey and described it to British doctors, who tried it on children. One of those children was Edward Jenner, the inventor of vaccination.*

As a country doctor in the late 1700s, Edward Jenner was investigating cowpox, a relatively harmless disease. He knew that milkmaids often contracted cowpox from cows. He had also heard that milkmaids who had cowpox were immune to smallpox. Jenner saw a connection, and he hypothesized that exposure to the pathogen that causes cowpox would give a person immunity to the smallpox pathogen also. In 1796, Jenner tested his hypothesis.

Jenner took matter from the cowpox sore of a milkmaid and injected it into an 8-year-old boy. Two months later, Jenner injected material from a sore of a smallpox patient. The boy remained healthy, even after several more injections. Jenner's experiment would be considered unethical today, but his observations led to millions of lives being saved through vaccination.

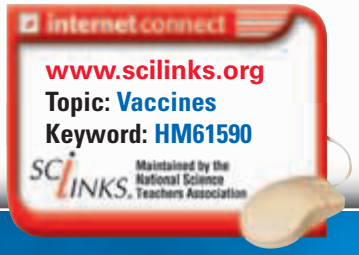
Science and medicine advanced slowly before the 20th century, and vaccination caught on only after scientists understood that germs cause disease. Louis Pasteur succeeded in vaccinating sheep against anthrax in 1881. In 1885, he injected a boy with killed rabies virus to save him from contracting the disease. This event helped explain vaccination, and soon scientists around the world began searching for the agents of disease and creating vaccines. By the early 1970s, vaccines had been developed for diphtheria, pertussis, tetanus, mumps, polio, measles, and rubella. In the United States, these illnesses have been virtually eliminated through vaccination.

Researchers soon discovered that the immune system can recognize a tiny piece of a pathogen and still form antibodies. By 1986, scientists had developed a recombinant hepatitis B vaccine by using harmless organisms altered to make a protein from the virus. The new vaccine cannot actually cause the disease, a rare but dangerous side effect of previous vaccines.

Vaccine research now focuses on conquering pathogens that have caused new outbreaks of disease around the world. These pathogens include HIV, the West Nile virus, the Ebola virus, and the coronavirus that causes SARS. In addition, researchers are working to improve existing vaccines, such as those for smallpox and anthrax.

Review

1. Why is it unnecessary for a vaccine to contain a whole pathogen?
2. **Critical Thinking** How can a person be immune to smallpox after exposure to cowpox?
3. **Critical Thinking** Do you think Pasteur's injection of rabies virus into a child would be considered unethical today?



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PROBLEMS OF THE IMMUNE SYSTEM

Sometimes, the immune system reacts to otherwise harmless antigens in ways that can be harmful. Three examples of such problems of the immune system are allergies, asthma, and autoimmune diseases.

Allergies

An **allergy** is a physical response to an antigen. The antigen can be a common substance that produces little or no response in the general population. Antigens that can trigger allergic reactions include pollen, animal dander (flakes of skin), dust mites, food, and fungal spores. Allergic symptoms are generally mild, including a runny nose, sneezing, watery eyes, or itchy swellings of the skin. However, some people have extreme and life-threatening reactions to allergies. Many of the symptoms of allergy result from the release of histamine by cells that are exposed to the antigen. Drugs called *antihistamines* help counteract the effects of histamine and can relieve some symptoms of allergies.

Asthma

Allergies can also trigger **asthma,** a respiratory disorder that causes the bronchioles (airways of the lungs) to narrow. Asthma attacks occur when the muscles covering the bronchioles overreact to substances in the air, as shown in Figure 47-9. Substances that can cause asthma attacks include cigarette smoke and allergens such as animal dander. During an asthma attack, the lining of the bronchioles and other respiratory tissues may also swell and become inflamed, making breathing difficult. Other symptoms of asthma include shortness of breath, wheezing, and coughing. Asthma attacks are serious. Thousands of people in the United States die from asthma each year.

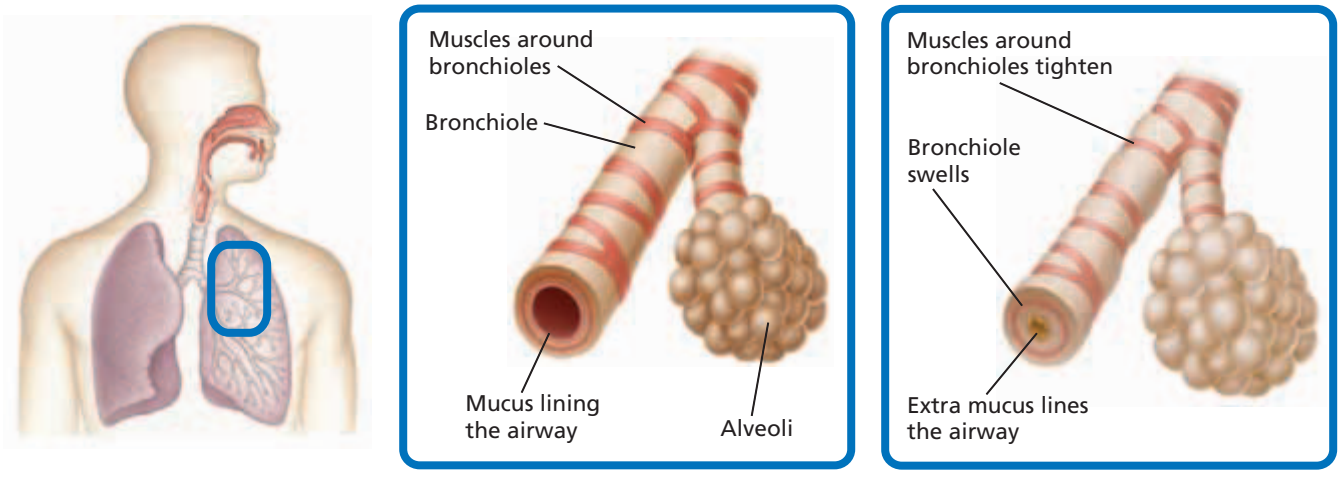

FIGURE 47-9

During an asthma attack, the muscles that encircle the airways of the lung (bronchioles) constrict, and inflammation of the respiratory tissues causes swelling and extra mucus to be produced in the airways. These reactions can make breathing difficult.

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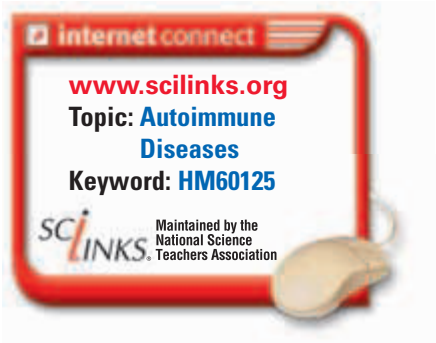
TABLE 47-2 *Autoimmune Diseases, Target Tissues, and Symptoms*

Disease	Tissues affected	Symptoms
Systemic lupus erythematosus	Connective tissue throughout the body	Facial rash, painful joints, fever, fatigue, kidney problems, weight loss
Type 1 diabetes	Insulin-producing cells in pancreas	Excessive urine production, excessive thirst, weight loss, fatigue, confusion
Rheumatoid arthritis	Joints	Painful, crippling inflammation of the joints
Psoriasis	Skin	Dry, scaly, red skin patches
Scleroderma	Multiple organs	Hardening and stiffening of the skin
Crohn's disease	Digestive system	Abdominal pain, nausea, vomiting, weight loss

Autoimmune Diseases

A disease in which the immune system attacks the organism's own cells is called an **autoimmune** (awt-oh-i-MYOON) **disease.** Lymphocytes that recognize and react to the body's own cells are usually eliminated during development, before they become functional. This removal of certain lymphocytes prevents an attack directed at the body's own tissues. However, in rare cases the immune system does respond to the body's own cells, attacking them as if they were pathogens. An autoimmune disease results.

Autoimmune diseases affect organs and tissues in various areas of the body. Multiple sclerosis is an autoimmune disease of the nervous system that affects mainly young adults. In this disease, T cells attack and slowly destroy the insulating material surrounding nerve cells in the brain, in the spinal cord, and in the nerves leading from the eyes to the brain. Symptoms include weakness, unsteadiness, tingling or burning sensations, and blurred vision. In severe cases, paralysis, blindness, and even death can result. Scientists are still searching for the causes of multiple sclerosis and other autoimmune diseases. Table 47-2 lists some other autoimmune diseases and describes their effects on the body.



SECTION 2 REVIEW

1. Describe the functions of the spleen and of the bone marrow.
2. What is an antigen?
3. How does the role of B cells in the immune response differ from that of helper T cells?
4. Explain how vaccination stimulates immunity to a disease.
5. Name one similarity and one difference between autoimmune diseases and allergies.

CRITICAL THINKING

6. **Recognizing Relationships** Explain how B cells depend on T cells.
7. **Evaluating an Argument** "A person who has just recovered from a cold cannot get the flu." Is this statement true? Explain your reasoning.
8. **Forming Reasoned Opinions** Would vaccine research be useful in preventing autoimmune diseases? Explain your reasoning.

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SECTION 3

OBJECTIVES

- **Describe** the relationship between HIV and AIDS.
- **Distinguish** between the three phases of HIV infection.
- **Identify** the two main ways that HIV is transmitted.
- **Determine** how the evolution of HIV affects the development of vaccines and treatment.

VOCABULARY

AIDS
HIV
opportunistic infection

HIV AND AIDS

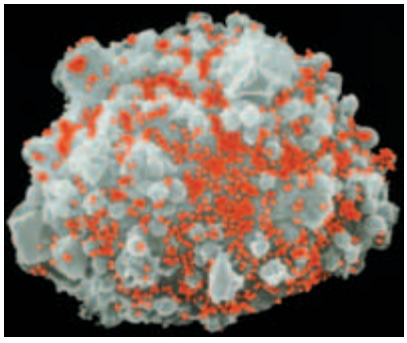
The immune system normally provides protection against infectious diseases. The importance of the immune system can be seen in diseases in which the immune system does not function properly. One of the deadliest of these diseases is ***AIDS*** *(acquired immunodeficiency syndrome), in which the immune system loses its ability to fight off pathogens and cancers. AIDS was recognized as a disease in 1981. Since then, it has killed more than 22 million people worldwide.*

THE COURSE OF HIV INFECTION

AIDS results from infection by the human immunodeficiency virus, or **HIV.** Once HIV has entered the bloodstream, HIV binds to CD4, a receptor protein on the surface of some cells. To enter a cell, HIV must also bind to an associated protein, or co-receptor. Macrophages, which have the CD4 receptor and a co-receptor called CCR5, are often the first cells of the immune system infected with HIV. The virus replicates inside the macrophages, and new viruses are released through "budding." This process does not destroy the macrophages. Viral replication of HIV results in many mutations. Eventually, a mutation may enable the virus to recognize other co-receptors, such as those found on helper T cells.

After release from macrophages, HIV attaches to and enters helper T cells. After viral replication, the new viruses are released from the T cell, as shown in Figure 47-10. These viruses then attach to other helper T cells, where the process repeats. Unlike macrophages, helper T cells are destroyed. Eventually, HIV kills enough helper T cells to cripple the immune system, leading to AIDS. HIV infection doesn't progress to AIDS on a specific timetable, but people tend to go through three phases of infection.

FIGURE 47-10
An HIV-infected helper T cell (grey mass) releases hundreds of new virus particles (red dots). (SEM 5,600×)



Phase I

Phase I of HIV infection is called the *asymptomatic stage,* because there are few or no symptoms. However, the amount of virus increases due to replication, as shown in Figure 47-11. The immune system begins an attack, and plasma cells make antibodies to fight the virus. However, it may take several weeks for the amount of anti-HIV antibodies to become large enough to result in a positive HIV test. HIV-infected people may feel well during phase I but can still infect other people. Phase I can last for up to 10 years or more.

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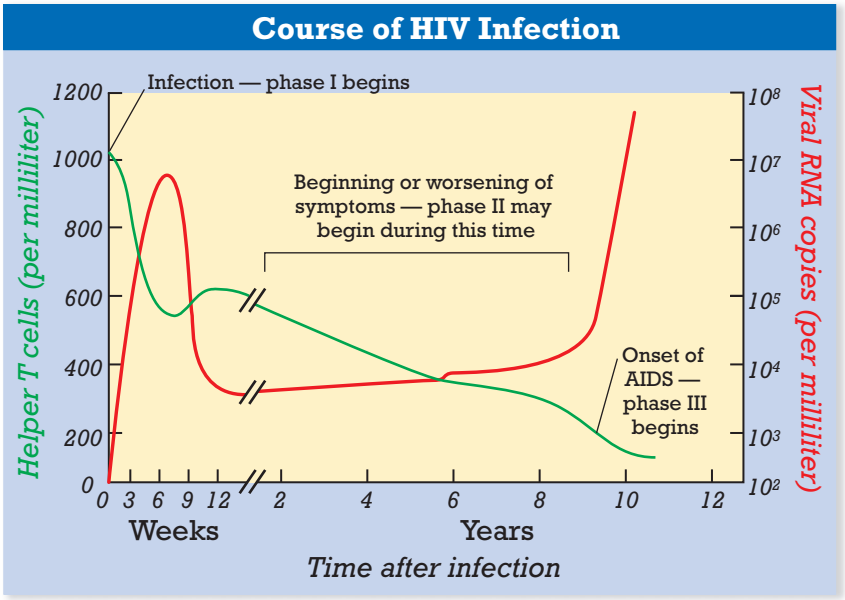

FIGURE 47-11

This graph shows an example of how the course of HIV infection can proceed. The course of HIV infection depends on both the numbers of virus particles and the numbers of helper T cells in the blood.

Phase II

The beginning or worsening of symptoms marks the start of the second phase of HIV infection. B cells continue to make a large amount of antibody against HIV. However, as shown in Figure 47-11, the number of T cells drops steadily as the virus continues to replicate. As the immune system fails, lymph glands become swollen, and fatigue, weight loss, fever, or diarrhea develop or worsen. Some infected people may notice mental changes, such as forgetfulness and abnormal thinking patterns.

Phase III

In phase III, the number of helper T cells drops so low that they can no longer stimulate B cells and cytotoxic T cells to fight invaders. As a consequence, the amount of anti-HIV antibody falls, and HIV levels rise dramatically. The virus continues destroying the few helper T cells remaining. AIDS is diagnosed when the helper T-cell count drops to 200 cells per milliliter of blood or lower (a normal amount is 600 to 700 helper T cells per milliliter).

AIDS may also be diagnosed if an opportunistic infection has developed. **Opportunistic infections** are illnesses caused by pathogens that produce disease in people with weakened immune systems. These organisms usually do not create problems in people with a healthy immune system. Opportunistic infections include pneumocystis pneumonia, tuberculosis, and a rare infection of the brain called *toxoplasmosis*. Rare cancers such as Kaposi's sarcoma, which causes purplish-red blotches on the skin, can also signal the onset of AIDS.

Drug therapy can slow the progress from HIV infection to AIDS. But AIDS is fatal. Few individuals live more than two years after an AIDS diagnosis. It is important to note that HIV itself does not cause death. Rather, death results from the weakened immune system's inability to fight opportunistic infections and cancers.

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TRANSMISSION OF HIV

HIV is transmitted by the transfer of body fluids containing HIV or HIV-infected cells. The most common means of infection is sexual contact with an infected person. The second most common means is the use of syringes and hypodermic needles that have been contaminated with blood containing HIV. People who inject intravenous drugs and who share needles are at very high risk of infection. HIV can also be transmitted from an infected mother to her infant before or during birth or through breast-feeding.

HIV is not transmitted through casual contact, such as shaking hands. HIV is apparently not transmitted through the air, in water, on toilet seats, or through insect bites. The likelihood of infection through a blood transfusion is extremely low.

VACCINES AND TREATMENTS

FIGURE 47-12

A scientist studies blood samples as part of the search for a treatment or vaccine for HIV.

Scientists trying to create vaccines and treatments for HIV, such as the scientist shown in Figure 47-12, must contend with its rapid rate of evolution. The genes that code for the virus's surface proteins mutate frequently. As a result, new variants of the virus with slightly different surface proteins are constantly appearing. To produce effective immunity, a vaccine against HIV must stimulate the immune system to respond to many variants of the virus. Although researchers are developing and testing several vaccines against HIV, none has yet proven effective.

In addition, HIV can quickly become resistant to drugs. Scientists now treat patients with a combination of three drugs. Because mutations are random, mutations that create resistance to all three drugs are not likely to occur. However, this therapy often requires patients to take 50 or more pills a day. Many HIV-infected patients find the plan difficult and expensive. Nevertheless, the multidrug treatment is the most effective plan currently available. Because there is not yet a vaccine or cure for HIV infection, the only way to prevent HIV infection is to avoid high-risk behaviors.

SECTION 3 REVIEW

1. Describe the relationship between HIV and AIDS.
2. State the developments during the course of HIV infection that can lead to a diagnosis of AIDS.
3. List two ways that HIV can be transmitted and two ways that it cannot.
4. Why have scientists been unable to develop an effective vaccine for HIV?

CRITICAL THINKING

5. **Recognizing Factual Accuracy** Evaluate the statement "HIV infection causes death."
6. **Analyzing Current Research** Explain how research on co-receptor blocking might affect the search for a treatment for HIV infection.
7. **Comparing Concepts** Identify one similarity and one difference between HIV and a cold virus.

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CHAPTER HIGHLIGHTS

SECTION 1 Nonspecific Defenses

- A pathogen is any agent that causes a disease. Robert Koch developed four basic steps, or postulates, for identifying the pathogen responsible for a disease.
- The skin and mucous membranes are nonspecific defenses that keep pathogens out of the body.
- The skin acts as an external barrier to pathogens and also releases substances that are toxic to pathogens.
- The mucous membranes protect the interior surfaces of the body and secrete mucus, a sticky fluid that traps pathogens.
- Injury to cells triggers an inflammatory response. Injured cells release chemical messengers that attract phagocytes through the capillary walls. Phagocytes then destroy the pathogens.
- White blood cells fight pathogens. Two types of phagocytes (neutrophils and macrophages) ingest pathogens. Natural killer cells pierce the cell membranes of infected cells.
- Nonspecific defenses also include an elevation in temperature (fever) and the activation of proteins such as the complement system and interferon.

Vocabulary

infectious disease (p. 957)
pathogen (p. 957)
Koch's postulates (p. 957)
mucous membrane (p. 958)
inflammatory response (p. 959)
histamine (p. 959)
phagocyte (p. 959)
neutrophil (p. 960)
macrophage (p. 960)
natural killer cell (p. 960)
complement system (p. 960)
interferon (p. 960)

SECTION 2 Specific Defenses: The Immune System

- The immune system consists of the cells and tissues that recognize and attack foreign substances in the body.
- Lymphocytes must be able to recognize foreign invaders and tell them apart from the cells of the body. Receptor proteins on a lymphocyte's plasma membrane allow the lymphocyte to recognize the invaders' antigens.
- The reaction of the body against an antigen is called an *immune response.* An immune response is a two-part assault on a pathogen: the cell-mediated immune response and the humoral immune response.
- Memory cells that remain after a primary response to an antigen allow a rapid secondary immune response if that antigen appears again. Vaccinations take advantage of the production of memory cells and the secondary immune response.
- An allergy is a physical response to an antigen that causes little or no response in the general population. Allergies can trigger asthma, a respiratory disorder that causes the bronchioles to narrow. An autoimmune disease is a disease in which the immune system attacks the organism's own cells.

Vocabulary

immune system (p. 961)
lymphocyte (p. 961)
thymus (p. 961)
spleen (p. 962)
B cell (p. 962)
T cell (p. 962)
antigen (p. 962)
immune response (p. 962)
helper T cell (p. 963)
cell-mediated immune response (p. 963)
cytotoxic T cell (p. 963)
humoral immune response (p. 964)
plasma cell (p. 964)
antibody (p. 964)
memory cell (p. 965)
immunity (p. 966)
vaccination (p. 966)
allergy (p. 968)
asthma (p. 968)
autoimmune disease (p. 969)

SECTION 3 HIV and AIDS

- AIDS results from infection by HIV. HIV can replicate inside macrophages and helper T cells.
- The course of HIV infection usually has three phases: phase I, the asymptomatic phase; phase II, the beginning or worsening of symptoms; and phase III, AIDS.
- HIV is transmitted mainly through sexual contact and the use of HIV-contaminated needles.
- Because its genes mutate often, HIV can quickly become resistant to medication. The rapid evolution of HIV also makes it difficult to develop an effective vaccine.

Vocabulary

AIDS (p. 970)
HIV (p. 970)
opportunistic infection (p. 971)

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CHAPTER REVIEW

USING VOCABULARY

1. For each pair of terms, explain how the meanings of the terms differ.
   a. *macrophage* and *natural killer cell*
   b. *B cell* and *T cell*
   c. *antigen* and *antibody*
   d. *allergy* and *asthma*
2. Explain the relationship between HIV and AIDS.
3. Use the following terms in the same sentence: *cell-mediated immune response, helper T cell, cytotoxic T cell,* and *interleukin-2*.
4. **Word Roots and Origins** The word *pathogen* is derived from the Greek *pathos,* which means "suffering" or "disease," and *-gen,* which means "to produce." Using this information, explain why the term *pathogen* is a good name for an infectious agent.

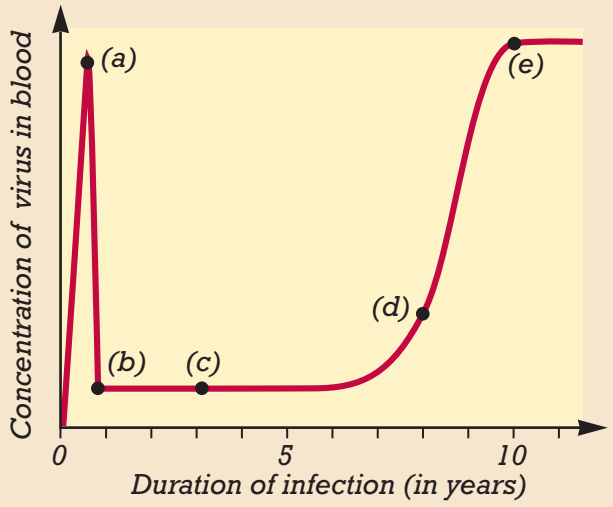
UNDERSTANDING KEY CONCEPTS

5. **Describe** the steps that must be followed to prove that a particular pathogen is responsible for a disease.
6. **Compare** the function of the mucous membranes with that of the skin.
7. **Summarize** the steps of the inflammatory response.
8. **Name** the chemical messenger that increases the permeability of the capillaries surrounding an injury.
9. **Identify** the roles that white blood cells play in the second line of nonspecific defenses.
10. **Explain** how fever and protein production help defend against infection.
11. **Name** one function of the thymus.
12. **Describe** how lymphocytes recognize and bind to pathogens.
13. **Explain** the role that helper T cells play in the immune response.
14. **Name** the type of cell that produces antibodies and releases them into the blood.
15. **Explain** the function of antibodies.
16. **State** the role that memory cells play in providing immunity against disease.
17. **Relate** vaccination to immunity.
18. **Describe** the cause of autoimmune diseases.
19. **Name** the point at which phase III in the course of HIV infection begins.
20. **List** two main ways HIV is usually transmitted.
21. **Identify** the problem scientists have encountered when trying to develop a vaccine against HIV.
22.  **CONCEPT MAPPING** Use the following terms to create a concept map: *pathogen, macrophage, helper T cell, cytotoxic T cell, B cell, plasma cell,* and *antibody*.

CRITICAL THINKING

23. **Making Comparisons** Scientists created an effective vaccine for smallpox but have not been able to do so for HIV. What does this suggest about the rate of evolution of the smallpox virus?
24. **Relating Concepts** Cytotoxic T cells attack and destroy some kinds of cancer cells. What can you conclude about the surface proteins of these cancer cells?
25. **Interpreting Graphics** The graph below shows the amount of HIV in the blood of an infected person over time. Use the graph to answer the following questions:
   a. What caused the peak in viral concentration at point a?
   b. Why did the level of virus drop between points a and b?
   c. Describe what is happening to both the virus and the immune system at points c and d.

Virus Concentration in HIV Infection



26. **Inferring Relationships** People who are severely burned often die from infection. Use what you know about disease transmission to explain why this situation is common.

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Standardized Test Preparation

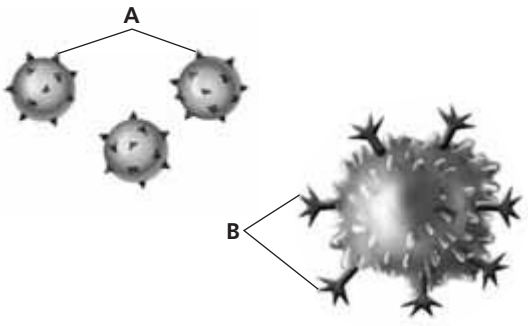
DIRECTIONS: Choose the letter of the answer choice that best answers the question.

1. Which of the following is part of the nonspecific defenses?
- **A.** the inflammatory response
- **B.** the primary immune response
- **C.** the humoral immune response
- **D.** the secondary immune response

2. Which of the following statements is false?
- **F.** Autoimmune diseases can be fatal.
- **G.** Autoimmune diseases are a type of cancer.
- **H.** Multiple sclerosis is an autoimmune disease.
- **J.** Autoimmune diseases target the body's cells.

3. Which of the following is the most common means of HIV transmission?
- **A.** receiving a blood transfusion
- **B.** performing experiments with HIV
- **C.** shaking hands with a person who has AIDS
- **D.** having sexual contact with an HIV-infected person

INTERPRETING GRAPHICS: The image below shows two kinds of structures involved in an immune response. Use the image to answer the questions that follow.



4. What are the structures labeled *A*?
- **F.** antigens
- **G.** interferons
- **H.** interleukins
- **J.** receptor proteins

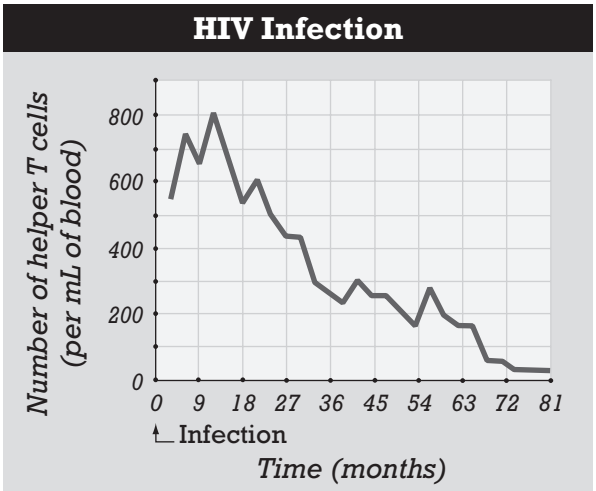
5. What are the structures labeled *B*?
- **A.** antigens
- **B.** interferons
- **C.** interleukins
- **D.** receptor proteins

6. Why do structures *A* and *B* interact with each other?
- **F.** Both are viral proteins.
- **G.** Both are "nonself" structures.
- **H.** They are complementary shapes.
- **J.** They are produced by the same cells.

DIRECTIONS: Complete the following analogy.

7. T cell : cell-mediated :: B cell :
- **A.** humoral
- **B.** infectious
- **C.** secondary
- **D.** inflammatory

INTERPRETING GRAPHICS: The graph below shows the number of helper T cells over time from the onset of HIV infection. Use the graph to answer the question that follows.



8. About how many months after infection did the number of T cells first drop below 200/mL?
- **F.** 18
- **G.** 39
- **H.** 51
- **J.** 58

SHORT RESPONSE

A person infected with HIV today might not test positive for HIV antibodies for up to 6 months.

Explain why an HIV antibody test may not be positive until several weeks after a person's exposure to HIV.

EXTENDED RESPONSE

The inflammatory response results from cell injury.

Part A Explain the role of histamine in the inflammatory response.

Part B Explain the usefulness of having more than one type of white blood cell respond in the inflammatory response.

Test TIP Whenever possible, highlight or underline numbers or words that are critical to correctly understanding a question.

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Simulating Disease Transmission

OBJECTIVES

- Simulate the transmission of a disease.
- Determine the original carrier of the disease.

PROCESS SKILLS

- organizing data
- analyzing data
- identifying
- modeling

MATERIALS

- lab apron
- safety goggles
- disposable gloves
- dropper bottle of unknown solution
- large test tube
- indophenol indicator

Background

1. What are the five main ways that human diseases can be transmitted?
2. How does a cold or flu spread from person to person?
3. How does the body fight invading viruses?
4. Why has the transmission of HIV become a great concern worldwide?
5. Why is a person with AIDS less able to combat infections than a person who does not have AIDS?

PART A Simulating the Transmission of a Disease

1. This investigation will involve the class in a simulation of disease transmission. After the simulation, you will try to identify the original infected person in the closed class population.
2. In your lab report, construct a data table similar to Table A.
3.  **CAUTION Put on a lab apron, goggles, and disposable gloves.**
4.  **CAUTION If you get any solution used in this investigation on your skin or clothing, wash it off at the sink while calling to your teacher. If you get any solution used in this investigation in your eyes, immediately flush your eyes with water at the eyewash station while calling to your teacher.** You have been given a dropper bottle of unknown solution and a clean test tube. The solution in the dropper bottle represents the pathogens that you carry. Handle the unknown solution with care because it is not simply water.
5. When your teacher says to begin, transfer three dropperfuls of your solution to your clean test tube. Then, replace the lid on the dropper bottle, and do not re-open it until Part B of this investigation.
6. Select one person to be your partner. Let one partner pour the contents of his or her test tube into the other partner's test tube. Then, pour half the solution back into the first test tube. You and your partner now share pathogens of any possible transmittable disease that either of you might have had. Record the name of your first partner (Round 1) in your data table in your lab report.
7. For Round 2, wait for your teacher's signal, and then find a different partner and exchange solutions in the same manner as you did in step 6. Record the name of your second partner (Round 2) in your lab report. Do not exchange solutions with the same person more than once. Repeat this procedure again for Round 3.
8. After all rounds are finished, your instructor will ask you to add one dropperful of indophenol indicator to your test tube to see if the fluids in your test tube have become infected. Infected solutions will be colorless or light pink. All uninfected solutions will appear blue. Record the outcome of your tests in your lab report.

TABLE A *LIST OF PARTNERS' NAMES*

Round number	Partner's name
1	
2	
3	

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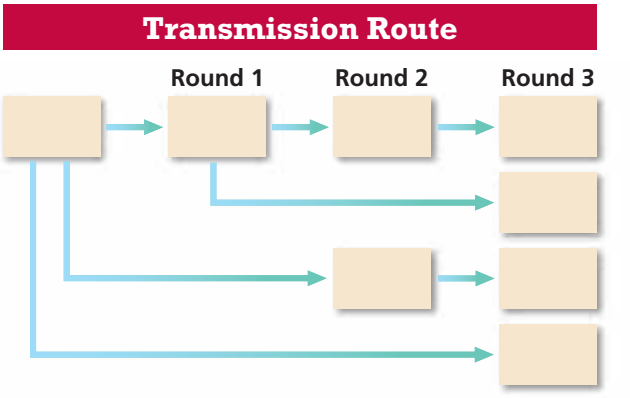
TABLE B *PATH OF DISEASE TRANSMISSION*

Name of infected person	Names of infected person's partners		
	Round 1	Round 2	Round 3

PART B Tracing the Source of the Disease

9. If you are an infected person, give your name to your teacher. As names of infected people are written on the chalkboard or on the overhead projector, record them in your lab report in a table similar to Table B shown above.
10. Try to trace the original source of the infection, and then determine the transmission route of the disease. In your table, cross out the names of all the uninfected partners in Rounds 1, 2, and 3. There should be only two people in Round 1 who were infected. One of these people was the original carrier.
11. Draw a diagram that shows the transmission route of the disease through all three rounds. Your diagram may look something like the chart below. Include your diagram in your lab report.



12. In your diagram, insert the names of the two people in Round 1 who were infected and the names of their partners in Rounds 2 and 3.
13. To test whether a person was the original disease carrier, pour a sample from his or her dropper bottle into a clean test tube, and add indophenol indicator.
14.  Clean up your materials, and wash your hands before leaving the lab.

Analysis and Conclusions

1. What might the clear fluid in each student's dropper bottle represent?
2. Does the simulated disease have any apparent symptoms?
3. What chemical is added to the test tubes when the rounds are completed?
4. What color indicates a positive result?
5. What color indicates a negative result?
6. Who was the original disease carrier?
7. After the three rounds, how many students were infected? Express this as a percentage of the number of students in the class.
8. If an epidemic occurred in your community, how might public-health officials work to stop the spread of the disease?

Further Inquiry

A public-health official is sent to investigate an outbreak of a new disease. Devise an experiment to allow the official to determine whether the disease has been caused by the passing of pathogens from person to person or by environmental conditions.

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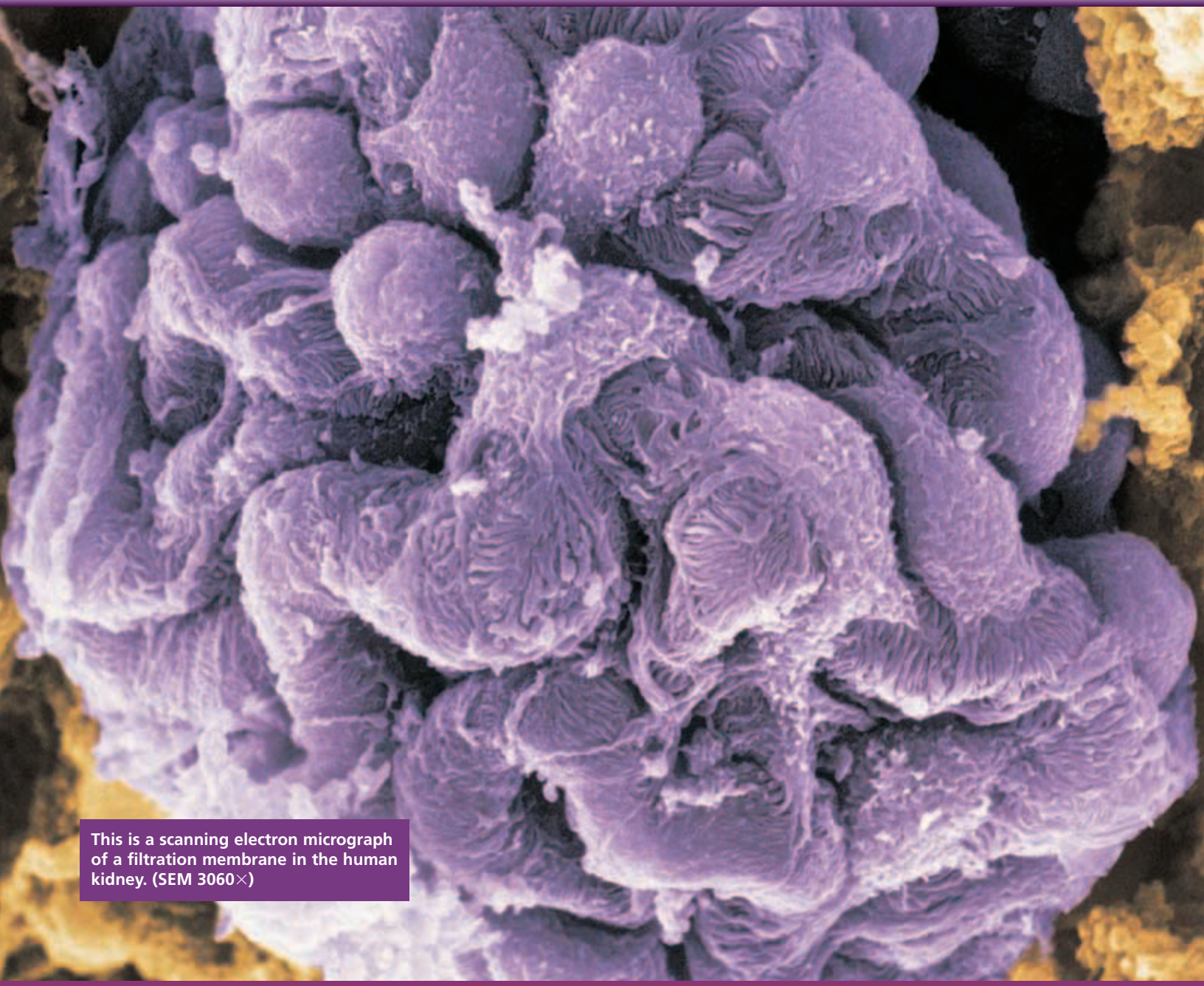
CHAPTER 48

Digestive and Excretory Systems



This is a scanning electron micrograph of a filtration membrane in the human kidney. (SEM 3060×)

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URINARY SYSTEM

The body must rid itself of the waste products of cellular activity. The process of removing metabolic wastes, called ***excretion,*** *is just as vital as digestion in maintaining the body's internal environment. Thus, the urinary system not only excretes wastes but also helps maintain homeostasis by regulating the content of water and other substances in the blood.*

SECTION 3

OBJECTIVES

- **Identify** the major parts of the kidney.
- **Relate** the structure of a nephron to its function.
- **Explain** how the processes of filtration, reabsorption, and secretion help maintain homeostasis.
- **Summarize** the path in which urine is eliminated from the body.
- **List** the functions of each of the major excretory organs.

VOCABULARY

excretion
renal cortex
renal medulla
renal pelvis
urea
ammonia
urine
nephron
Bowman's capsule
glomerulus
renal tubule
filtration
reabsorption
secretion
loop of Henle
ureter
urinary bladder
urethra

KIDNEYS

The main waste products that the body must eliminate are carbon dioxide, from cellular respiration, and nitrogenous compounds, from the breakdown of proteins. The lungs excrete most of the carbon dioxide, and nitrogenous wastes are eliminated by the kidneys. The excretion of water is necessary to dissolve wastes and is closely regulated by the kidneys, the main organs of the urinary system.

Humans have two bean-shaped kidneys, each about the size of a clenched fist. The kidneys are located one behind the stomach and the other behind the liver. Together, they regulate the chemical composition of the blood.

Structure

Figure 48-15 shows the three main parts of the kidney. The **renal cortex,** the outermost portion of the kidney, makes up about a third of the kidney's tissue mass. The **renal medulla** is the inner two-thirds of the kidney. The **renal pelvis** is a funnel-shaped structure in the center of the kidney. Also, notice in Figure 48-15 that blood enters the kidney through a renal artery and leaves through a renal vein. The renal artery transports nutrients and wastes to the kidneys. The nutrients are used by kidney cells to carry out their life processes. One such process is the removal of wastes brought by the renal artery.

The most common mammalian metabolic waste is **urea** (yoo-REE-uh), a nitrogenous product made by the liver. Nitrogenous wastes are initially brought to the liver as **ammonia,** a chemical compound of nitrogen so toxic that it could not remain long in the body without harming cells. The liver removes ammonia from the blood and converts it into the less harmful substance urea. The urea enters the bloodstream and is then removed by the kidneys.

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NEPHRONS

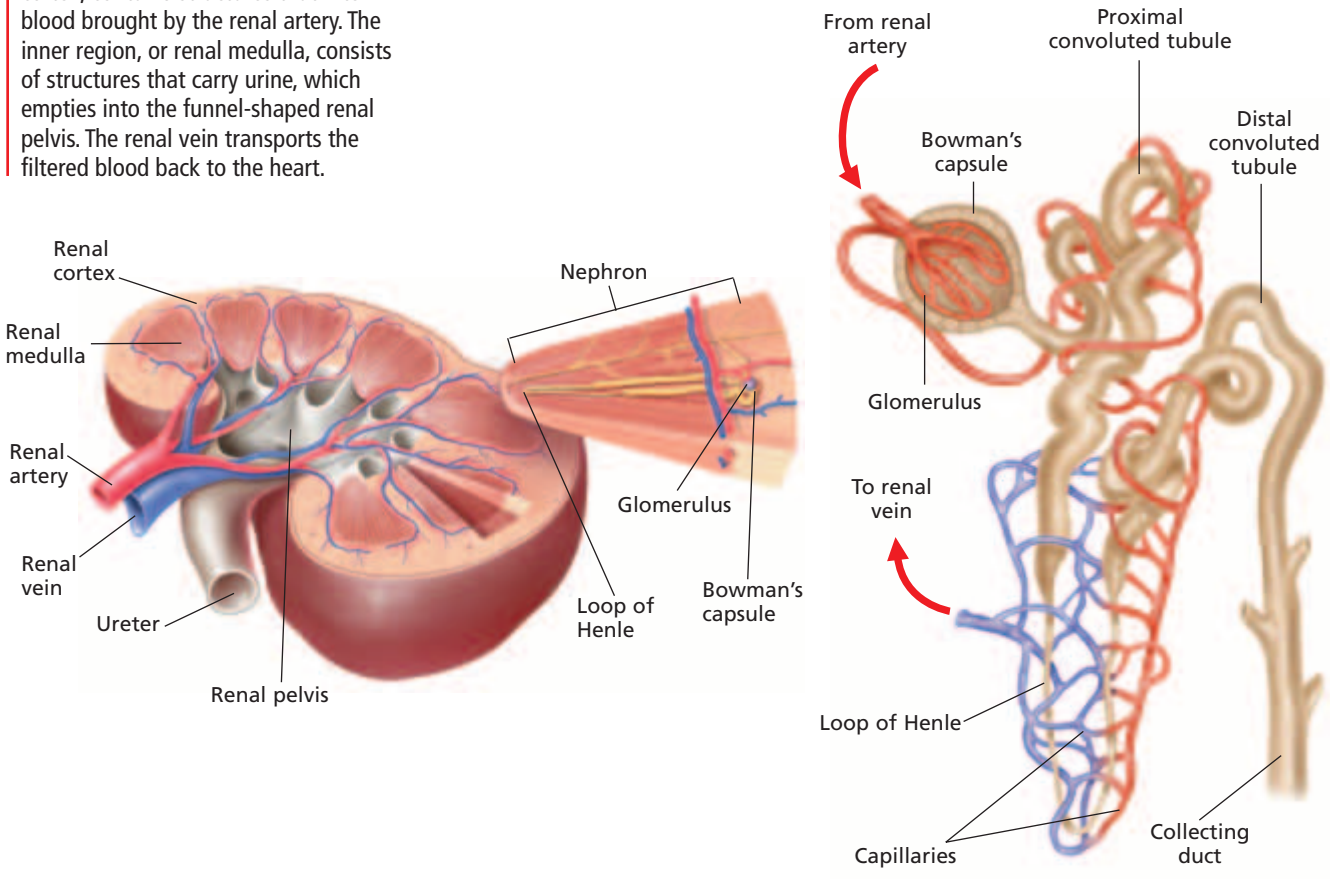
The substances removed from the blood by the kidneys—toxins, urea, water, and mineral salts—form an amber-colored liquid called **urine.** Urine is made in structures called **nephrons** (NEF-RAHNZ), the functional units of the kidney. Nephrons are tiny tubes in the kidneys. One end of a nephron is a cup-shaped capsule surrounding a tight ball of capillaries that retains cells and large molecules in the blood and passes wastes dissolved in water through the nephron. The cup-shaped capsule is called **Bowman's capsule.** Within each Bowman's capsule, an arteriole enters and splits into a fine network of capillaries called a **glomerulus** (gloh-MER-yoo-luhs).

Take a close look at the structure of the nephron, shown in Figure 48-15. Notice the close association between a nephron of the kidney and capillaries of the circulatory system. Initially, fluid passes from the glomerulus into a Bowman's capsule of the nephron. As the fluid travels through the nephron, nutrients that passed into the Bowman's capsule are reabsorbed into the bloodstream. What normally remains in the nephron are waste products and some water, which form urine that passes out of the kidney.

Each kidney consists of more than a million nephrons. If they were stretched out, the nephrons from both kidneys would extend for 80 km (50 mi). As you read about the structure of a nephron, locate each part in Figure 48-15.

FIGURE 48-15

The outer region of the kidney, the renal cortex, contains structures that filter blood brought by the renal artery. The inner region, or renal medulla, consists of structures that carry urine, which empties into the funnel-shaped renal pelvis. The renal vein transports the filtered blood back to the heart.



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Each nephron has a cup-shaped structure, called a Bowman's capsule, that encloses a bed of capillaries. This capillary bed, called a glomerulus, receives blood from the renal artery. Fluids are forced from the blood through the capillary walls and into the Bowman's capsule. The material filtered from the blood then flows through the **renal tubule,** which consists of three parts: the proximal convoluted tubule, the loop of Henle, and the distal convoluted tubule. Blood remaining in the glomerulus then flows through a network of capillaries. The long and winding course of both the renal tubule and the surrounding capillaries provides a large surface area for the exchange of materials.

As the filtrate flows through a nephron, its composition is modified by the exchange of materials among the renal tubule, the capillaries, and the extracellular fluid. Various types of exchanges take place in the different parts of the renal tubule. To understand how the structure of each part of the nephron is related to its function, we will examine the three major processes that take place in the nephron: filtration, reabsorption, and secretion. Figure 48-16 shows the site of each of these processes in the nephron.

Word Roots and Origins

glomerulus

from the Latin *glom,* meaning "little ball of yarn"

FILTRATION

Materials from the blood are forced out of the glomerulus and into the Bowman's capsule during a process called **filtration.** Blood in the glomerulus is under relatively high pressure. This pressure forces water, urea, glucose, vitamins, and salts through the thin capillary walls of the glomerulus and into the Bowman's capsule. About one-fifth of the fluid portion of the blood filters into the Bowman's capsule. The rest remains in the capillaries, along with proteins and cells that are too large to pass through the capillary walls. In a healthy kidney, the filtrate—the fluid that enters the nephron—does not contain large protein molecules.

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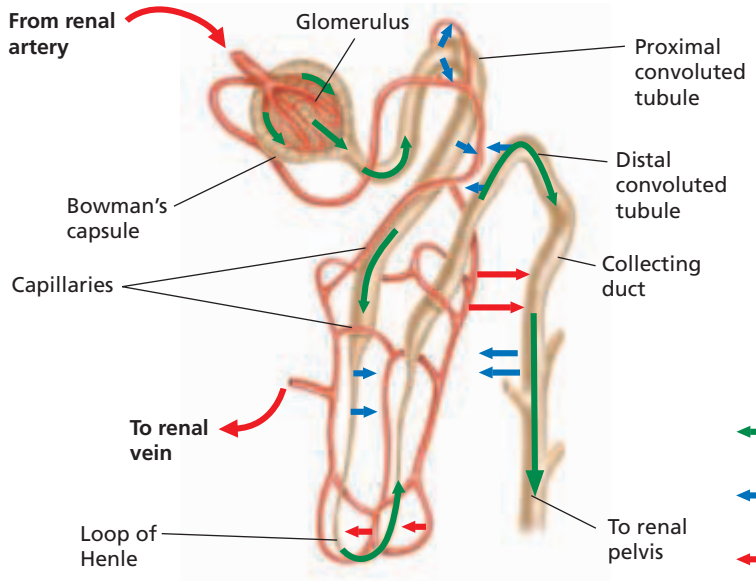

FIGURE 48-16
Color-coded arrows indicate where in the nephron the filtrate travels, and where reabsorption and secretion occur.

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Eco Connection

Kidneys and Pollution

According to data from the U.S. Environmental Protection Agency, indoor areas, where we spend up to 90 percent of our time, contain substances that may be hazardous to our health. Because of their function in excretion, kidneys often are exposed to hazardous chemicals that have entered the body through the lungs, skin, or gastrointestinal tract. Household substances that, in concentration, can damage kidneys include paint, varnishes, furniture oils, glues, aerosol sprays, air fresheners, and lead.

Many factors in our environment are difficult to control, but the elimination of pollutants from our indoor living areas is fairly simple. The four steps listed below may help reduce the effects of many indoor pollutants.

1. Identify sources of pollutants in your home.
2. Eliminate the sources, if possible.
3. Seal off those sources that cannot be eliminated.
4. Ventilate to evacuate pollutants and bring in fresh air.

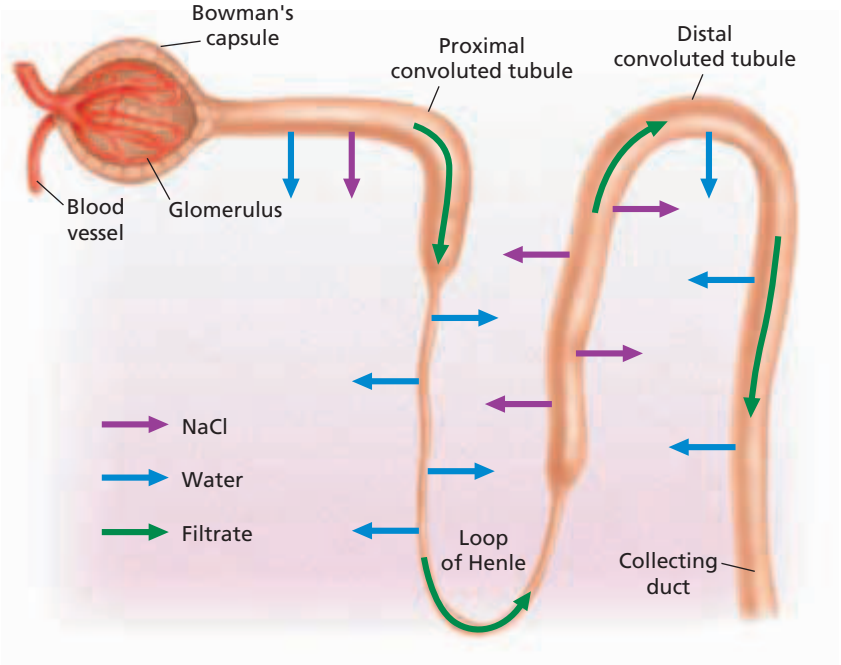
REABSORPTION AND SECRETION

The body needs to retain many of the substances that were removed from the blood by filtration. Thus, as the filtrate flows through the renal tubule, these materials return to the blood by being selectively transported through the walls of the renal tubule and into the surrounding capillaries. This process is called **reabsorption.** Most reabsorption occurs in the proximal convoluted tubule. In this region, about 75 percent of the water in the filtrate returns to the capillaries by osmosis. Glucose and minerals, such as sodium, potassium, and calcium, are returned to the blood by active transport. Some additional reabsorption occurs in the distal convoluted tubule.

When the filtrate reaches the distal convoluted tubule, some substances pass from the blood into the filtrate through a process called **secretion.** These substances include wastes and toxic materials. The pH of the blood is adjusted by hydrogen ions that are secreted from the blood into the filtrate.

Formation of Urine

The fluid and wastes that remain in the distal convoluted tubule form urine. The urine from several renal tubules flows into a collecting duct. Notice in Figure 48-17 that the urine is further concentrated in the collecting duct by the osmosis of water through the wall of the duct. This process allows the body to conserve water. In fact, osmosis in the collecting duct, together with reabsorption in other parts of the tubule, returns to the blood about 99 of every 100 mL (about 3.4 oz) of water in the filtrate.



FORMATION OF URINE

FIGURE 48-17

The sodium chloride that is actively transported out of the loop of Henle makes the extracellular environment surrounding the collecting duct hypertonic. Thus, water moves out of the collecting duct by osmosis into this hypertonic environment, increasing the concentration of urine.

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The Loop of Henle

The function of the **loop of Henle** (HEN-lee) is closely related to that of the collecting duct. Water moves out of the collecting duct because the concentration of sodium chloride is higher in the fluid surrounding the collecting duct than it is in the fluid inside the collecting duct. This high concentration of sodium chloride is created and maintained by the loop of Henle. Cells in the wall of the loop transport chloride ions from the filtrate to the fluid between the loops and the collecting duct. Positively charged sodium ions follow the chloride ions into the fluid. This process ensures that the sodium chloride concentration of the fluid between the loops and the collecting duct remains high and thus promotes the reabsorption of water from the collecting duct.

ELIMINATION OF URINE

Urine from the collecting ducts flows through the renal pelvis and into a narrow tube called a **ureter** (yoo-REET-uhr). A ureter leads from each kidney to the **urinary bladder,** a muscular sac that stores urine. Muscular contractions of the bladder force urine out of the body through a tube called the **urethra** (yoo-REE-thruh). Locate the ureters, urinary bladder, and urethra in Figure 48-18.

At least 500 mL (17 oz) of urine must be eliminated every day because this amount of fluid is needed to remove potentially toxic materials from the body and to maintain homeostasis. A normal adult eliminates from 1.5 L (1.6 qt) to 2.3 L (2.4 qt) of urine a day, depending on the amount of water taken in and the amount of water lost through respiration and perspiration.

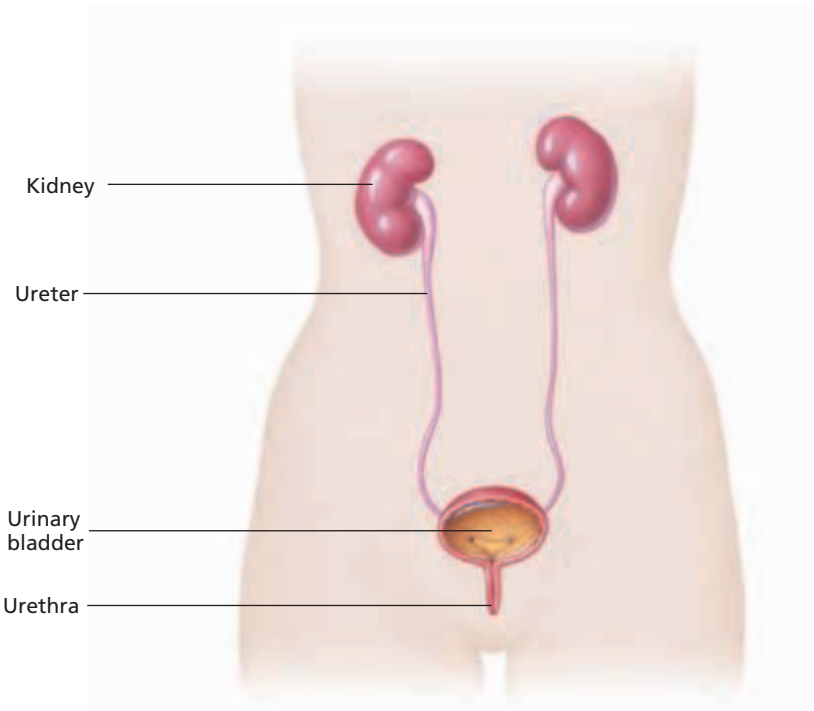

FIGURE 48-18
Urine travels from each kidney through a ureter to the urinary bladder, where it is stored until it is eliminated from the body through the urethra.

Quick Lab

Analyzing Kidney Filtration

Materials disposable gloves, lab apron, safety goggles, 20 mL of test solution, 3 test tubes, filter, beaker, 15 drops each of biuret and Benedict's solution, 2 drops IKI solution, 3 pipets, wax marker pen

Procedure

1. Put on your gloves, lab apron, and safety goggles.
2. Put 15 drops of the test solution into each of the test tubes. Label the test tubes "Protein," "Starch," and "Glucose."
3. Add 15 drops of biuret solution to the test tube labeled "Protein." Record your observations.
4. Add 15 drops of Benedict's solution to the test tube labeled "Glucose." Record your observations.
5. Add two drops of IKI solution to the test tube labeled "Starch." Record your observations.
6. Discard the tested solutions, and rinse your test tubes as your teacher directs.
7. Pour the remaining test solution through a filter into a beaker. Using the test solution from the beaker, repeat steps 3–5.

Analysis Which compounds passed through the filter paper? If some did not, explain why. How does the filtration of this activity resemble the activity of the kidney?

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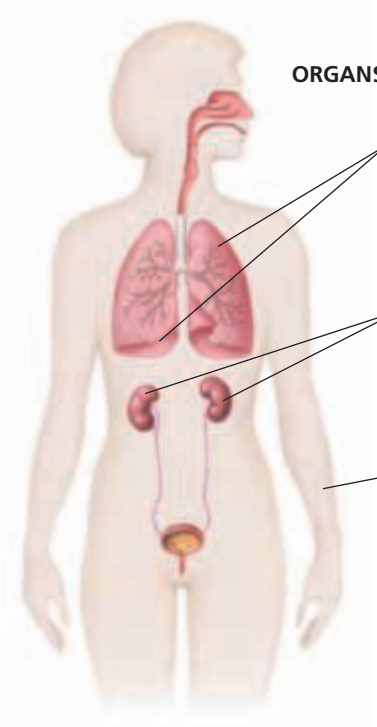

FIGURE 48-19

The lungs, the kidneys, and the skin all function as excretory organs. The main excretory products are carbon dioxide, nitrogen wastes (urea), salts, and water.

THE EXCRETORY ORGANS

Although the kidneys, lungs, and skin belong to different organ systems, they all have a common function: waste excretion.

The kidneys are the primary excretory organs of the body. They play a vital role in maintaining the homeostasis of body fluids.

The lungs are the primary site of carbon dioxide excretion. The lungs carry out detoxification, altering harmful substances so that they are not poisonous. The lungs are also responsible for the excretion of the volatile substances in onions, garlic, and other spices.

The skin helps the kidneys control the salt composition of the blood. Some salt, water, nitrogen waste and other substances are excreted through perspiration. A person working in extreme heat may lose water through perspiration at the rate of 1 L per hour. This amount of perspiration represents a loss of about 10 to 30 g of salt per day. Both the water and salt must be replenished to maintain normal body functions.

Figure 48-19 summarizes some waste substances and the organ(s) that excrete them. Notice that undigested food is not in the figure. Undigested food is not excreted in the scientific sense; it is eliminated, meaning it is expelled as feces from the body without ever passing through a membrane or being subjected to metabolic processes. The term *excretion* correctly refers to the process during which substances must pass through a membrane to leave the body.

SECTION 3 REVIEW

1. Illustrate and label the major parts of the kidney.
2. Explain how the structure of a nephron relates to its function.
3. Describe three processes carried out in the kidney that help maintain homeostasis.
4. Identify five of the structures through which urine is eliminated.
5. Explain the function of each of the organs involved in excretion.

CRITICAL THINKING

6. **Relating Concepts** Explain why a high concentration of protein in the urine may indicate damaged kidneys.
7. **Recognizing Relationships** Why would there be a decrease in urine output if a person had lost a large amount of blood?
8. **Analyzing Concepts** Given the definition of *excretion,* why do you think the large intestine is not classified as a major excretory organ?

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CHAPTER HIGHLIGHTS

SECTION 1 Nutrients

- The human body needs six nutrients—carbohydrates, proteins, lipids, vitamins, minerals, and water—to grow and function.
- Carbohydrates, found in foods such as breads, provide most of the body's energy. The body quickly processes monosaccharides. Cellulose cannot be digested but is needed for fiber.
- Proteins, found in foods such as meats, help the body grow and repair tissues. Essential amino acids must be obtained from foods.
- Lipids, found in foods such as oils, are used to build cell membranes.
- Vitamins act as coenzymes to enhance enzyme function.
- Minerals are inorganic substances used to build red blood cells and bones and for muscle and nerve functions.
- Water helps regulate body temperature and transports nutrients and wastes.

Vocabulary

nutrient (p. 979) **vitamin** (p. 982) **mineral** (p. 982) **dehydration** (p. 984)

SECTION 2 Digestive System

- Mechanical digestion involves the breaking of food into smaller particles. Chemical digestion involves changing the chemical nature of the food substance.
- The mouth, teeth, and tongue initiate mechanical digestion. Chemical digestion of carbohydrates begins in the mouth.
- The esophagus is a passageway through which food passes from the mouth to the stomach by peristalsis.
- The stomach has layers of muscles that churn the food to assist in mechanical digestion. Pepsin in the stomach begins the chemical digestion of proteins.
- Bile assists in the mechanical digestion of lipids. Enzymes secreted by the pancreas complete the digestion of the chyme.
- The digested nutrients are absorbed through the villi of the small intestine.
- The large intestine absorbs water from the undigested mass. The undigested mass is eliminated as feces through the anus.

Vocabulary

digestion (p. 985)
gastrointestinal tract (p. 985)
saliva (p. 986)
pharynx (p. 986)
epiglottis (p. 986)
peristalsis (p. 987)
gastric fluid (p. 988)
ulcer (p. 988)
cardiac sphincter (p. 988)
chyme (p. 988)
pyloric sphincter (p. 988)
gallbladder (p. 989)
villus (p. 990)
colon (p. 991)

SECTION 3 Urinary System

- Excretion is the removal of metabolic wastes from the body.
- The kidneys are the main organs of excretion and of the urinary system.
- Nephrons are the functional units of the kidneys. Through filtration, reabsorption, and secretion, they remove wastes and return nutrients and water to the blood.
- The urine passes through a ureter and is stored in the urinary bladder until it is eliminated through the urethra.
- Urine must be eliminated from the body to remove toxic materials and to maintain homeostasis.
- The lungs and the skin also play an important role in the excretion of wastes.

Vocabulary

excretion (p. 993)
renal cortex (p. 993)
renal medulla (p. 993)
renal pelvis (p. 993)
urea (p. 993)
ammonia (p. 993)
urine (p. 994)
nephron (p. 994)
Bowman's capsule (p. 994)
glomerulus (p. 994)
renal tubule (p. 995)
filtration (p. 995)
reabsorption (p. 996)
secretion (p. 996)
loop of Henle (p. 997)
ureter (p. 997)
urinary bladder (p. 997)
urethra (p. 997)

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CHAPTER REVIEW

USING VOCABULARY

1. For each set of terms, choose the one that does not belong, and explain why it does not belong.
   a. *carbohydrate, protein, lipid,* and *mineral*
   b. *pharynx, epiglottis, bolus,* and *esophagus*
   c. *cardiac sphincter, gastric pits, renal medulla,* and *pyloric sphincter*
   d. *absorption, filtration, secretion,* and *reabsorption*
2. Use the following terms in the same sentence: *gallbladder, gastric fluid, pepsin,* and *saliva.*
3. **Word Roots and Origins** The word *protein* is derived from the Greek *proteios,* which means "of prime importance." Using this information, explain why the term *protein* is a good name for the nutrient it describes.

UNDERSTANDING KEY CONCEPTS

4. **Identify** which of the six nutrients needed by the body are organic and which are inorganic.
5. **State** the daily number of servings needed from each food group in the USDA Food Guide pyramid in order to maintain a healthy diet.
6. **Propose** a vegetarian diet that includes all of the nutrients needed by the human body.
7. **Explain** the role of inorganic nutrients in keeping the body healthy.
8. **Name** the nutrient that makes up more than 90 percent of the fluid part of blood.
9. **Name** the nutrient associated with heart disease when it is consumed in high levels.
10. **List** the organs of the digestive system and their functions.
11. **Contrast** the processes involved in mechanical and chemical digestion.
12. **Describe** how the stomach carries out mechanical digestion.
13. **Identify** the source and function of each major digestive enzyme.
14. **Predict** the problems a person might have if his or her small intestine were not functioning properly.
15. **Identify** the function of the large intestine.
16. **Identify** the major parts of the kidney.
17. **Explain** the relationship between Bowman's capsule, the proximal tubule, the loop of Henle, and the distal tubule.
18. **Identify** the processes that occur in the nephron that maintain homeostasis.
19. **Summarize** how urine is stored and eliminated from the body.
20. **Describe** the function of two organs other than kidneys that are also involved in excretion.
21. **CONCEPT MAPPING** Use the following terms to create a concept map that shows the process of digestion: *bile, chemical digestion, chyme, digestion, liver, mechanical digestion, molar, pancreas, saliva, small intestine,* and *stomach.*

CRITICAL THINKING

22. **Applying Information** In some countries, many children suffer from a type of malnutrition called *kwashiorkor.* They have swollen stomachs and become increasingly thin until they die. Even when given rice and water, these children still die. What type of nutritional deficiency might these children have?
23. **Analyzing Concepts** Why is it important that the large intestine reabsorb water and not eliminate it?
24. **Predicting Patterns** The loop of Henle functions to conserve water by aiding in reabsorption. Its length varies among mammal species. Would you expect the loop of Henle of an animal such as the beaver, which lives in a watery environment, to be longer or shorter than that found in humans? Explain your answer.
25. **Recognizing Relationships** Look at the pictures of the teeth of different animals. What can you tell about the human diet by comparing the teeth of humans with those of other animals shown here?

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Standardized Test Preparation

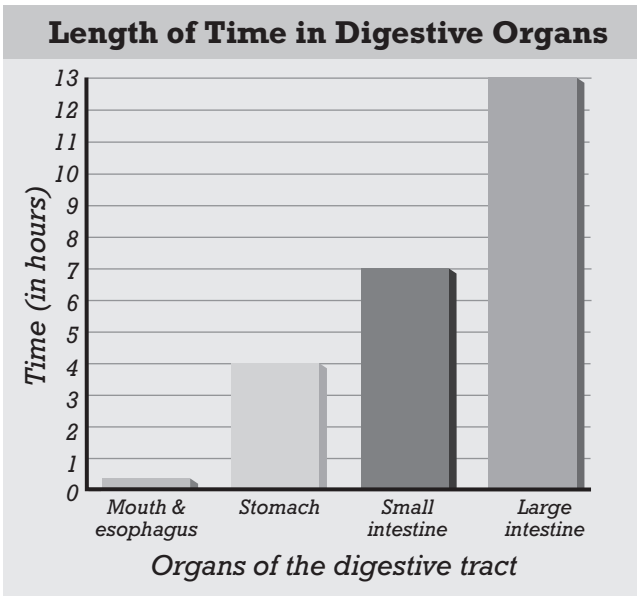
DIRECTIONS: Choose the letter of the answer choice that best answers the question.

1. What is the primary function of carbohydrates?
- **A.** to aid in digestion
- **B.** to break down molecules
- **C.** to regulate the flow of chyme
- **D.** to supply the body with energy

2. How can dehydration best be prevented?
- **F.** by perspiring
- **G.** by inhaling air
- **H.** by drinking water
- **J.** by not drinking water

3. Why is the epiglottis important?
- **A.** It regulates the flow of chyme.
- **B.** It prevents food from going down the trachea.
- **C.** It separates the pharynx from the nasal cavity.
- **D.** It is the passage through which food travels to the stomach.

INTERPRETING GRAPHICS: The graph below shows the approximate length of time food spends in each digestive organ. Use the graph below to answer the following question.

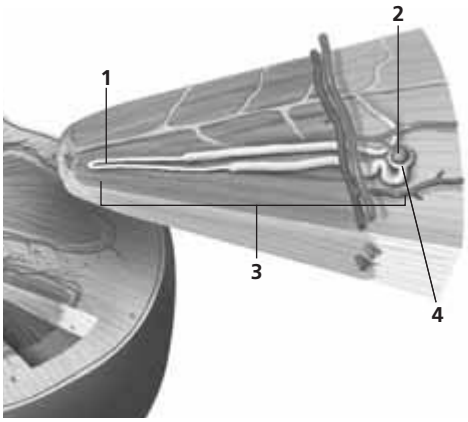


4. Bile breaks up large fat droplets. Approximately how long is the food in the digestive tract before it comes into contact with bile?
- **F.** 4 hours
- **G.** 7 hours
- **H.** 11 hours
- **J.** 13 hours

DIRECTIONS: Complete the following analogy.

5. lung : alveolus :: kidney :
- **A.** ureter
- **B.** nephron
- **C.** microvillus
- **D.** glomerulus

INTERPRETING GRAPHICS: The figure below shows a cross section of a kidney. Use the figure to answer the question that follows.



6. Which part of the model represents the loop of Henle?
- **F.** 1
- **G.** 2
- **H.** 3
- **J.** 4

SHORT RESPONSE

The liver and pancreas are accessory organs of the gastrointestinal tract.

In what two ways do the liver and pancreas differ from other digestive organs?

EXTENDED RESPONSE

When a person's kidneys stop functioning, urea builds up in the blood. For the urea to be removed, the person must be attached to a mechanical kidney, also called a dialysis machine.

Part A What would happen if the person did not have the urea removed from his or her blood?

Part B Using your understanding of how a normal kidney functions, suggest a design for the major components of a dialysis machine.

Test TIP Study of the digestive and urinary systems is often aided by drawing flowcharts of the processes described.

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Modeling Human Digestion

OBJECTIVES

- Test a model of digestion in the human stomach.

PROCESS SKILLS

- modeling
- hypothesizing
- observing
- predicting
- inferring

MATERIALS

- safety goggles
- lab apron
- glass-marking pencil
- 5 test tubes with stoppers
- test-tube rack
- scalpel
- cooked egg white
- balance
- 10 mL graduated cylinder
- 1% pepsin solution
- 0.2% hydrochloric acid
- 1% sodium bicarbonate
- distilled water
- red and blue litmus paper
- lined paper
- disposable gloves

Background

1. How is food changed from the chunks you chew with your teeth to the chyme absorbed in your small intestine?
2. What type of organic compound does the enzyme pepsin digest?

PART A Setting Up

1. Label five test tubes 1, 2, 3, 4, and 5, and place them in a test-tube rack.
2. CAUTION **Always cut in a direction away from your body.** Use a scalpel to cut a firm, cooked egg white into fine pieces.
3. Using the balance, measure and place equal amounts (about 6 g) of the fine egg white sample into each test tube, as shown in the illustration above.
4. CAUTION **Put on safety goggles and a lab apron. If you get hydrochloric acid solution on your skin or clothes, wash it off at the sink while calling to your teacher. If you get any solutions in this investigation in your eyes, immediately flush them out at the eyewash station while calling to your teacher.** Use a clean graduated cylinder to add the solutions listed below to the test tubes. Rinse the cylinder between additions so that you do not contaminate the samples.
   - test tube 1—10 mL of water
   - test tube 2—10 mL of pepsin solution
   - test tube 3—10 mL of hydrochloric acid
   - test tube 4—5 mL of pepsin solution and 5 mL of sodium bicarbonate solution
   - test tube 5—5 mL of pepsin and 5 mL of hydrochloric acid

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DEGREE OF DIGESTION OF EGG WHITE UNDER VARYING CONDITIONS

Test-tube number	Contents	pH	Degree of digestion
1	egg white 10 mL water		
2	egg white 10 mL 1% pepsin solution		
3	egg white 10 mL 0.2% hydrochloric acid solution		
4	egg white 5 mL 1% pepsin solution 5 mL 1% sodium bicarbonate solution		
5	egg white 5 mL 1% pepsin solution 5 mL 0.2% hydrochloric acid solution		

5. Stopper and gently shake each test tube.
6. In your lab report, make a data table like the one shown above.
7. In your lab report, write a hypothesis which predicts which test tube will show the most digestion after 48 hours. Explain your reasoning.
8. Label your test-tube rack with your initials. Store the test-tube rack for 48 hours at room temperature. Leave a note on the rack cautioning others not to spill the acids or bases.
9.  Clean up your lab materials, and wash your hands before leaving the lab.

PART B Recording the Results

10. After 48 hours, measure the pH of each solution with red and blue litmus paper. Record your results in the data table you created in your lab report.
11. Look for the egg white in each test tube. In your data table, describe the degree to which the egg white has broken down and dissolved in each test tube.
12.  Clean up your lab materials, and wash your hands before leaving the lab.

Analysis and Conclusions

1. What conditions caused the greatest digestion of cooked egg white?
2. Which test tube best modeled the chemical composition in the human stomach?
3. What information do test tubes 1, 2, and 3 give you? What do they control?
4. Compare test tubes 4 and 5. What can you conclude about the effects of the chemical environment on the activity of pepsin?
5. List some other foods that pepsin is likely to digest.
6. Do you think that pepsin would digest butter? Explain your answer.

Further Inquiry

Design an experiment to test the digestion of a food containing carbohydrates, such as a potato or an apple.

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