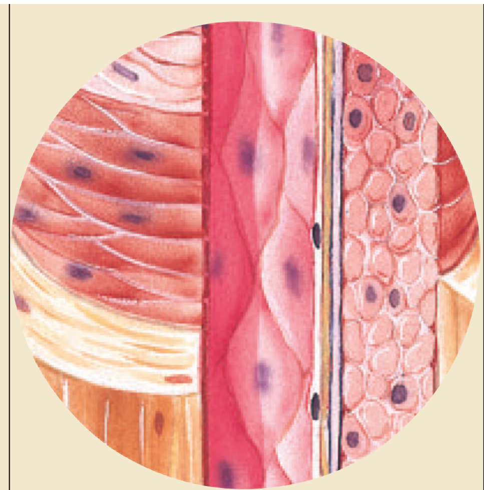
18

Materials Exchange in the Body



CHAPTER 18

Chapter Outline

Key Concepts	Applications
Understand the concept of surface area-to-volume ratio.	• Explain why cells are small. • Describe why food must be broken down into small particles. • Understand why a long small intestine is necessary for digestion and absorption.
Understand that the body must maintain a nearly constant temperature, pH, oxygen concentration, and low quantities of toxic materials.	• Understand how the circulatory, excretory, and respiratory systems interact to maintain homeostasis.
Understand that molecules enter and leave the circulatory system through a surface.	• Explain why the lungs, gut, and kidneys have large numbers of capillaries and a large surface area. • Recognize that diseases that reduce the surface area of the lungs or kidneys will impair their function.
Understand that the circulatory system transports molecules, cells, and heat.	• Explain why a strongly pumping heart and open arteries and veins are essential to good health. • Explain the significance of a clotting mechanism. • Recognize that the blood carries cells of the immune system.
Understand that the blood is under pressure and some of the liquid leaks out between the cells of the capillaries.	• Describe the significance of the lymphatic system in returning lymph to the circulatory system.
Understand the respiratory system is responsible for the exchange of oxygen and carbon dioxide.	• Describe how the processes of breathing, circulation, and exercise are interrelated. • Explain the function of breathing to oxygen and carbon dioxide exchange. • Describe how the circulatory system and respiratory system interact to maintain homeostasis.
Understand that food must be broken down to small molecules before they can enter the bloodstream.	• Explain the role of the various organs of the digestive system in the enzymatic, mechanical, and chemical digestion of foods.
Understand how the kidneys function.	• Explain why one should drink several glasses of water each day. • Describe the role of the kidneys in regulating blood pH. • Recognize that the kidneys regulate the salt and water content and water volume of the body.

18.1 Exchanging Materials: Basic Principles

Living things are complex machines with many parts that must work together in a coordinated fashion. All systems are integrated and affect one another in many ways. For example, when you run up a hill, your leg and arm muscles move in a coordinated way to provide power. They burn fuel (glucose) for energy and produce carbon dioxide and lactic acid as waste products, which tend to lower the pH of the blood. Your heart beats faster to provide oxygen and nutrients to the muscles, you breathe faster to supply the muscles with oxygen and to get rid of carbon dioxide, and the blood vessels in the muscles dilate to allow more blood to flow to them. As you run you generate excess heat. As a result, more blood flows to the skin to get rid of the heat and sweat glands begin to secrete, thus cooling the skin. All of these automatic internal adjustments help the body maintain a constant level of oxygen, carbon dioxide, and glucose in the blood; constant pH; and constant body temperature. They can be summed up in the concept of *homeostasis*. **Homeostasis** is the maintenance of a constant internal environment as a result of monitoring and modifying the functioning of various systems. To explore the various mechanisms that help organisms maintain homeostasis, we will begin at the cellular level.

Cells are highly organized units that require a constant flow of energy in order to maintain themselves. The energy they require is provided in the form of nutrient molecules that enter the cell. Oxygen is required for the efficient release of energy from the large organic molecules that serve as fuel. Inevitably, as oxidation takes place, waste products form that are useless or toxic. These must be removed from the cell. All these exchanges of food, oxygen, and waste products must take place through the cell surface.

As a cell grows its volume increases, and the amount of metabolic activity required to maintain it rises. The quantity of materials that must be exchanged between the cell and its surroundings increases. Thus growth cannot continue indefinitely. The ultimate size of a cell is limited by one or more of the following interrelated factors:

1. *The strength of the membrane:* As the cell increases in size, the membrane will eventually not be strong enough to withstand the forces caused by the mass of material inside it. If you had a balloon and kept adding water to it, eventually the balloon would burst. Similarly, dams have failed when too much water was accumulated behind them.
2. *The cell surface area:* If materials are to enter a cell they must pass through a surface. The cell membrane is a selectively permeable barrier to the passage of material in and out of the cell. The amount of surface will determine how much material can pass. If you were to pour water through two coffee filters of different size, the one with the largest surface area would allow the water to pass through more rapidly.
3. *The surface area-to-volume ratio:* The metabolic needs of a cell are determined by its volume and the ability to exchange materials between the cell and its surroundings are determined by its surface area. As a cell increases in size, its volume increases faster than its surface area. This relationship between surface area and volume is often expressed as the **surface area-to-volume ratio (SA/V).**

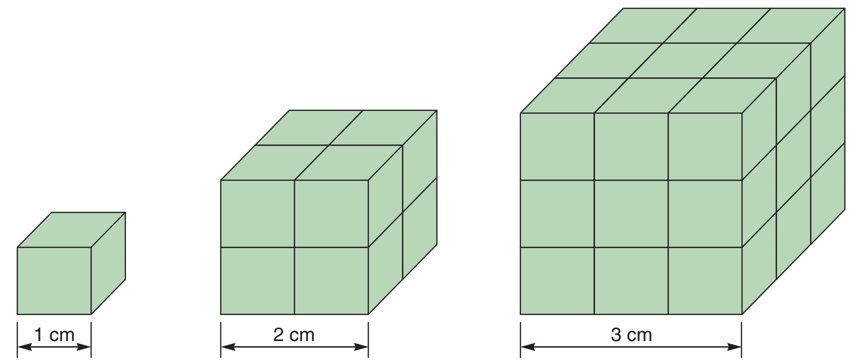
Assume that we have a cube 1 centimeter on a side, as shown in figure 18.1. This cube will have a volume of 1 cubic centimeter (1 cm^3). Each side of the cube will have a surface area of 1 square centimeter (1 cm^2) and, because there are six surfaces on a cube, it will have a total surface area of 6 square centimeters (6 cm^2). It has a surface area-to-volume ratio of 6:1 (6 cm^2 of surface to 1 cm^3 of volume). If we increase the size of the cube so that each side has an area of 4 square centimeters, the total surface area of the cube will be 24 square centimeters (6 surfaces $\times$ 4 cm^2 per square = 24 cm^2). However, the volume now becomes 8 cubic centimeters, because each side of this new, larger cube is 2 centimeters (2 cm $\times$ 2 cm $\times$ 2 cm = 8 cm^3). Therefore, the surface area-to-volume ratio is 24:8, which reduces to 3:1. So you can see that as an object increases in size its volume increases faster than its surface area.

The ability to transport materials into or out of a cell is determined by its surface area, whereas its metabolic demands are determined by its volume. So the larger a cell becomes, the more difficult it is to satisfy its needs. Some cells overcome this handicap by having highly folded cell membranes that substantially increase their surface areas. This is particularly true of cells that line the intestine or are involved in the transport of large numbers of nutrient molecules. These cells have many tiny, folded extensions of the cell membrane called **microvilli** (figure 18.2).

In a similar way, the structure of an automobile radiator increases the efficiency of heat exchange between the engine and the air. The radiator has many fins attached to tubes through which a coolant fluid is pumped. Because of the large surface area provided by the fins, heat from the engine can be efficiently radiated away.

In addition to the limitation that surface area presents to the transport of materials, large cells also have a problem with diffusion. The molecular process of diffusion is quite rapid over short distances but becomes very slow over longer distances. Diffusion is generally insufficient to handle the needs of cells if it must take place over a distance of more than 1 millimeter. The center of the cell would die before it received the molecules it needed if the distance were greater. Because of this and the problems presented by the surface area-to-volume ratio, it is understandable that the basic unit of life, the cell, must remain small.

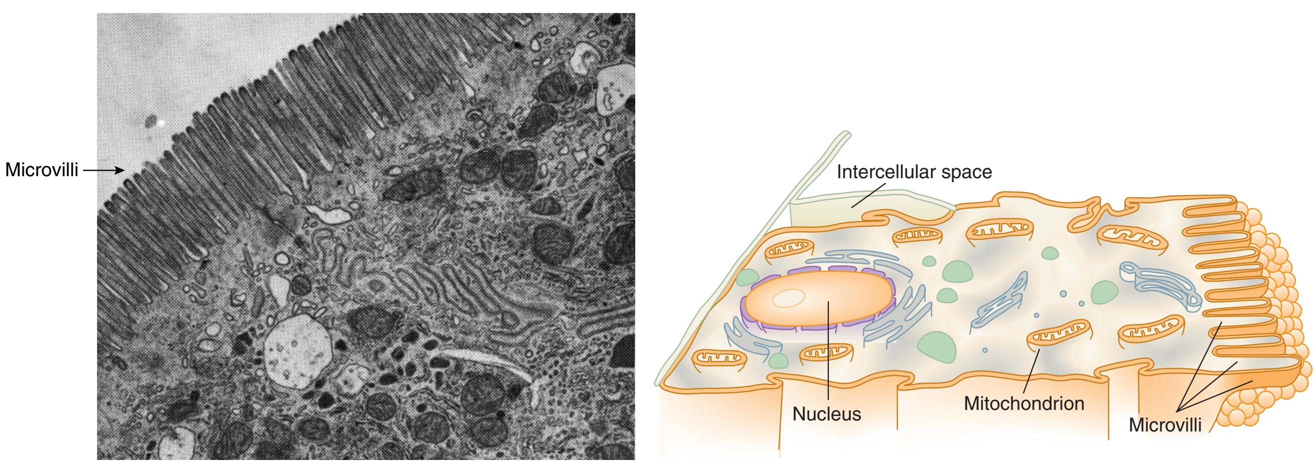
All single-celled organisms are limited to a small body size because they handle the exchange of molecules through



Surface area (length × width × number of sides)	6 cm^2	24 cm^2	54 cm^2
Volume (length × width × height)	1 cm^3	8 cm^3	27 cm^3
Surface area-to-volume ratio	6:1	3:1	2:1

Figure 18.1

The Surface Area-to-Volume Ratio
As the size of an object increases, its volume increases faster than its surface area. Therefore, the surface area-to-volume ratio decreases. The measurements shown here are for illustrative purposes only.



(a) (b)

Figure 18.2

Intestinal Cell Surface Folding
Intestinal cells that are in contact with the food in the gut have highly folded surfaces. The tiny projections of these cells are called microvilli. These can be clearly seen in the photomicrograph in (*a*). The drawing in (*b*) shows that only one surface has these projections.

their cell membranes. Large, multicellular organisms consist of a multitude of cells, many of which are located far from the surface of the organism. Each cell within a multicellular organism must solve the same materials-exchange problems as single-celled organisms. Large organisms have several interrelated systems that are involved in the exchange and transport of materials so that each cell can meet its metabolic needs. Diffusion, facilitated diffusion, and active transport are all involved in moving molecules across cell membranes. These topics are presented in chapter 4.

18.2 Circulation

Large, multicellular organisms like humans consist of trillions of cells. Because many of these cells are buried within the organism far from the body surface, there must be some sort of distribution system to assist them in solving their materials-exchange problems. The primary mechanism used is the circulatory system.

The circulatory system consists of several fundamental parts. **Blood** is the fluid medium that assists in the transport of materials and heat. The **heart** is a pump that forces the fluid blood from one part of the body to another. The heart pumps blood into **arteries,** which distribute blood to organs. It flows into successively smaller arteries until it reaches tiny vessels called **capillaries,** where materials are exchanged between the blood and tissues through the walls of the capillaries. The blood flows from the capillaries into **veins** that combine into larger veins that ultimately return the blood to the heart from the tissues.

The Nature of Blood

Blood is a fluid that consists of several kinds of cells suspended in a watery matrix called **plasma.** This fluid plasma also contains many kinds of dissolved molecules. The primary function of the blood is to transport molecules, cells, and heat from one part of the body to another. The major kinds of molecules that are distributed by the blood are respiratory gases (oxygen and carbon dioxide), nutrients of various kinds, waste products, disease-fighting antibodies, and chemical messengers (hormones). Blood has special characteristics that allow it to distribute respiratory gases very efficiently. Although little oxygen is carried as free, dissolved oxygen in the plasma, *red blood cells (RBCs)* contain **hemoglobin,** an iron-containing molecule, to which oxygen molecules readily bind. This allows for much more oxygen to be carried than could be possible if it were simply dissolved in the blood. Because hemoglobin is inside red blood cells, it is possible to assess certain kinds of health problems by counting the number of red blood cells. If the number is low, the person will not be able to carry oxygen efficiently and will tire easily. This condition, in which a person has reduced oxygen-carrying capacity, is called **anemia.** Anemia can also result when a person does not get enough iron. Because iron is a central atom in hemoglobin molecules, people with an iron deficiency are not able to manufacture sufficient hemoglobin. They can be anemic even though their number of red blood cells may be normal.

Red blood cells are also important in the transport of carbon dioxide. Carbon dioxide is produced as a result of normal aerobic respiration of food materials in the cells of the body. If it is not eliminated, it causes the blood to become more acidic (lowers its pH), eventually resulting in death. Carbon dioxide can be carried in the blood in three forms: about 7% is dissolved in the plasma, about 23% is carried attached to hemoglobin molecules, and 70% is carried as bicarbonate ions. An enzyme in red blood cells known as **carbonic anhydrase** assists in converting carbon dioxide into bicarbonate ions (HCO_3^-), which can be carried as dissolved ions in the plasma of the blood. The following reversible chemical equation shows the changes that occur.

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

When the blood reaches the lungs, dissolved carbon dioxide is lost from the plasma, and carbon dioxide is released from the hemoglobin molecules as well. In addition, the bicarbonate ions reenter the red blood cells and can be converted back into molecular carbon dioxide by the same enzyme-assisted process that converts carbon dioxide to bicarbonate ions. The importance of this mechanism will be discussed later when the exchange of gases at the lung surface is described.

Heat is also transported by the blood. Heat is generated by metabolic activities and must be lost from the body. To handle excess body heat, blood is shunted to the surface of the body, where heat can be radiated away. In addition, humans and some other animals have the ability to sweat. The evaporation of sweat from the body surface also gets rid of excess heat. If the body is losing heat too rapidly, blood flow is shunted away from the skin, and metabolic heat is conserved. Vigorous exercise produces an excess of heat so that, even in cold weather, blood is shunted to the skin and the skin feels hot.

The plasma also carries nutrient molecules from the gut to other locations where they are modified, metabolized, or incorporated into cell structures. Amino acids and simple sugars are carried as dissolved molecules in the blood. Lipids, which are not water soluble, are combined with proteins and carried as suspended particles, called lipoproteins. Most lipids do not enter the bloodstream directly from the small intestine but are carried to the bloodstream by the lymphatic system. Other organs, like the liver, manufacture or modify molecules for use elsewhere; therefore they must constantly receive raw materials and distribute their products to the cells that need them through the transportation function of the blood.

In addition, many different kinds of hormones are produced by the brain, reproductive organs, digestive organs, and glands of the body. These are secreted into the bloodstream and transported throughout the body. Tissues with appropriate receptors bind to these molecules and respond to these chemical messengers.

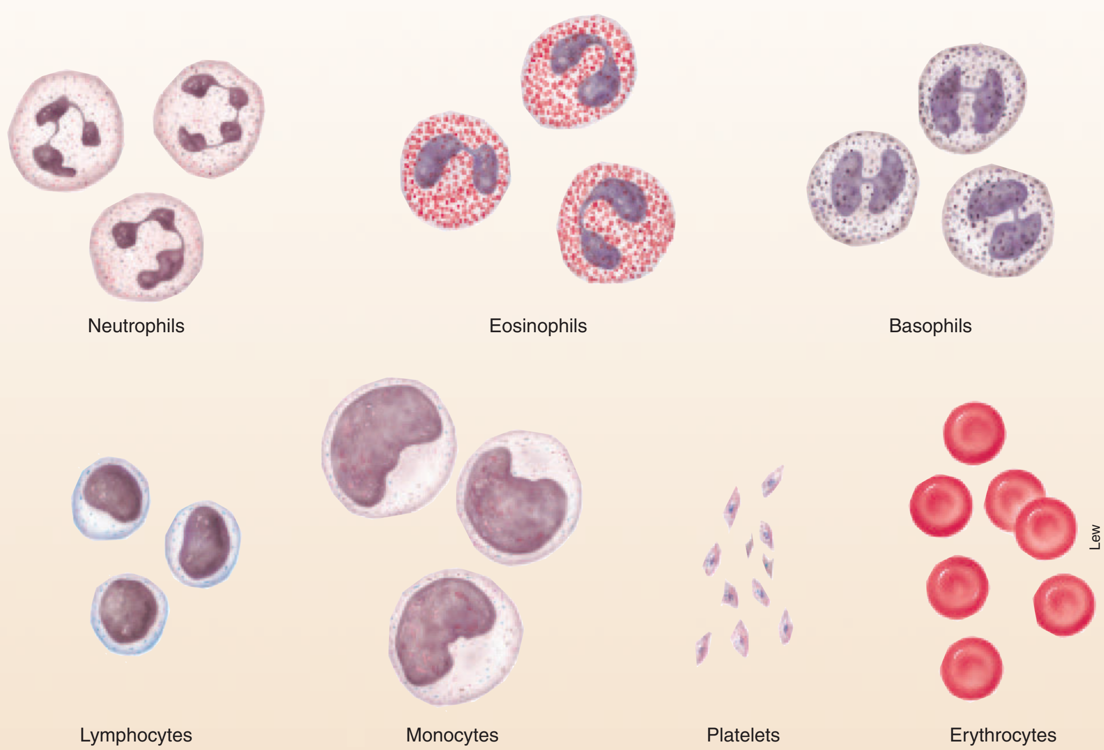
The Immune System

Table 18.1 lists the variety of cells found in blood. Whereas the red, hemoglobin-containing erythrocytes serve in the transport of oxygen and carbon dioxide, the *white blood cells (WBCs)* carried in the blood are involved in defending against harmful agents. These cells help the body resist many diseases. They constitute the core of the **immune system.** The

Table 18.1

THE COMPOSITION OF BLOOD

Component	Quantity Present	Function
Plasma	55%	Maintain fluid nature of blood
Water	91.5%	
Protein	7.0%	
Other materials	1.5%	
Cellular material	45%	
Red blood cells (erythrocytes)	4.3–5.8 million/mm^3	Carry oxygen and carbon dioxide
White blood cells (leukocytes)	5–9 thousand/mm^3	Immunity
Lymphocytes	25%–30% of white cells present	
Monocytes	3%–7% of white cells present	
Neutrophils	57%–67% of white cells present	
Eosinophils	1%–3% of white cells present	
Basophils	less than 1% of white cells present	
Platelets	250–400 thousand/mm^3	Clotting



various WBCs participate in providing immunity in several ways. First, immune system cells are able to recognize cells and molecules that are foreign to the body. If a molecule is recognized as foreign, certain WBCs produce *antibodies (immunoglobulins)* that attach to the foreign materials. The foreign molecules that stimulate the production of antibodies are called *antigens (immunogens)*. When harmful microorganisms (e.g., bacteria, viruses, fungi), cancer cells, or toxic molecules enter the body, other WBCs (1) recognize, (2) boost their abilities to respond to, (3) move toward, and (4) destroy the problem causers. *Neutrophils, eosinophils, basophils,* and *monocytes* are specific kinds of WBCs capable of engulfing foreign material, a process called phagocytosis. Thus they are often called *phagocytes*. Although most can move from the bloodstream into the surrounding tissue, monocytes undergo such a striking increase in size that they are given a different name—*macrophages*. Macrophages can be found throughout the body and are the most active of the phagocytes.

The other major type of white cells, *lymphocytes,* work with phagocytes to provide protection. The two major types are *T-lymphocytes (T-cells)* and *B-lymphocytes (B-cells).* T-cells are involved in a cell-mediated immune response in which cells directly attack potentially dangerous objects. This highly complex response involves the release of chemical messengers that coordinate the response, an increase in the population of T-cells and B-cells, and stimulation of B-cell and macrophage activities. Some T-cells are capable of killing dangerous cells by destroying their cell membranes. T-cells are primarily involved in fighting infections of viruses, fungi, protozoa, worms, and cancer cells.

B-cells are involved in antibody-mediated immunity in which B-cells produce antibody molecules that are released into the bloodstream and are distributed to all parts of the body. These antibodies attach to the foreign molecules, causing them to clump together. This clumping may destroy their harmful properties, make them more susceptible to chemical attack, or make them more recognizable for phagocytes. Many kinds of diseases caused by viruses and bacteria are controlled by antibodies produced by B-cells.

Another kind of cellular particle in the blood is the platelet. These are fragments of specific kinds of white blood cells and are important in blood clotting. They collect at the site of a wound where they break down, releasing molecules. This begins a series of reactions that results in the formation of fibers that trap blood cells and form a plug in the opening of the wound.

The Heart

Blood can perform its transportation function only if it moves. The organ responsible for providing the energy to pump the blood is the heart. In order for a fluid to flow through a tube, there must be a pressure difference between the two ends of the tube. Water flows through pipes because it is under pressure. Because the pressure is higher behind a faucet than at the spout, water flows from the spout when the faucet is opened. The circulatory system can be analyzed from the same point of view. The heart is a muscular pump that provides the pressure necessary to propel the blood throughout the body. It must continue its cycle of contraction and relaxation, or blood stops flowing and body cells are unable to obtain nutrients or get rid of wastes. Some cells, such as brain cells, are extremely sensitive to having their flow of blood interrupted because they require a constant supply of glucose and oxygen. Others, such as muscle cells or skin cells, are much better able to withstand temporary interruptions of blood flow.

The hearts of humans, other mammals, and birds consist of four chambers and four sets of valves that work together to ensure that blood flows in one direction only. Two of these chambers, the right and left **atria** (singular, *atrium*), are relatively thin-walled structures that collect blood from the major veins and empty it into the larger, more muscular ventricles (figure 18.3). Most of the flow of blood from the atria to the ventricles is caused by the lowered pressure produced within the ventricles as they relax. The contraction of the thin-walled atria assists in emptying them more completely.

The right and left **ventricles** are chambers that have powerful muscular walls whose contraction forces blood to flow through the arteries to all parts of the body. The valves between the atria and ventricles, known as **atrioventricular valves,** are important one-way valves that allow the blood to flow from the atria to the ventricles but prevent flow in the opposite direction. Similarly, there are valves in the aorta and pulmonary artery, known as **semilunar valves.** The **aorta** is the large artery that carries blood from the left ventricle to the body, and the **pulmonary artery** carries blood from the right ventricle to the lungs. The semilunar valves prevent blood from flowing back into the ventricles. If the atrioventricular or semilunar valves are damaged or function improperly, the efficiency of the heart as a pump is diminished, and the person may develop an enlarged heart or other symptoms. Malfunctioning heart valves are often diagnosed because they cause abnormal sounds as the blood passes through them. These sounds are referred to as heart murmurs. Similarly, if the muscular walls of the ventricles are weakened because of infection, damage from a heart attack, or lack of exercise, the pumping efficiency of the heart is reduced and the person develops symptoms that may include chest pain, shortness of breath, or fatigue. The pain is caused by an increase in the amount of lactic acid in the muscle because the heart muscle is not getting sufficient blood to satisfy its needs. It is important to understand that the muscle of the heart receives blood from coronary arteries that are branches of the aorta. It is not nourished by the blood that flows through its chambers. If heart muscle does not get sufficient oxygen for a period of time, the portion of the heart muscle not receiving blood dies. Shortness of breath and fatigue result because the heart is not able to pump blood efficiently to the lungs, muscles, and other parts of the body.

The right and left sides of the heart have slightly different jobs because they pump blood to different parts of the body. The right side of the heart receives blood from the general body and pumps it through the pulmonary arteries to the lungs, where exchange of oxygen and carbon dioxide takes place and the blood returns from the lungs to the left atrium. This is called **pulmonary circulation.** The larger, more powerful left side of the heart receives blood from the lungs, delivers it through the aorta to all parts of the body, and returns it to the right atrium by way of veins. This is known as **systemic circulation.** Both circulatory pathways are shown in figure 18.4. The systemic circulation is responsible for gas, nutrient, and waste exchange in all parts of the body except the lungs.

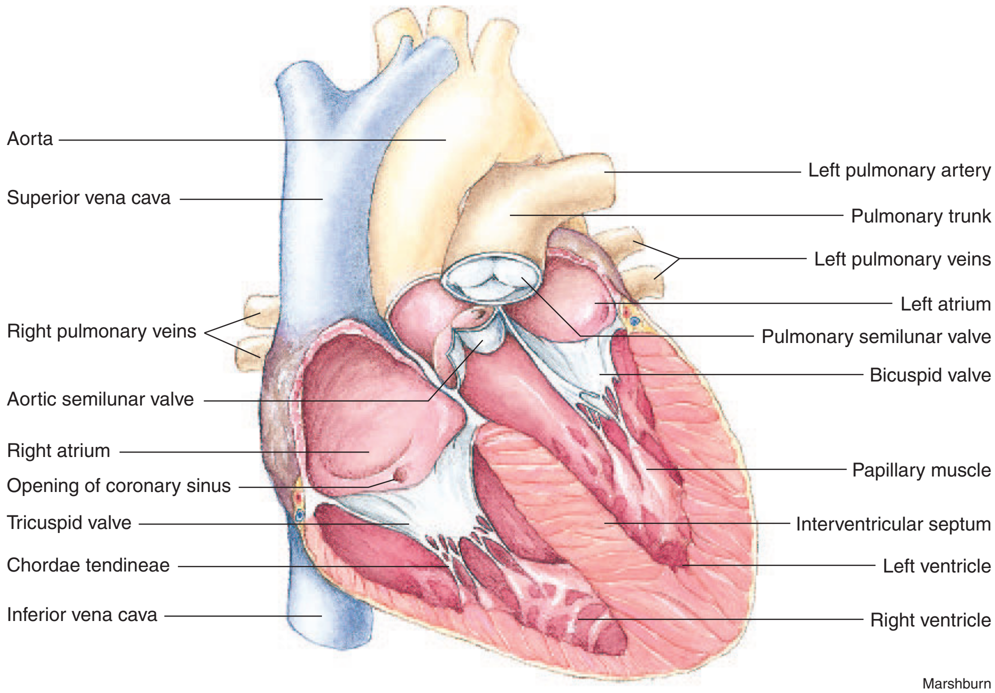


Figure 18.3

The Anatomy of the Heart
The heart consists of two thin-walled chambers called atria that contract to force blood into the two ventricles. When the ventricles contract, the atrioventricular valves (bicuspid and tricuspid) close, and blood is forced into the aorta and pulmonary artery. Semilunar valves in the aorta and pulmonary artery prevent the blood from flowing back into the ventricles when they relax.

Arteries and Veins

Arteries and veins are the tubes that transport blood from one place to another within the body. Figure 18.5 compares the structure and function of arteries and veins. Arteries carry blood away from the heart because it is under considerable pressure from the contraction of the ventricles. The contraction of the walls of the ventricles increases the pressure in the arteries. A typical pressure recorded in a large artery while the heart is contracting is about 120 millimeters of mercury. This is known as the **systolic blood pressure.** The pressure recorded while the heart is relaxing is about 80 millimeters of mercury. This is known as the **diastolic blood pressure.** A blood pressure reading includes both numbers and is recorded as 120/80. (Originally, blood pressure was measured by how high the pressure of the blood would cause a column of mercury [Hg] to rise in a tube. Although the devices used today have dials or digital readouts and contain no mercury, they are still calibrated in mmHg.)

The walls of arteries are relatively thick and muscular, yet elastic. Healthy arteries have the ability to expand as blood is pumped into them and return to normal as the pressure drops. This ability to expand absorbs some of the pressure and reduces the peak pressure within the arteries, thus reducing the likelihood that they will burst. If arteries become hardened and less resilient, the peak blood pressure rises and they are more likely to rupture. The elastic nature of the arteries is also responsible for assisting the flow of blood. When they return to normal from their stretched condition they give a little push to the blood that is flowing through them.

Blood is distributed from the large aorta through smaller and smaller blood vessels to millions of tiny capillaries. Some of the smaller arteries, called **arterioles,** may contract or relax to regulate the flow of blood to specific parts of the body. Major parts of the body that receive differing amounts of blood, depending on need, are the digestive system, muscles, and skin. When light-skinned people *blush,* it is because many arterioles in the skin have expanded, allowing a large volume of blood to flow to the capillaries of the skin. Because the blood is red, their skin reddens. Similarly, when people exercise, there is an increased blood flow to muscles to accommodate their increased metabolic needs for oxygen and glucose and to get rid of wastes. Exercise also

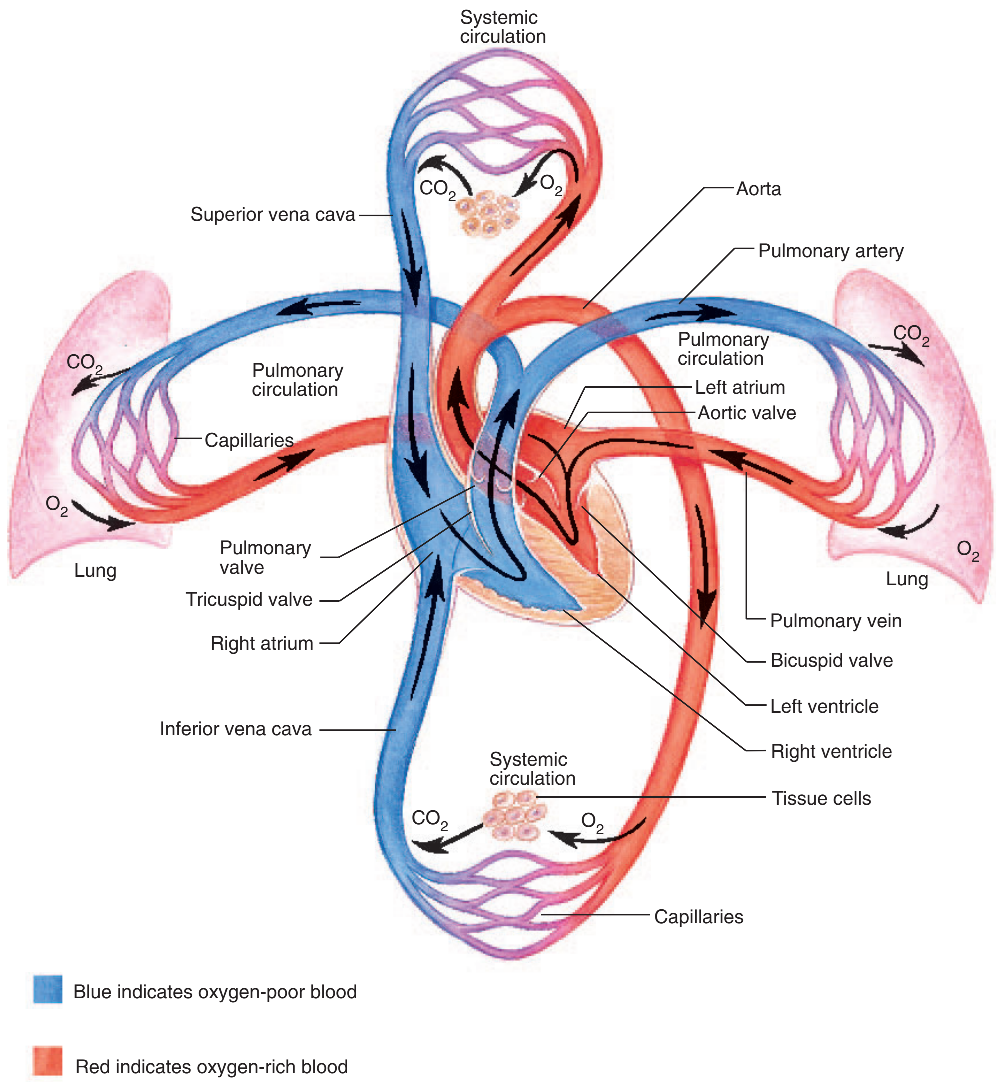


Figure 18.4

Pulmonary and Systemic Circulation

The right ventricle pumps blood that is poor in oxygen to the two lungs by way of the pulmonary arteries, where it receives oxygen and turns bright red. The blood is then returned to the left atrium by way of four pulmonary veins. This part of the circulatory system is known as pulmonary circulation. The left ventricle pumps oxygen-rich blood by way of the aorta to all parts of the body except the lungs. This blood returns to the right atrium, depleted of its oxygen, by way of the superior vena cava from the head region and the inferior vena cava from the rest of the body. This portion of the circulatory system is known as systemic circulation.

results in an increased flow of blood to the skin, which allows for heat loss. At the same time, the amount of blood flowing to the digestive system is reduced. Athletes do not eat a full meal before exercising because the additional flow of blood to the digestive system reduces the amount of blood available to go to muscles and lungs needed for vigorous exercise. Muscular cramps may result if insufficient blood is getting to the muscles.

Veins collect blood from the capillaries and return it to the heart. The pressure in these blood vessels is very low. Some of the largest veins may have a blood pressure of 0.0 mmHg for brief periods. The walls of veins are not as muscular as those of arteries. Because of the low pressure, veins must have valves that prevent the blood from flowing backward, away from the heart. Veins are often found at the surface of the body and are seen as blue lines. *Varicose veins* result when veins contain faulty valves that do not allow efficient return of blood to the heart. Therefore, blood pools in these veins, and they become swollen bluish networks.

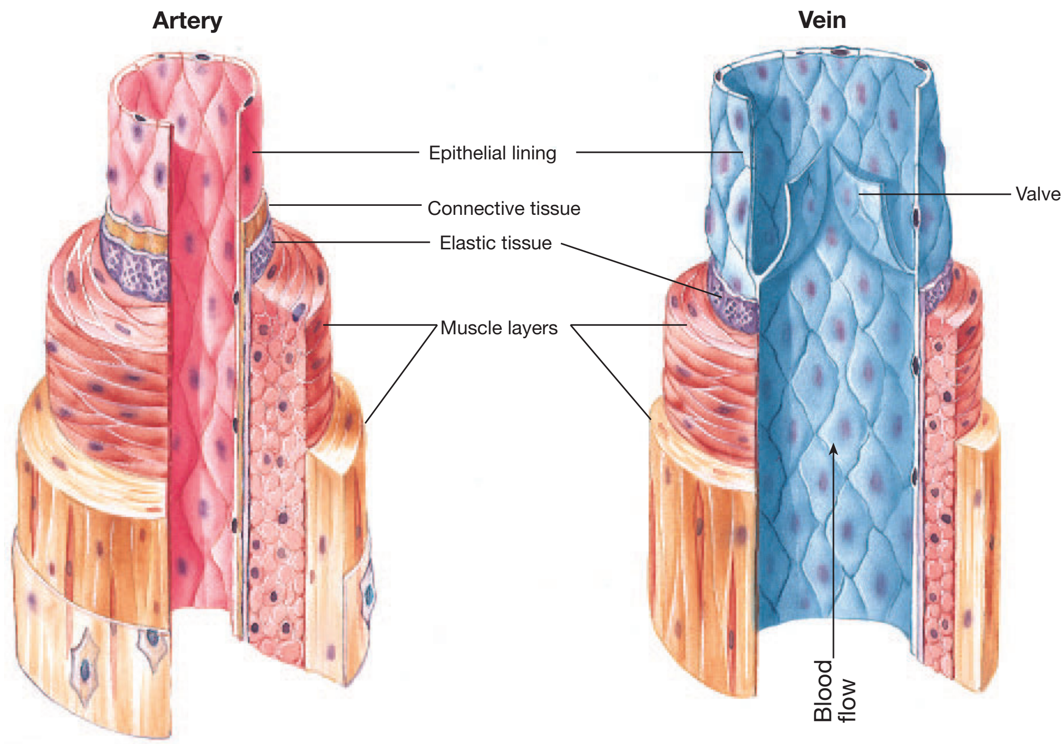


Figure 18.5

The Structure of Arteries and Veins
The walls of arteries are much thicker than the walls of veins. (The pressure in arteries is much higher than the pressure in veins.) The pressure generated by the ventricles of the heart forces blood through the arteries. Veins often have very low pressure. The valves in the veins prevent the blood from flowing backward, away from the heart.

Because pressure in veins is so low, muscular movements of the body are important in helping return blood to the heart. When muscles of the body contract, they compress nearby veins, and this pressure pushes blood along in the veins. Because the valves allow blood to flow only toward the heart, this activity acts as an additional pump to help return blood to the heart. People who sit or stand for long periods without using their leg muscles tend to have a considerable amount of blood pool in the veins of their legs and lower body. Thus less blood may be available to go to the brain and the person may faint.

Although the arteries are responsible for distributing blood to various parts of the body and arterioles regulate where blood goes, it is the function of capillaries to assist in the exchange of materials between the blood and cells.

Capillaries

Capillaries are tiny, thin-walled tubes that receive blood from arterioles. They are so small that red blood cells must go through them in single file. They are so numerous that each cell in the body has a capillary located near it. It is estimated that there are about 1,000 square meters of surface area represented by the capillary surface in a typical human. Each capillary wall consists of a single layer of cells and therefore presents only a thin barrier to the diffusion of materials between the blood and cells. It is also possible for liquid to flow through tiny spaces between the individual cells of most capillaries (figure 18.6). The flow of blood through these smallest blood vessels is relatively slow. This allows time for the diffusion of such materials as oxygen, glucose, and water from the blood to surrounding cells, and for the movement of such materials as carbon dioxide, lactic acid, and ammonia from the cells into the blood.

In addition to molecular exchange, considerable amounts of water and dissolved materials leak through the small holes in the capillaries. This liquid is known as **lymph.** Lymph is produced when the blood pressure forces water and some small dissolved molecules through the walls of the capillaries. Lymph bathes the cells but must eventually be returned to the circulatory system by lymph vessels or swelling will occur. Return is accomplished by the **lymphatic system,** a collection of thin-walled tubes that branch throughout the body. These tubes collect lymph that is filtered from

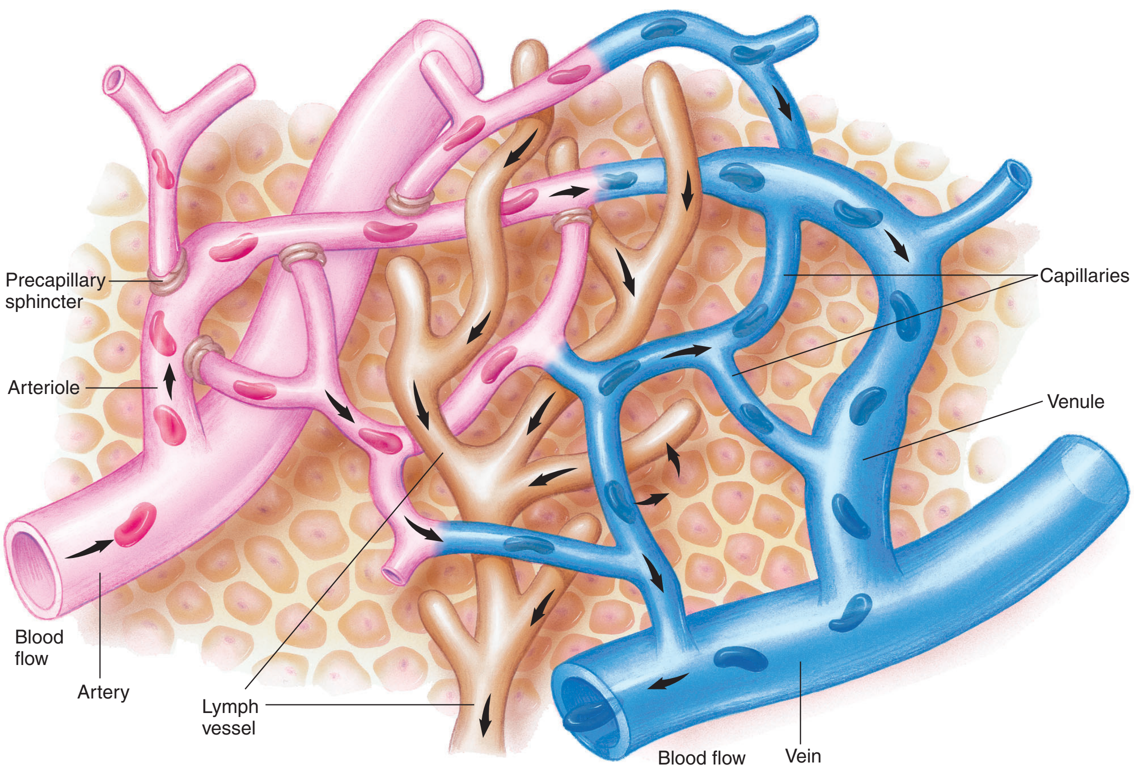


Figure 18.6

Capillaries
Capillaries are tiny blood vessels. Exchange of cells and molecules can occur between blood and tissues through their thin walls. Molecules diffuse in and out of the blood, and cells such as monocytes can move from the blood through the thin walls into the surrounding tissue. There is also a flow of liquid through holes in the capillary walls. This liquid, called lymph, bathes the cells and eventually enters small lymph vessels that return lymph to the circulatory system near the heart.

the circulatory system and ultimately empty it into major blood vessels near the heart. As the lymph makes its way back to the circulatory system, it is filtered by lymph nodes that contain large numbers of white blood cells that remove microorganisms and foreign particles. There are many lymph nodes located throughout the body. The tonsils and adenoids are large masses of lymph node tissue. The spleen also contains large numbers of white blood cells and serves to filter the blood. The thymus gland is located over the breastbone and is large and active in children. Its primary function is to produce T-lymphocytes that are distributed throughout the body and establish themselves in lymph nodes. The thymus shrinks in size in adulthood, but the descendants of the T-lymphocytes it produced earlier in life are still active throughout the lymphatic system. Figure 18.7 shows the structure of the lymphatic system.

Some of this leakage through the capillary walls is normal, but the flow is subject to changes in pressure inside the capillaries and in the tissues, and changes in the permeability of the capillary wall. If pressure inside the capillary increases, more fluid may leak from the capillaries into the tissues and cause swelling. This swelling is called *edema*, and it is common in circulatory disorders. Another cause of edema is an increase in the permeability of the capillaries. This is commonly associated with injury to a part of the body: A sprained ankle or smashed thumb are examples you have probably experienced.

18.3 Gas Exchange

The lungs demonstrate this interplay between blood flow, capillary exchange, and surface area.

Respiratory Anatomy

The **lungs** are organs of the body that allow gas exchange to take place between the air and blood. Associated with the lungs is a set of tubes that conducts air from outside the body to the lungs. The single large-diameter **trachea** is supported

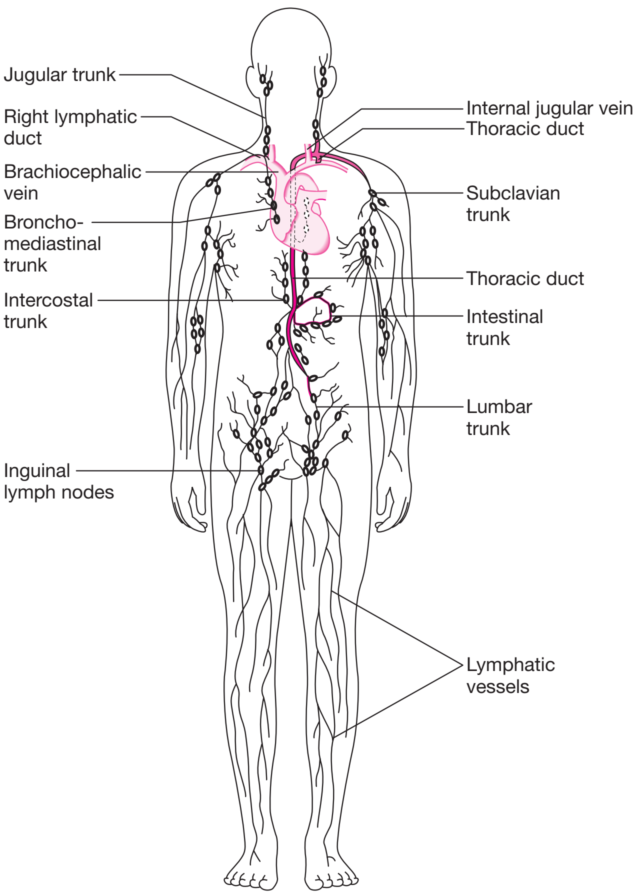


Figure 18.7

The Lymphatic System
The lymphatic system consists of many ducts that transport lymph fluid back toward the heart. Along the way the lymph is filtered in the lymph nodes, and bacteria and other foreign materials are removed before the lymph is returned to the circulatory system near the heart.

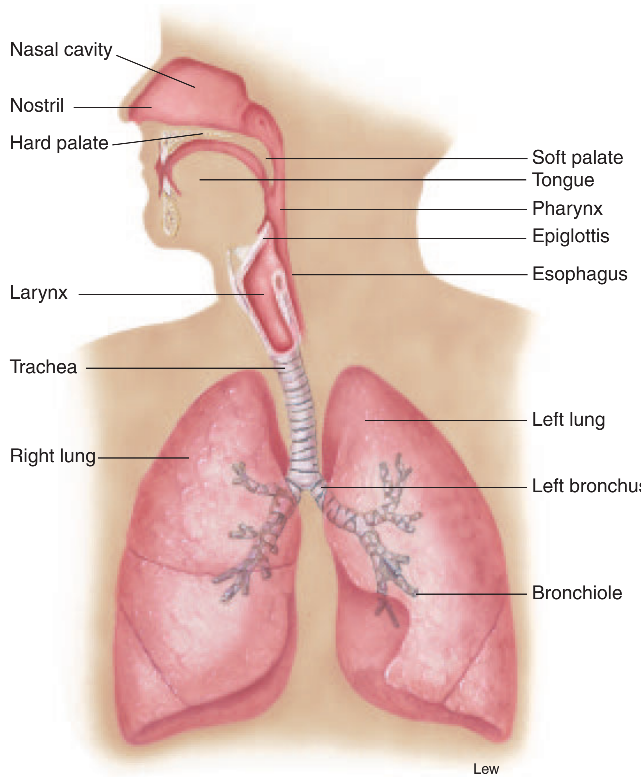


Figure 18.8

Respiratory Anatomy
Although the alveoli of the lungs are the places where gas exchange takes place, there are many other important parts of the respiratory system. The nasal cavity cleans, warms, and humidifies the air entering the lungs. The trachea is also important in cleaning the air going to the lungs.

by rings of cartilage that prevent its collapse. It branches into two major **bronchi** (singular, *bronchus*) that deliver air to smaller and smaller branches. Bronchi are also supported by cartilage. The smallest tubes, known as **bronchioles,** contain smooth muscle and are therefore capable of constricting. Finally, the bronchioles deliver air to clusters of tiny sacs, known as **alveoli** (singular, *alveolus*), where the exchange of gases takes place between the air and blood.

The nose, mouth, and throat are also important parts of the air-transport pathway because they modify the humidity and temperature of the air and clean the air as it passes. The lining of the trachea contains cells with cilia that beat in a direction to move mucus and foreign materials from the lungs. The foreign matter may then be expelled by swallowing, coughing, or other means. Figure 18.8 illustrates the various parts of the respiratory system.

Breathing System Regulation

Breathing is the process of moving air in and out of the lungs. It is accomplished by the movement of a muscular organ known as the **diaphragm,** which separates the chest cavity and the lungs from the abdominal cavity. In addition, muscles located between the ribs (*intercostal* muscles) are attached to the ribs in such a way that their contraction causes the chest wall to move outward and upward, which increases the size of the chest cavity. During inhalation, the diaphragm moves downward and the external intercostal muscles of the chest wall contract, causing the volume of the chest cavity to increase. This results in a lower pressure in the chest cavity compared to the outside air pressure. Consequently, air flows

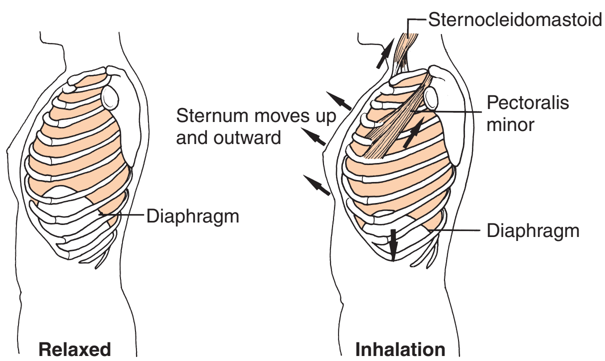


Figure 18.9

Breathing Movements
During inhalation, the diaphragm and external intercostal muscles between the ribs contract, causing the volume of the chest cavity to increase. During a normal exhalation, these muscles relax, and the chest volume returns to normal.

from the outside high-pressure area through the trachea, bronchi, and bronchioles to the alveoli. During normal relaxed breathing, exhalation is accomplished by the chest wall and diaphragm simply returning to their normal, relaxed positions. Muscular contraction is not involved (figure 18.9).

However, when the body's demand for oxygen increases during exercise, the only way that the breathing system can respond is by exchanging the gases in the lungs more rapidly. This can be accomplished both by increasing the breathing rate and by increasing the volume of air exchanged with each breath. Increase in volume exchanged per breath is accomplished in two ways. First, the muscles of inhalation can contract more forcefully, resulting in a greater change in the volume of the chest cavity. In addition, the lungs can be emptied more completely by contracting the muscles of the abdomen, which forces the abdominal contents upward against the diaphragm and compresses the lungs. A set of internal intercostal muscles also helps compress the chest. You are familiar with both mechanisms: When you exercise you breathe more deeply and more rapidly.

Several mechanisms can cause changes in the rate and depth of breathing, but the primary mechanism involves the amount of carbon dioxide present in the blood. Carbon dioxide is a waste product of aerobic cellular respiration and becomes toxic in high quantities because it combines with water to form carbonic acid:

$$CO_2 + H_2O \longrightarrow H_2CO_3$$

As mentioned previously, if carbon dioxide cannot be eliminated, the pH of the blood is lowered. Eventually, this may result in death.

Exercising causes an increase in the amount of carbon dioxide in the blood because muscles are oxidizing glucose more rapidly. This lowers the pH of the blood. Certain brain cells and specialized cells in the aortic arch and carotid arteries are sensitive to changes in blood pH. When they sense a lower blood pH, nerve impulses are sent more frequently to the diaphragm and intercostal muscles. These muscles contract more rapidly and more forcefully, resulting in more rapid, deeper breathing. Because more air is being exchanged per minute, carbon dioxide is lost from the lungs more rapidly. When exercise stops, blood pH rises, and breathing eventually returns to normal (figure 18.10). Bear in mind, however, that moving air in and out of the lungs is of no value unless oxygen is diffusing into the blood and carbon dioxide is diffusing out.

Lung Function

The lungs are organs that allow blood and air to come in close contact with each other. Air flows in and out of the lungs during breathing. The blood flows through capillaries in the lungs and is in close contact with the air in the cavities of the lungs. For oxygen to enter the body or carbon dioxide to exit the body the molecules must pass through a surface. The efficiency of exchange is limited by the surface area available. This problem is solved in the lungs by the large number of tiny sacs, the alveoli. Each alveolus is about 0.25 to 0.5 millimeters across. However, alveoli are so numerous that the total surface area of all these sacs is about 70 square meters—comparable to the floor space of many standard-sized classrooms! Associated with these alveoli are large numbers of capillaries (figure 18.11). The walls of both the capillaries and alveoli are very thin, and the close association of alveoli and capillaries in the lungs allows the easy diffusion of oxygen and carbon dioxide across these membranes.

Another factor that increases the efficiency of gas exchange is that both the blood and air are moving. Because blood is flowing through capillaries in the lungs, the capillaries continually receive new blood that is poor in oxygen and high in carbon dioxide. As blood passes by the alveoli, it is briefly exposed to the gases in the alveoli, where it gains oxygen and loses carbon dioxide. Thus, blood that leaves the lungs is high in oxygen and low in carbon dioxide. Although the movement of air in the lungs is not in one direction, as is the case with blood, the cycle of inhalation and exhalation allows air that is high in carbon dioxide and low in oxygen to exit the body and brings in new air that is rich in oxygen and low in carbon dioxide. This oxygen-rich blood is then sent to the left side of the heart and pumped throughout the body.

Any factor that interferes with the flow of blood or air or alters the effectiveness of gas exchange in the lungs reduces the efficiency of the organism. A poorly pumping heart sends less blood to the lungs, and the person experiences shortness of breath as a symptom. Similarly, diseases like *asthma,* which causes constriction of the bronchioles,

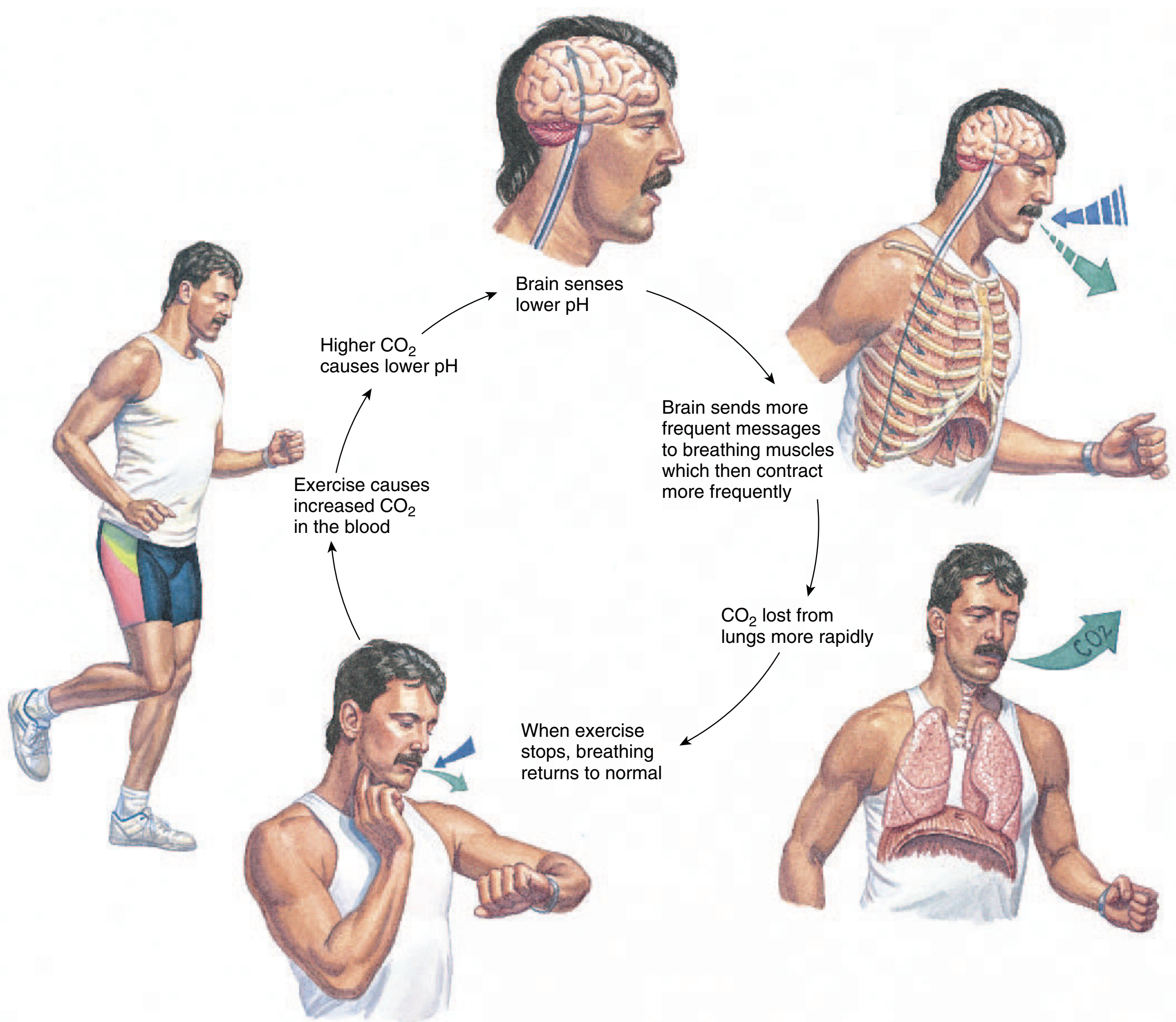


Figure 18.10

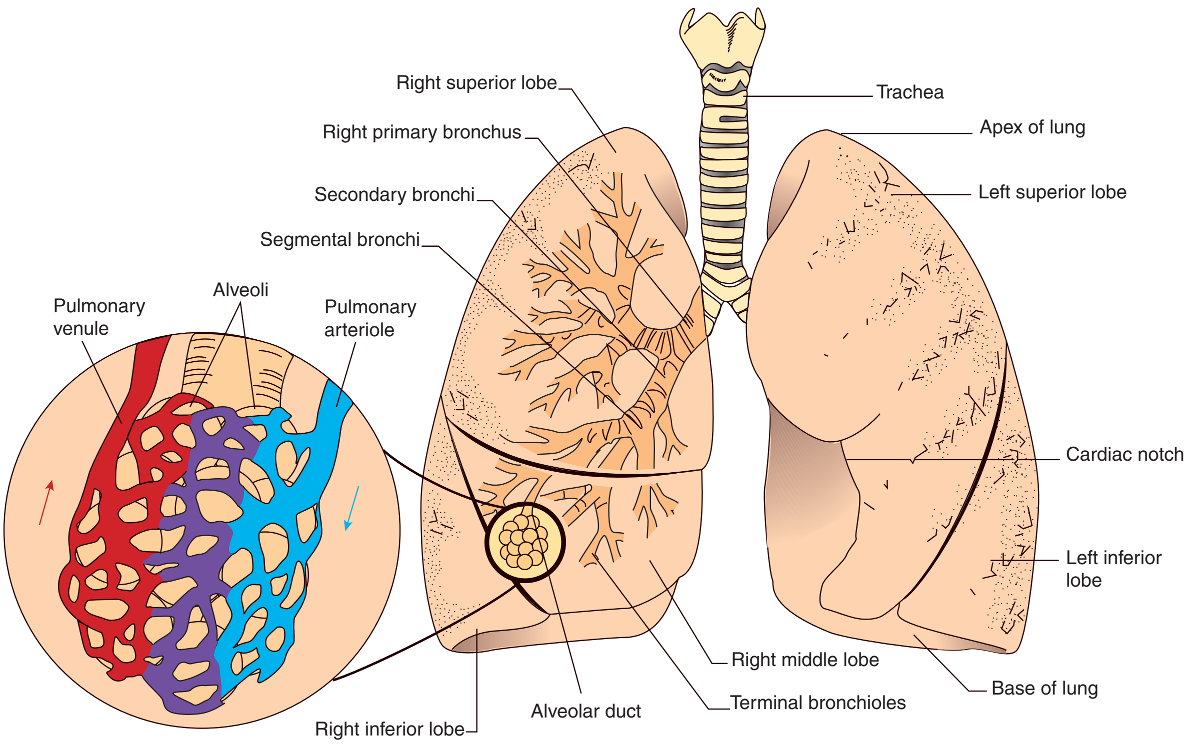
The Control of Breathing Rate

The rate of breathing is controlled by specific cells in the brain that sense the pH of the blood. When the amount of CO_2 increases, the pH drops (becomes more acid) and the brain sends more frequent messages to the diaphragm and intercostal muscles, causing the breathing rate to increase. More rapid breathing increases the rate at which CO_2 is lost from the blood; thus the blood pH rises (becomes less acid) and the breathing rate decreases.

reduce the flow of air into the lungs and inhibit gas exchange.

Any process that reduces the number of alveoli will also reduce the efficiency of gas exchange in the lungs. *Emphysema* is a progressive disease in which some of the alveoli are lost. As the disease progresses, those afflicted have less and less respiratory surface area and experience greater and greater difficulty getting adequate oxygen, even though they may be breathing more rapidly. Often emphysema is accompanied by an increase in the amount of connective tissue and the lungs do not stretch as easily, further reducing the ability to exchange gases.

The breathing mechanism is designed to get oxygen into the bloodstream so that it can be distributed to the cells that are carrying on the oxidation of food molecules, such as glucose and fat. Obtaining food molecules involves a variety of organs and activities associated with the digestive system.



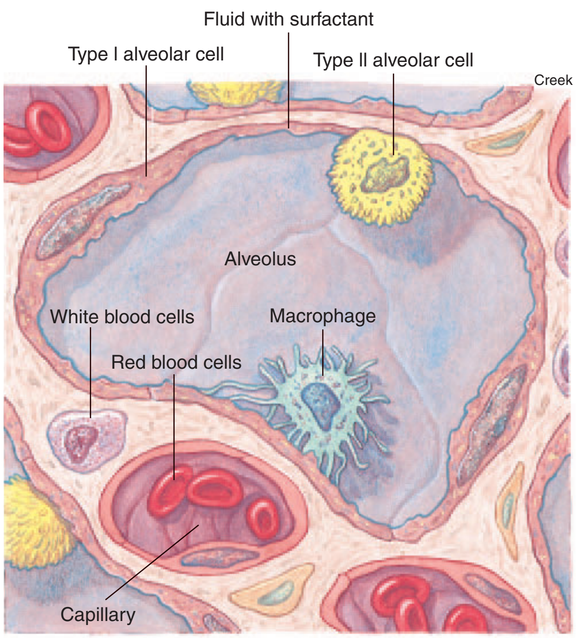


Figure 18.11

The Association of Capillaries with Alveoli
The exchange of gases takes place between the air-filled alveolus and the blood-filled capillary. The capillaries form a network around the saclike alveoli. The thin walls of the alveolus and capillary are in direct contact with one another; their combined thickness is usually less than 1 micrometer (a thousandth of a millimeter).

18.4 Obtaining Nutrients

All cells must have a continuous supply of nutrients that provides the energy they require and the building blocks needed to construct the macromolecules typical of living things. The specific functions of various kinds of nutrients are discussed in chapter 19. This section will deal with the processing and distribution of different kinds of nutrients.

The digestive system consists of a muscular tube with several specialized segments. In addition, there are glands that secrete digestive juices into the tube. Four different kinds of activities are involved in getting nutrients to the cells that need them: mechanical processing, chemical processing, nutrient uptake, and chemical alteration.

Mechanical and Chemical Processing

The digestive system is designed as a disassembly system. Its purpose is to take large chunks of food and break them down to smaller molecules that can be taken up by the circulatory system and distributed to cells. The first step in this process is mechanical processing.

It is important to grind large particles into small pieces by chewing in order to increase their surface areas and allow for more efficient chemical reactions. It is also important to add water to the food, which further disperses the particles and provides the watery environment needed for these chemical reactions. Materials must also be mixed so that all the molecules that need to interact with one another have a good chance of doing so. The oral cavity and the stomach are the major body regions involved in reducing the size of food particles. The teeth are involved in cutting and grinding food to increase its surface area. This is another example of the surface area-to-volume concept presented at the beginning of this chapter. The watery mixture that is added to the food in the oral cavity is known as *saliva,* and the three pairs of glands that produce saliva are known as **salivary glands.** Saliva contains the enzyme **salivary amylase,** which initiates the chemical breakdown of starch. Saliva also lubricates the oral cavity and helps bind food before swallowing.

In addition to having taste buds that help identify foods, the tongue performs the important service of helping position the food between the teeth and pushing it to the back of the throat for swallowing. The oral cavity is very much like a food processor in which mixing and grinding take place. Figure 18.12 describes and summarizes the functions of these structures.

Once the food has been chewed, it is swallowed and passes down the esophagus to the stomach. The process of swallowing involves a complex series of events. First, a ball of food, known as a *bolus,* is formed by the tongue and moved to the back of the mouth cavity. Here it stimulates the walls of the throat, also known as the **pharynx.** Nerve endings in the lining of the pharynx are stimulated, causing a reflex contraction of the walls of the esophagus, which transports the bolus to the stomach. Because both food and air pass through the pharynx, it is important to prevent food from getting into the lungs. During swallowing the larynx is pulled upward. This causes a flap of tissue called the *epiglottis* to cover the opening to the trachea and prevent food from entering the trachea. In the stomach, additional liquid, called **gastric juice,** is added to the food. Gastric juice contains enzymes and hydrochloric acid. The major enzyme of the stomach is **pepsin,** which initiates the chemical breakdown of protein. The pH of gastric juice is very low, generally around pH2. Consequently, very few kinds of bacteria or protozoa emerge from the stomach alive. Those that do have special protective features that allow them to survive as they pass through the stomach. The entire mixture is churned by the contractions of the three layers of muscle in the stomach wall. The combined activities of enzymatic breakdown, chemical breakdown by hydrochloric acid, and mechanical processing by muscular movement result in a thoroughly mixed liquid called *chyme.* Chyme eventually leaves the stomach through a valve known as the **pyloric sphincter** and enters the small intestine (How Science Works 18.1).

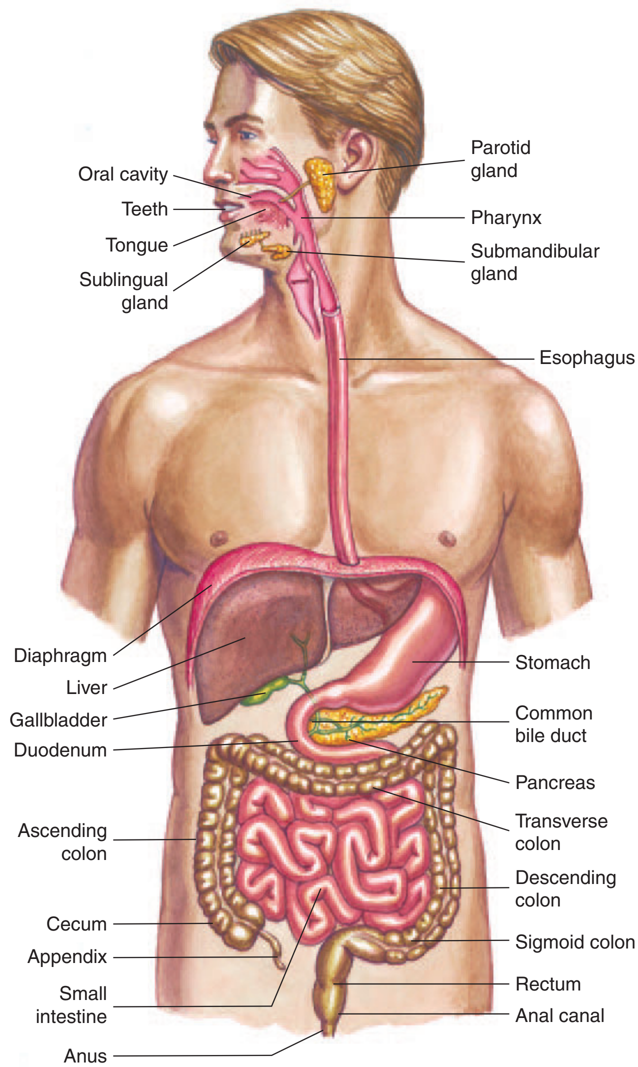


Figure 18.12

The Digestive System
The teeth, tongue, and enzymes from the salivary glands modify the food before it is swallowed. The stomach adds acid and enzymes and further changes the texture of the food. The food is eventually emptied into the duodenum, where the liver and pancreas add their secretions. The small intestine also adds enzymes and is involved in absorbing nutrients. The large intestine is primarily involved in removing water.

The first part of the **small intestine** is known as the **duodenum.** In addition to producing enzymes, the duodenum secretes several kinds of hormones that regulate the release of food from the stomach and the release of secretions from the pancreas and liver. The **pancreas** produces a number of different digestive enzymes and also secretes large amounts of bicarbonate ions, which neutralize stomach acid so that the pH of the duodenum is about pH8. The **liver** is a

HOW SCIENCE WORKS 18.1

An Accident and an Opportunity

On the morning of June 6, 1822, on Mackinac Island in northern Lake Huron, a 19-year-old French-Canadian fur trapper named Alexis St. Martin was shot in the stomach by the accidental discharge from a shotgun. The army surgeon at Fort Mackinac, Michigan, Dr. William Beaumont, was called to attend the wounded man. Part of the stomach and body wall had been shot away and parts of St. Martin's clothing were imbedded in the wound. Although Dr. Beaumont did not expect St. Martin to live he quickly cleaned the wound, pushed portions of the lung and stomach that were protruding back into the cavity, and dressed the wound. Finding St. Martin alive the next day, Beaumont was surprised and encouraged to do what he could to extend his life. In fact, Beaumont cared for St. Martin for two years. When the wound was completely healed the stomach had fused to the body wall and a hole allowed Beaumont to look into the stomach. Fortunately for St. Martin a flap of tissue from the lining of the stomach closed off the opening so that what he ate did not leak out.

Beaumont found that he could look through the opening and observe the activities in the stomach and recognized that this presented an opportunity to study the function of the stomach in a way that had not been done before. He gathered gastric juice, had its components identified, introduced food into the hole with a string attached so that he could retrieve the food particles that were partially digested for examination, and observed the effect of emotion on digestion. He discovered many things that were new to science and contrary to the teachings of the time. He recounted many of his observations and experiments in his journal. "I consider myself but a humble inquirer after truth—a simple experimenter. And if I have been led to conclusions opposite to the opinions of many who have been considered luminaries of physiology, and, in some instances, from all the professors of this science, I hope the claim of sincerity will be conceded to me, when I say that such difference of opinion has been forced upon me by the convictions of experiment, and the fair deductions of reasoning."

The following are some of his important discoveries.

1. He measured the temperature of the stomach and found that it does not heat up when food is introduced as was thought at the time. "But from the result of a great number of experiments and examinations, made with a view to asserting the truth of this opinion, in the empty and full state of the organ, . . . I am convinced that there is no alteration of temperature. . . ."
2. He found that pure gastric juice contains large amounts of hydrochloric acid. This was contrary to the prevailing opinion that gastric juice was simply water. "I think I am warranted, from the result of all the experiments, in saying, that the gastric juice, so far from being 'inert as water,' as some authors assert, is the most general solvent in nature, of alimentary matter—even the hardest bone cannot withstand its action."
3. He observed that gastric juice is not stored in the stomach but is secreted when food is eaten. "The gastric juice does not accumulate in the cavity of the stomach, until alimentary matter is received, and excite its vessels to discharge their contents, for the immediate purpose of digestion."
4. He realized that digestion begins immediately when food enters the stomach. The prevailing opinion of the day was that nothing happened for an hour or more. "At 2 o'clock P.M.—twenty minutes after having eaten an ordinary dinner of boiled, salted beef, bread, potatoes, and turnips, and drank [sic] a gill of water, I took from his stomach, through the artificial opening, a gill of the contents. . . . Digestion had evidently commenced, and was perceptually progressing, at the time."
5. He discovered that food in the stomach satisfies hunger even though it is not eaten. "To ascertain whether the sense of hunger would be allayed without food being passed through the oesophagus [sic], he fasted from breakfast time, til 4 o'clock, P.M., and became quite hungry. I then put in at the aperture, three and a half drachms of lean, boiled beef. The sense of hunger immediately subsided, and stopped the borborygmus, or croaking noise, caused by the motion of the air in the stomach and intestines, peculiar to him since the wound, and almost always observed when the stomach is empty."

St. Martin did not take kindly to these probings and twice ran away from Beaumont's care back to Canada where he married, had two children, and resumed his former life as a voyageur and fur trapper. He did not die until the age of 83, having lived over 60 years with a hole in his stomach.

large organ in the upper abdomen that performs several functions. One of its functions is the secretion of **bile.** When bile leaves the liver, it is stored in the **gallbladder** prior to being released into the duodenum. When bile is released from the gallbladder, it assists mechanical mixing by breaking large fat globules into smaller particles. This process is called *emulsification*.

Emulsification is important because fats are not soluble in water, yet the reactions of digestion must take place in a water solution. Bile causes large globules of fat to be broken into much smaller units (increasing the surface area-to-volume ratio) much as soap breaks up fat particles into smaller globules that are suspended in water and washed away. The activity of bile is important for the further digestion of fats in the intestine.

Along the length of the intestine, additional watery juices are added until the mixture reaches the **large intestine.** The large intestine is primarily involved in reabsorbing the water that has been added to the food tube along with saliva, gastric juice, bile, pancreatic secretions, and intestinal juices. The large intestine is also home to a variety of different kinds of bacteria. Most live on the undigested food that

Table 18.2

DIGESTIVE ENZYMES AND THEIR FUNCTIONS

Enzyme	Site of Production	Molecules Altered	Molecules Produced
Salivary amylase	Salivary glands	Starch	Smaller polysaccharides (many sugar molecules attached together)
Pepsin	Stomach lining	Proteins	Peptides (several amino acids)
Gastric lipase	Stomach lining	Fats	Fatty acids and glycerol
Chymotrypsin	Pancreas	Polypeptides (long chains of amino acids)	Peptides
Trypsin	Pancreas	Polypeptides	Peptides
Carboxypeptidase	Pancreas	Peptides	Smaller peptides and amino acids
Pancreatic amylase	Pancreas	Polysaccharides	Disaccharides
Pancreatic lipase	Pancreas	Fats	Fatty acids and glycerol
Nuclease	Pancreas	Nucleic acids	Nucleotides
Aminopeptidase	Intestinal lining	Peptides	Smaller peptides and amino acids
Dipeptidase	Intestinal lining	Dipeptides	Amino acids
Lactase	Intestinal lining	Lactose	Glucose and galactose
Maltase	Intestinal lining	Maltose	Glucose
Sucrase	Intestinal lining	Sucrose	Glucose and fructose
Nuclease	Intestinal lining	Nucleic acids	Nucleotides

makes it through the small intestine. Some provide additional benefit by producing vitamins that can be absorbed from the large intestine. A few kinds may cause disease.

Several different kinds of enzymes have been mentioned in this discussion. Each is produced by a specific organ and has a specific function. Chapter 5 introduced the topic of enzymes and how they work. Some enzymes, such as those involved in glycolysis, the Krebs cycle, and protein synthesis are produced and used inside cells; others, such as the digestive enzymes, are produced by cells and secreted into the digestive tract. Digestive enzymes are simply a special class of enzymes and have the same characteristics as the enzymes you studied previously. They are protein molecules that speed up specific chemical reactions and are sensitive to changes in temperature or pH. The various digestive enzymes, the sites of their production, and their functions are listed in table 18.2.

Nutrient Uptake

The process of digestion results in a variety of simple organic molecules that are available for absorption from the tube of the gut into the circulatory system. As we move simple sugars, amino acids, glycerol, and fatty acids into the circulatory system, we encounter another situation where surface area is important. The amount of material that can be taken up is limited by the surface area available. This problem is solved by increasing the surface area of the intestinal tract in several ways. First, the small intestine is a very long tube; the longer the tube, the greater the internal surface area. In a typical adult human it is about 3 meters long. In addition to length, the lining of the intestine consists of millions of fingerlike projections called **villi,** which increase the surface area. When we examine the cells that make up the villi, we find that they also have folds in their surface membranes. All of these characteristics increase the surface area available for the transport of materials from the gut into the circulatory system (figure 18.13). Scientists estimate that the cumulative effect of all of these features produces a total intestinal surface area of about 250 square meters. That is equivalent to about half the area of a football field.

The surface area by itself would be of little value if it were not for the intimate contact of the circulatory system with this lining. Each villus contains several capillaries and a branch of the lymphatic system called a **lacteal.** The close association between the intestinal surface and the circulatory and lymphatic systems allows for the efficient uptake of nutrients from the cavity of the gut into the circulatory system.

Several different kinds of processes are involved in the transport of materials from the intestine to the circulatory system. Some molecules, such as water and many ions, simply diffuse through the wall of the intestine into the circulatory system. Other materials, such as amino acids and simple sugars, are assisted across the membrane by carrier molecules. Fatty acids and glycerol are absorbed into the intestinal lining cells where they are resynthesized into fats and enter lacteals in the villi. Because the lacteals are part of the lymphatic system, which eventually empties its contents into the circulatory system, fats are also transported by the blood. They just reach the blood by a different route.

Chemical Alteration: The Role of the Liver

When the blood leaves the intestine, it flows directly to the liver through the **hepatic portal vein.** Portal veins are blood vessels

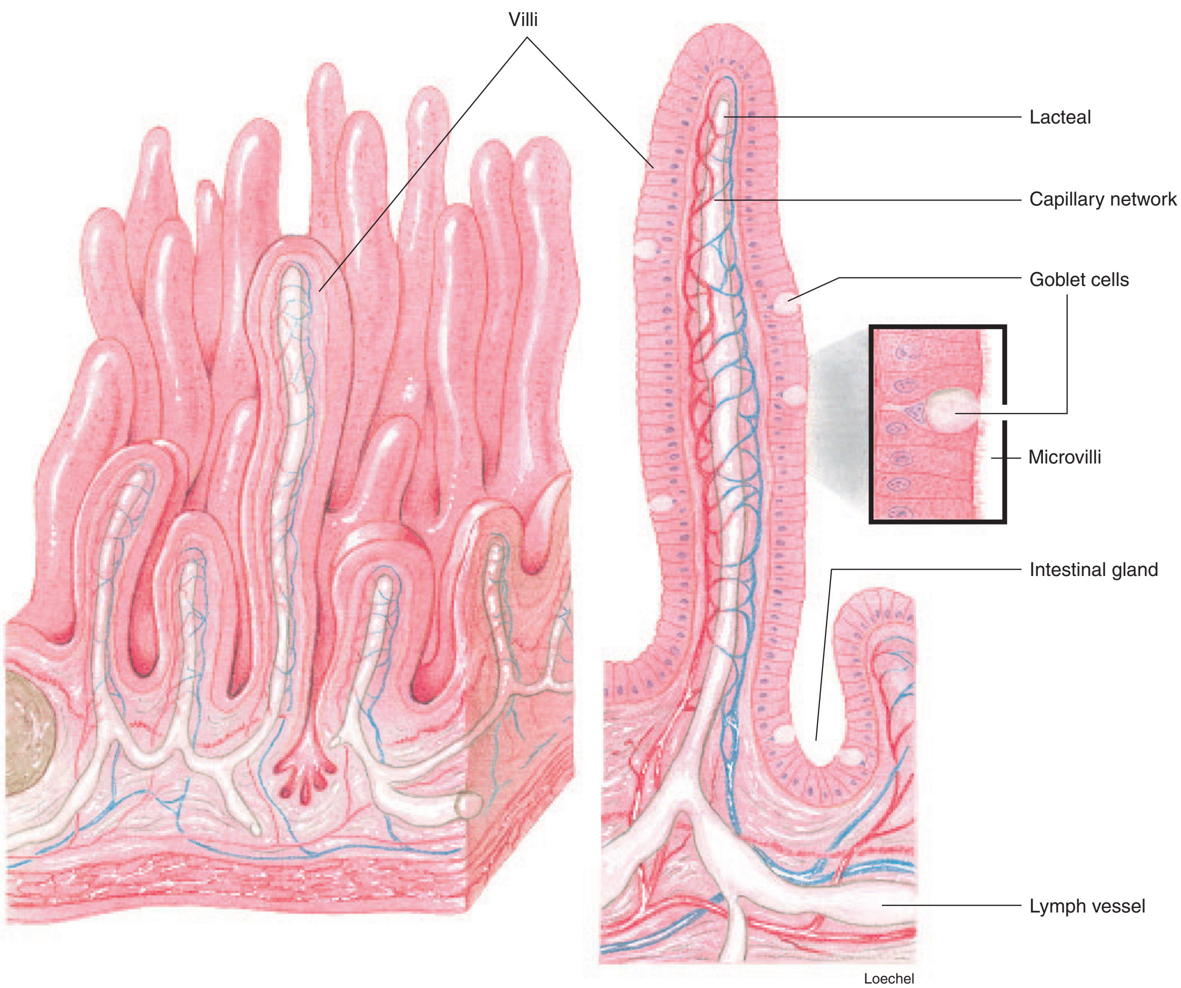


Figure 18.13

The Exchange Surface of the Intestine

The surface area of the intestinal lining is increased by the many fingerlike projections known as villi. Within each villus are capillaries and lacteals. Most kinds of materials enter the capillaries, but most fat-soluble substances enter the lacteals, giving them a milky appearance. Lacteals are part of the lymphatic system. Because the lymphatic system empties into the circulatory system, fat-soluble materials also eventually enter the circulatory system. The close relationship between the vessels and the epithelial lining of the villus allows for efficient exchange of materials from the intestinal cavity to the circulatory system.

that collect blood from capillaries in one part of the body and deliver it to a second set of capillaries in another part of the body without passing through the heart. Thus the hepatic portal vein collects nutrient-rich blood from the intestine and delivers it directly to the liver. As the blood flows through the liver, enzymes in the liver cells modify many of the molecules and particles that enter them. One of the functions of the liver is to filter any foreign organisms from the blood that might have entered through the intestinal cells. It also detoxifies many dangerous molecules that might have entered with the food.

Many foods contain toxic substances that could be harmful if not destroyed by the liver. Ethyl alcohol is one obvious example. Many plants contain various kinds of toxic molecules that are present in small quantities and could accumulate to dangerous levels if the liver did not perform its role of detoxification.

In addition, the liver is responsible for modifying nutrient molecules. The liver collects glucose molecules and synthesizes glycogen, which can be stored in the liver for later use. When glucose is in short supply, the liver can convert some of its stored glycogen back into glucose. Although amino acids are not stored, the liver can change the relative numbers of different amino acids circulating in the blood. It can remove the amino group from one kind of amino acid and attach it to a different carbon skeleton, generating a different amino acid. The liver is also able to take the amino group off amino acids so that what remains of the amino acid can be used in aerobic respiration. The toxic amino groups are then converted to urea by the liver. Urea is secreted back into the bloodstream and is carried to the kidneys for disposal in the urine.

18.5 Waste Disposal

Because cells are modifying molecules during metabolic processes, harmful waste products are constantly being formed. Urea is a common waste; many other toxic materials must be eliminated as well. Among these are large numbers of hydrogen ions produced by metabolism. This excess of hydrogen ions must be removed from the bloodstream. Other molecules, such as water and salts, may be consumed in excessive amounts and must be removed. The primary organs involved in regulating the level of toxic or unnecessary molecules are the **kidneys** (figure 18.14).

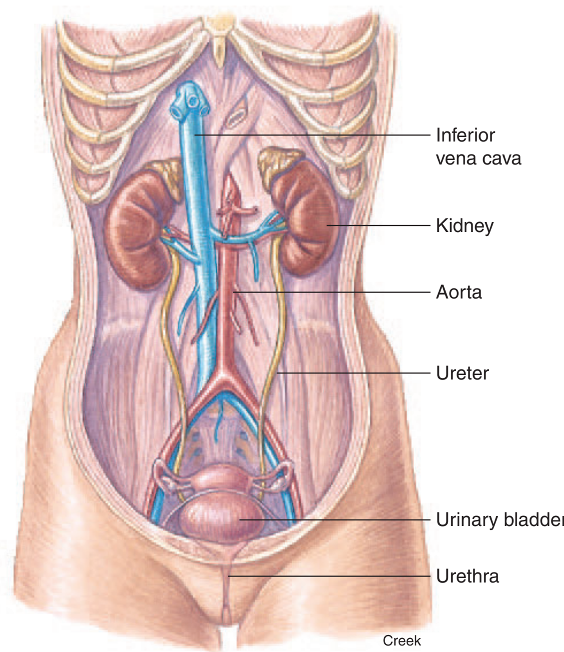


Figure 18.14

The Urinary System
The primary organs involved in removing materials from the blood are the kidneys. The urine produced by the kidneys is transported by the ureters to the urinary bladder. From the bladder, the urine is emptied to the outside of the body by way of the urethra.

Kidney Structure

The kidneys consist of about 2.4 million tiny units called **nephrons.** At one end of a nephron is a cup-shaped structure called **Bowman's capsule,** which surrounds a knot of capillaries known as a **glomerulus** (figure 18.15). In addition to Bowman's capsule, a nephron consists of three distinctly different regions: the **proximal convoluted tubule,** the **loop of Henle,** and the **distal convoluted tubule.** The distal convoluted tubule of a nephron is connected to a collecting duct that transports fluid to the ureters, and ultimately to the urinary bladder, where it is stored until it can be eliminated.

Kidney Function

As in the other systems discussed in this chapter, the excretory system involves a close connection between the circulatory system and a surface. In this case the large surface is provided by the walls of the millions of nephrons, which are surrounded by capillaries. Three major activities occur at these surfaces: filtration, reabsorption, and secretion. The glomerulus presents a large surface for the filtering of material from the blood to Bowman's capsule. Blood that enters the glomerulus is under pressure from the muscular contraction of the heart. The capillaries of the glomerulus are quite porous and provide a large surface area for the movement of water and small dissolved molecules from the blood into Bowman's capsule. Normally, only the smaller molecules, such as glucose, amino acids, and ions, are able to pass through the glomerulus into the Bowman's capsule at the end of the nephron. The various kinds of blood cells and larger molecules like proteins do not pass out of the blood into the nephron. This physical filtration process allows many kinds of molecules to leave the blood and enter the nephron. The volume of material filtered in this way through the approximately 2.4 million nephrons of our kidneys is about 7.5 liters per hour. Because your entire blood supply is about 5 to 6 liters, there must be some method of recovering much of this fluid.

Surrounding the various portions of the nephron are capillaries that passively accept or release molecules on the basis of diffusion gradients. The walls of the nephron are made of cells that actively assist in the transport of materials. Some molecules are reabsorbed from the nephron and picked up by the capillaries that surround them, whereas other molecules are actively secreted into the nephron from the capillaries. Each portion of the nephron has cells with specific secretory abilities.

The proximal convoluted tubule is primarily responsible for reabsorbing valuable materials from the fluid moving through it. Molecules like glucose, amino acids, and sodium ions are actively transported across the membrane of the proximal convoluted tubule and returned to the blood. In addition, water moves across the membrane because it follows the absorbed molecules and diffuses to the area where water molecules are less common. By the time the fluid has reached the end of the proximal convoluted tubule, about 65% of the fluid has been reabsorbed into the capillaries surrounding this region.

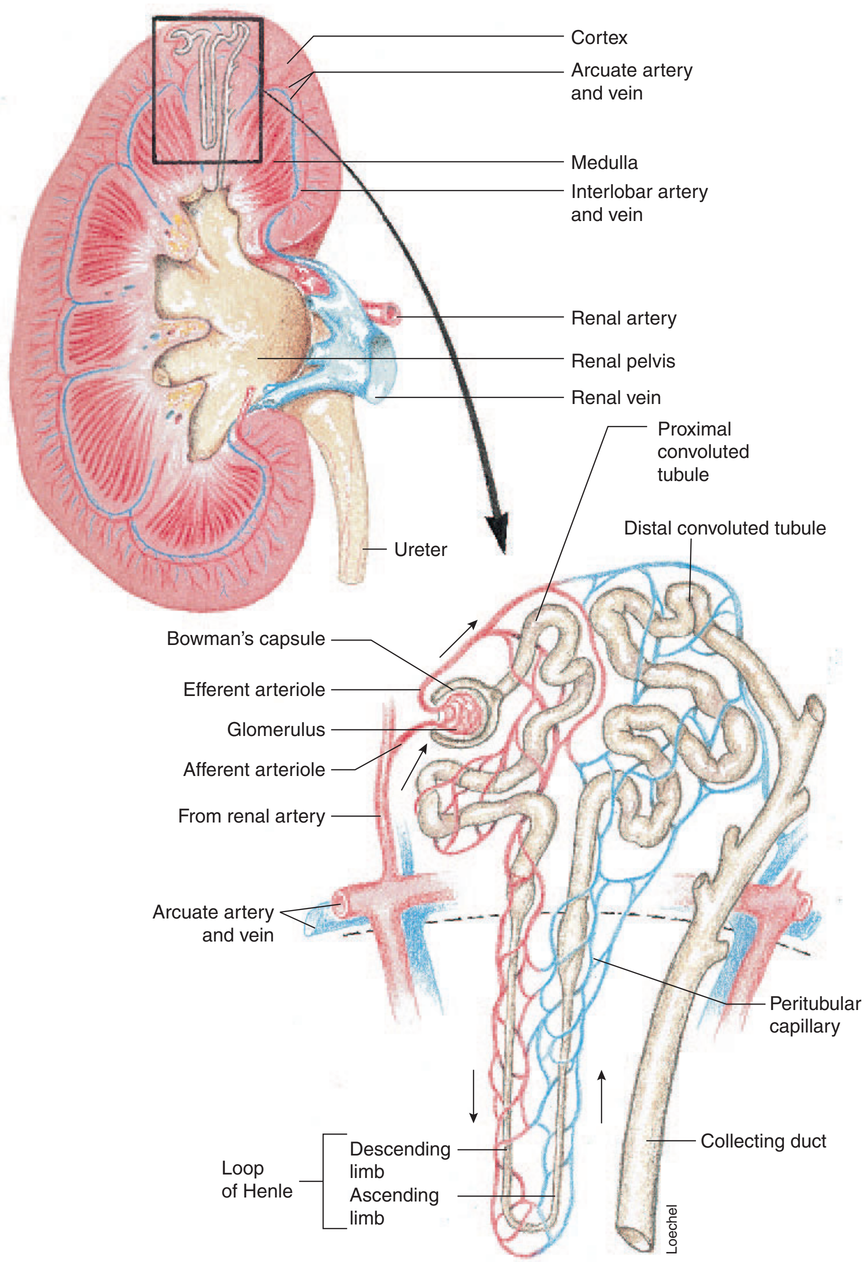


Figure 18.15

The Structure of the Nephron
The nephron and the closely associated blood vessels create a system that allows for the passage of materials from the circulatory system to the nephron by way of the glomerulus and Bowman's capsule. Materials are added to and removed from the fluid in the nephron via the tubular portions of the nephron.

The next portion of the tubule, the loop of Henle, is primarily involved in removing additional water from the nephron. Although the details of the mechanism are complicated, the principles are rather simple. The cells of the ascending loop of Henle actively transport sodium ions from the nephron into the space between nephrons where sodium ions accumulate in the fluid that surrounds the loop of Henle. The collecting ducts pass through this region as they carry urine to the ureters. Because the area these collecting ducts pass through is high in sodium ions, water within the collecting ducts diffuses from the ducts and is picked up by surrounding capillaries. However, the ability of water to pass through the wall of the collecting duct is regulated by hormones. Thus it is possible to control water loss from the body by regulating the amount of water lost from the collecting ducts. For example, if you drank a liter of water or some other liquid, the excess water would not be allowed to leave the collecting duct and would exit the body as part of the urine. However, if you were dehydrated, most of the water passing through the collecting ducts would be reabsorbed, and very little urine would be produced. The primary hormone involved in regulating water loss is the antidiuretic hormone (ADH). When the body has excess water, cells in the hypothalamus of the brain respond and send a signal to the pituitary and only a small amount of ADH is released and water is lost. When you are dehydrated these same brain cells cause more ADH to be released and water leaves the collecting duct and is returned to the blood.

The distal convoluted tubule is primarily involved in fine-tuning the amounts of various kinds of molecules that are lost in the urine. Hydrogen ions (H^+), sodium ions (Na^+), chloride ions (Cl^-), potassium ions (K^+), and ammonium ions (NH_4^+) are regulated in this way.

Some molecules that pass through the nephron are relatively unaffected by the various activities going on in the kidney. One of these is urea, which is filtered through the glomerulus into Bowman's capsule. As it passes through the nephron, much of it stays in the tubule and is eliminated in the urine. Many other kinds of molecules, such as minor metabolic waste products and some drugs, are also treated in

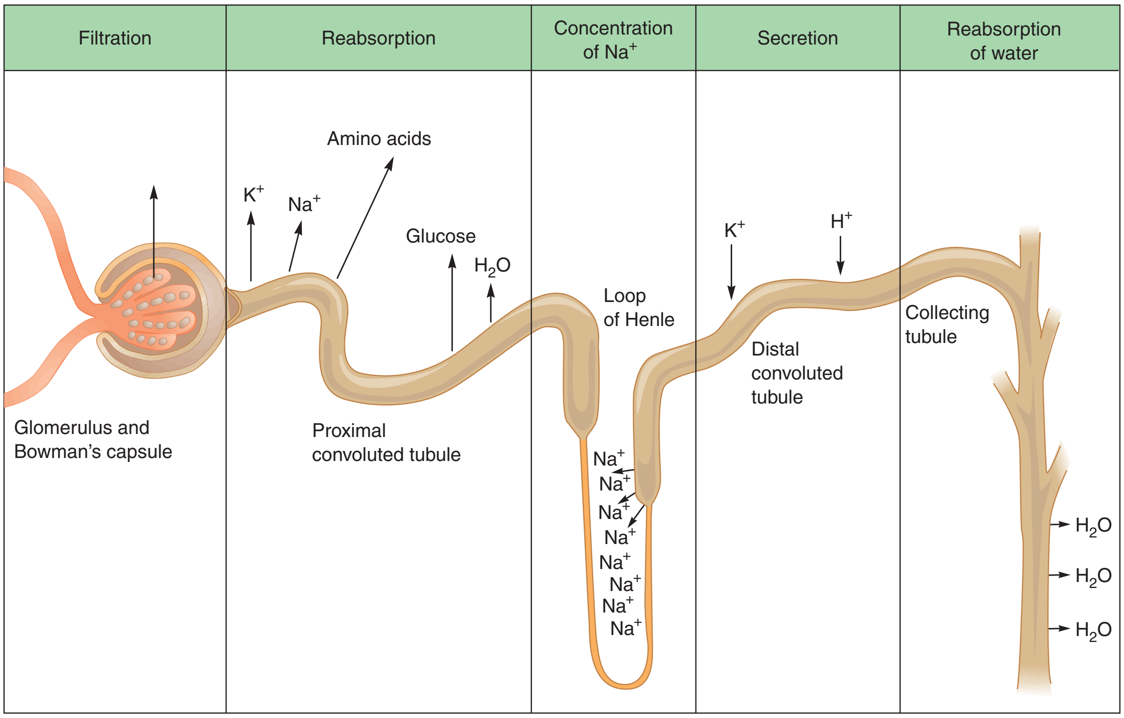


Figure 18.16

Specific Functions of the Nephron
Each portion of the nephron has specific functions. The glomerulus and Bowman's capsule accomplish the filtration of fluid from the bloodstream into the nephron. The proximal convoluted tubule reabsorbs a majority of the material filtered. The loop of Henle concentrates Na^+ so that water will move from the collecting tubule. The distal convoluted tubule regulates pH and ion concentration by differential secretion of K^+ and H^+.

this manner. Figure 18.16 summarizes the major functions of the various portions of the kidney tubule system.

SUMMARY

The body's various systems must be integrated in such a way that the internal environment stays relatively constant. This concept is called homeostasis. This chapter surveys four systems of the body—the circulatory, respiratory, digestive, and excretory systems—and describes how they are integrated. All of these systems are involved in the exchange of materials across cell membranes. Because of problems of exchange, cells must be small. Exchange is limited by the amount of surface area present, so all of these systems have special features that provide large surface areas to allow for necessary exchanges.

The circulatory system consists of a pump, the heart, and blood vessels that distribute the blood to all parts of the body. The blood is a carrier fluid that transports molecules and heat. The exchange of materials between the blood and body cells takes place through the walls of the capillaries. Because the flow of blood can be regulated by the contraction of arterioles, blood can be sent to different parts of the body at different times. Hemoglobin in red blood cells is very important in the transport of oxygen. Carbonic anhydrase is an enzyme in red blood cells that converts carbon dioxide into bicarbonate ions that can be easily carried by the blood.

The respiratory system consists of the lungs and associated tubes that allow air to enter and leave the lungs. The diaphragm and muscles of the chest wall are important in the process of breathing. In the lungs, tiny sacs called alveoli provide a large surface area in association with capillaries, which allows for rapid exchange of oxygen and carbon dioxide.

The digestive system is involved in disassembling food molecules. This involves several processes: grinding by the teeth and stomach, emulsification of fats by bile from the liver, addition of water to dissolve molecules, and enzymatic action to break complex molecules into simpler molecules for absorption. The intestine provides a large surface area for the absorption of nutrients because it is long and its wall contains many tiny projections that increase surface area. Once absorbed, the materials are carried to the liver, where molecules can be modified.

The excretory system is a filtering system of the body. The kidneys consist of nephrons into which the circulatory system filters fluid. Most of this fluid is useful and is reclaimed by the cells that make up the walls of these tubules. Materials that are present in excess or those that are harmful are allowed to escape. Some molecules may also be secreted into the tubules before being eliminated from the body.

THINKING CRITICALLY

It is possible to keep a human being alive even if the heart, lungs, kidneys, and digestive tract are not functioning by using heart-lung machines in conjunction with kidney dialysis and intravenous feeding. This implies that the basic physical principles involved in the functioning of these systems is well understood because the natural functions can be duplicated with mechanical devices. However, these machines are expensive and require considerable maintenance. Should society be spending money to develop smaller, more efficient mechanisms that could be used to replace diseased or damaged hearts, lungs, and kidneys? Debate this question.

CONCEPT MAP TERMINOLOGY

Construct a concept map to show relationships among the following concepts.

alveoli
bile
capillaries
emphysema
microvilli
nephron
pepsin
salivary amylase
small intestine
surface area-to-volume ratio
villi

KEY TERMS

alveoli
anemia
aorta
arteries
arterioles
atria
atrioventricular valves
bile
blood
Bowman's capsule
breathing
bronchi
bronchioles
capillaries
carbonic anhydrase
diaphragm
diastolic blood pressure
distal convoluted tubule
duodenum
gallbladder
gastric juice
glomerulus
heart
hemoglobin
hepatic portal vein
homeostasis
immune system
kidneys
lacteals
large intestine
liver
loop of Henle
lung
lymph
lymphatic system
microvilli
nephrons
pancreas
pepsin
pharynx
plasma
proximal convoluted tubule
pulmonary artery
pulmonary circulation
pyloric sphincter
salivary amylase
salivary glands
semilunar valves
small intestine
surface area-to-volume ratio (SA/V)
systemic circulation
systolic blood pressure
trachea
veins
ventricles
villi

e—LEARNING CONNECTIONS *www.mhhe.com/enger10*

Topics	Questions	Media Resources
18.1 Exchanging Materials: Basic Principles	1. List three reasons cells must be small.	**Quick Overview** • Homeostasis **Key Points** • Exchanging materials: Basic principles
18.2 Circulation	2. What are the functions of the heart, arteries, veins, arterioles, blood, and capillaries?	**Quick Overview** • Moving through the body **Key Points** • Circulation **Animations and Review** • Human breathing • Human circulation: Blood and blood vessels

Topics	Questions	Media Resources
18.2 Circulation (*continued*)		**Labeling Exercises** • Veins • Artery • Capillary bed • External anatomy of heart • Internal anatomy of heart • Blood circuits • Plaque
18.3 Gas Exchange	3. How do red blood cells assist in the transportation of oxygen and carbon dioxide? 4. Describe the mechanics of breathing. 5. How are blood pH and breathing interrelated?	**Quick Overview** • Diffusion in two directions at once **Key Points** • Gas exchange **Labeling Exercises** • Respiratory tract I • Respiratory tract II **Case Study** • Breathing liquids: Reality or science fiction **Food for Thought** • Smoking ban
18.4 Obtaining Nutrients	6. Describe three ways in which the digestive system increases its ability to absorb nutrients. 7. List three functions of the liver. 8. Name five digestive enzymes and their functions. 9. What is the role of bile in digestion? 10. How is fat absorption different from absorption of carbohydrate and protein?	**Quick Overview** • Digestion and absorption **Key Points** • Obtaining nutrients **Labeling Exercises** • Swallowing • Digestive system **Interactive Concept Maps** • Digestion **Experience This!** • Solubility and digestion
18.5 Waste Disposal	11. What is the function of the glomerulus, proximal convoluted tubule, loop of Henle, and distal convoluted tubule?	**Quick Overview** • Filtering blood **Key Points** • Waste disposal **Animations and Review** • Human excretion • Kidney anatomy **Interactive Concept Maps** • Text concept map