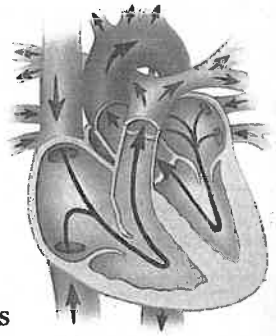
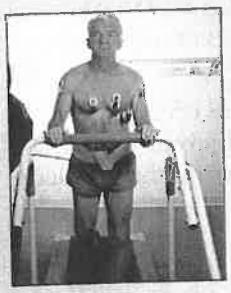
chapter 15

THE CARDIOVASCULAR SYSTEM: HEART



did you know? ***What is a "heart-healthy diet" and how does it help your heart? A heart-healthy diet is one that is low in saturated fats, high in fruits and vegetables, and contains plenty of fiber. A heart-healthy diet encourages the consumption of fish but warns against too much sugar and salt. A heart-healthy diet is actually an "artery-healthy diet" because it is associated with health improvements that reduce the risk of artery disease: better blood cholesterol levels, better blood pressure, and less obesity. Coronary artery disease is the leading cause of death from heart disease, so by keeping the heart's arteries healthy, the heart stays healthy as well.***



Focus on Wellness, page 376

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In the last chapter we examined the composition and functions of blood. For blood to reach body cells and exchange materials with them, it must be constantly pumped by the heart through the body's blood vessels. The heart beats about 100,000 times every day, which adds up to about 35 million beats in a year. The left side of the heart pumps blood through an estimated 100,000 km (60,000 mi) of blood vessels. The right side of the heart pumps blood through the lungs, enabling blood to pick up oxygen and unload carbon dioxide. Even while you are sleeping, your heart pumps 30 times its own weight each minute, which amounts to about 5 liters (5.3 qt) to the lungs and the same volume to the rest of the body. At this rate, the heart pumps more than 14,000 liters (3,600 gal) of blood in a day, or 10 million liters (2.6 million gal) in a year. You don't spend all your time sleeping, however, and your heart pumps more vigorously when you are active. Thus, the actual blood volume the heart pumps in a single day is much larger.

The scientific study of the normal heart and the diseases associated with it is ***cardiology*** (kar′-dē-OL-ō-jē; *cardio-* = heart; *-logy* = study of). This chapter explores the design of the heart and the unique properties that permit it to pump for a lifetime without a moment of rest.

looking back to move ahead . . .

- **Functions of Blood (page 346)**
- **Membranes (page 90)**
- **Muscular Tissue (page 90)**
- **Cardiac Muscle Tissue (page 186)**
- **Free Radicals (page 25)**
- **ANS Neurotransmitters (page 277)**

STRUCTURE AND ORGANIZATION OF THE HEART

OBJECTIVES
- **Describe the location of the heart and the structure and functions of the pericardium.**
- **Describe the layers of the heart wall and the chambers of the heart.**
- **Identify the major blood vessels that enter and exit the heart.**
- **Describe the structure and functions of the valves of the heart.**

Location and Coverings of the Heart

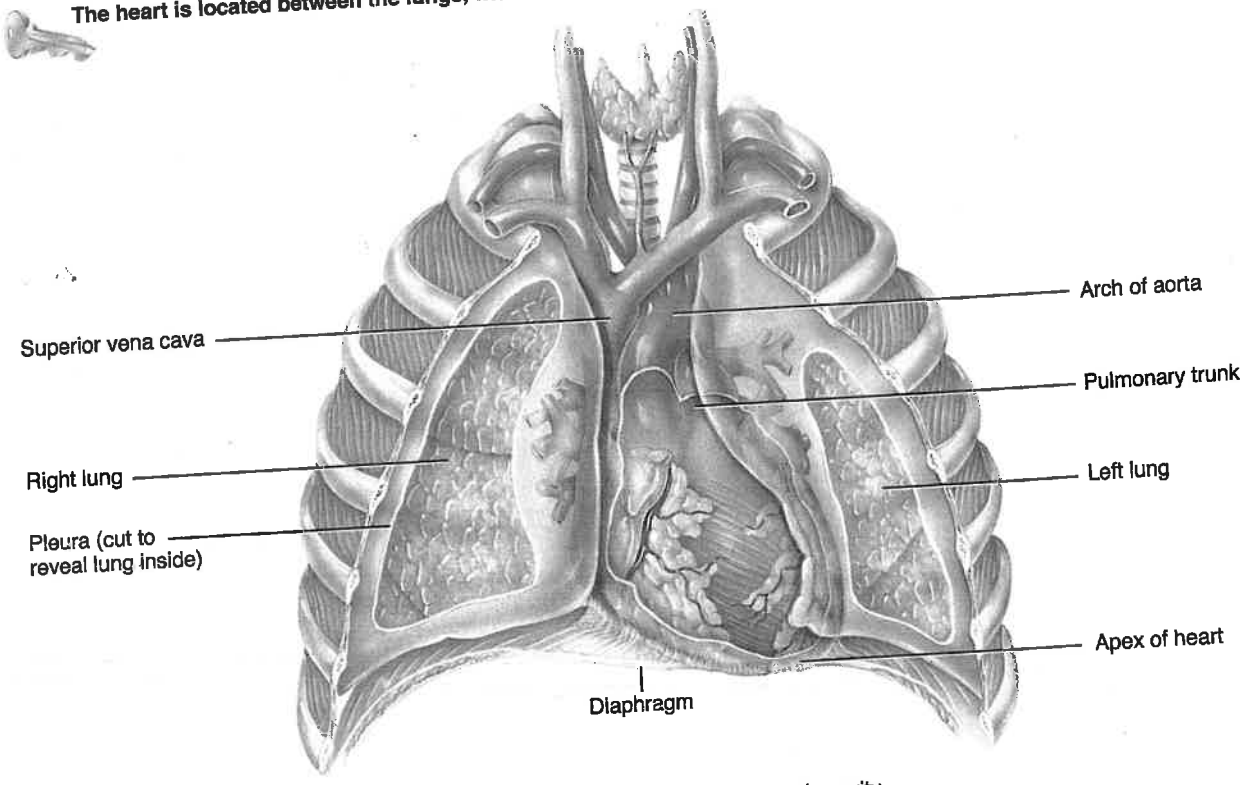
The ***heart*** is situated between the two lungs in the thoracic cavity, with about two-thirds of its mass lying to the left of the body's midline (Figure 15.1). Your heart is about the size of your closed fist. The pointed end, the *apex*, is formed by the tip of the left ventricle, a lower chamber of the heart, and rests on the diaphragm. The *base* of the heart is its posterior surface. It is formed by the atria (upper chambers of the heart), mostly the left atrium, into which the four pulmonary veins open, and a portion of the right atrium that receives the superior and inferior vena cavae (see Figure 15.3b). The base lies opposite the apex.

The membrane that surrounds and protects the heart and holds it in place is the ***pericardium*** (*peri-* = around). It consists of two parts: the fibrous pericardium and the serous pericardium (Figure 15.2). The outer ***fibrous pericardium*** is a tough, inelastic, dense irregular connective tissue. It prevents overstretching of the heart, provides protection, and anchors the heart in place.

The inner ***serous pericardium*** is a thinner, more delicate membrane that forms a double layer around the heart. The outer ***parietal layer*** of the serous pericardium is fused to the fibrous pericardium, and the inner ***visceral layer*** of the serous pericardium, also called the ***epicardium*** (*epi-* = on top of), adheres tightly to the surface of the heart. Between the parietal and visceral layers of the serous pericardium is a thin film of fluid. This fluid, known as ***pericardial fluid***, reduces friction between the membranes as the heart moves. The ***pericardial cavity*** is the space that contains the pericardial fluid.

Figure 15.1 Position of the heart and associated blood vessels in the thoracic cavity. In this and subsequent illustrations, vessels that carry oxygenated blood are colored red; vessels that carry deoxygenated blood are colored blue.

The heart is located between the lungs, with about two-thirds of its mass to the left of the midline.

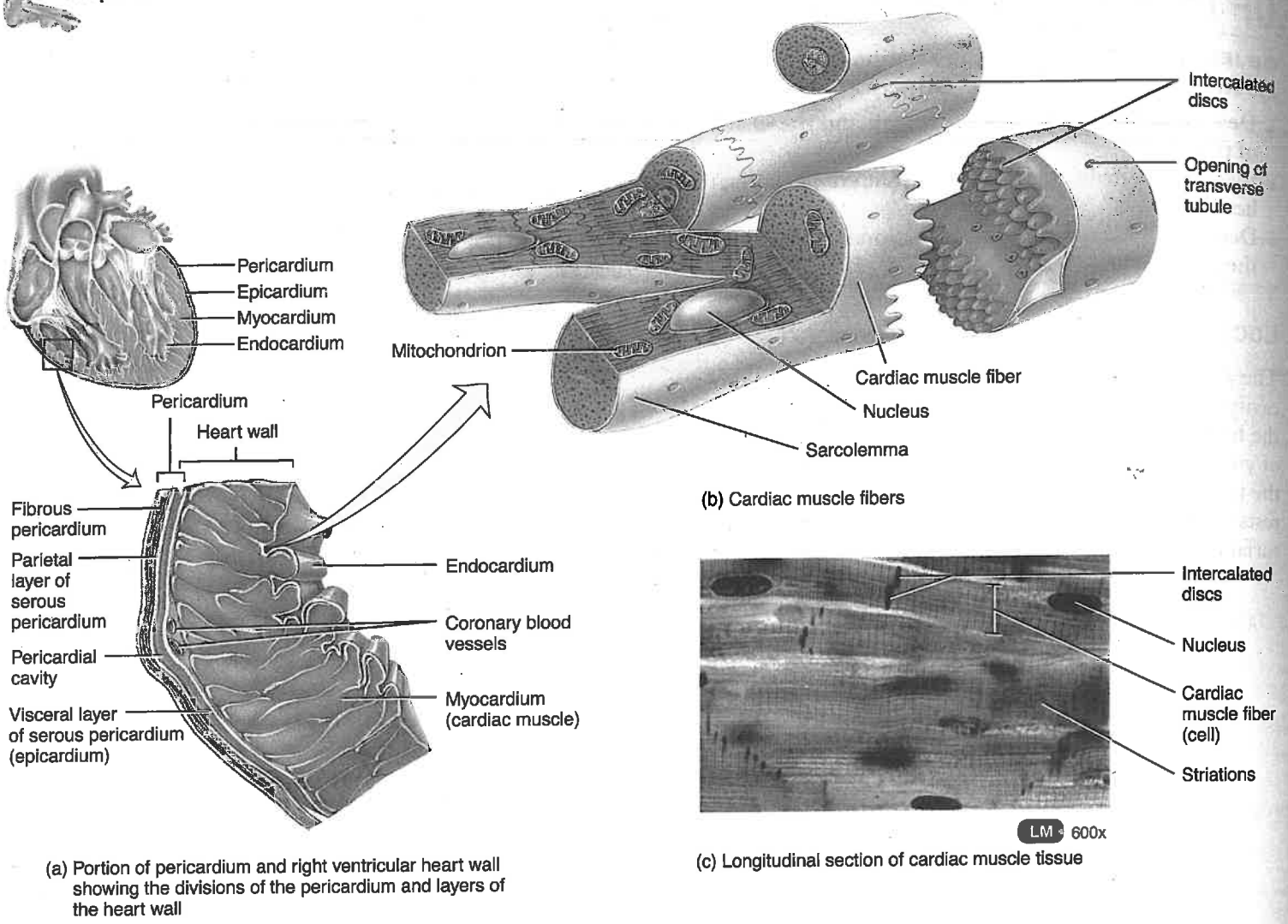


Anterior view of the heart in the thoracic cavity

What forms the base of the heart?

Figure 15.2 Pericardium and heart wall.

The pericardium is a sac that surrounds and protects the heart.



Which layer is both a part of the pericardium and a part of the heart wall?

Inflammation of the pericardium is called **pericarditis** (per′-i-kar-DĪ-tis). In one form of this condition, there is a buildup of pericardial fluid. If a great deal of fluid accumulates, this is a life-threatening condition because the fluid compresses the heart, a condition called *cardiac tamponade* (tam′-pon- ĀD). As a result of the compression, ventricular filling is decreased, cardiac output is reduced, venous return to the heart is diminished, blood presure falls, and breathing is difficult.

Heart Wall

The wall of the heart (Figure 15.2a) is composed of three layers: epicardium (external layer), myocardium (middle layer), and endocardium (inner layer). The ***epicardium***, which is also known as the visceral layer of serous pericardium, is the thin, transparent outer layer of the wall. It is composed of mesothelium and connective tissue.

The ***myocardium*** (*myo-* = muscle) consists of cardiac muscle tissue, which constitutes the bulk of the heart. This tissue is found only in the heart and is specialized in structure and function. The myocardium is responsible for the pumping action of the heart. Cardiac muscle fibers (cells) are involuntary, striated, and branched, and the tissue is arranged in interlacing bundles of fibers (Figure 15.2b).

Cardiac muscle fibers form two separate networks—one atrial and one ventricular. Each cardiac muscle fiber connects with other fibers in the networks by thickenings of the sarcolemma (plasma membrane) called ***intercalated discs***. Within the discs are ***gap junctions*** that allow action potentials to conduct from one cardiac muscle fiber to the next. The intercalated discs also link cardiac muscle fibers to one

another so they do not pull apart. Each network contracts as a functional unit, so the atria contract separately from the ventricles. In response to a single action potential, cardiac muscle fibers develop a prolonged contraction, 10–15 times longer than the contraction observed in skeletal muscle fibers. Also, the refractory period of a cardiac fiber lasts longer than the contraction itself. Thus, another contraction of cardiac muscle cannot begin until relaxation is well underway. For this reason, tetanus (maintained contraction) cannot occur in cardiac muscle tissue.

The ***endocardium*** (*endo-* = within) is a thin layer of simple squamous epithelium that lines the inside of the myocardium and covers the valves of the heart and the tendons attached to the valves. It is continuous with the epithelial lining of the large blood vessels.

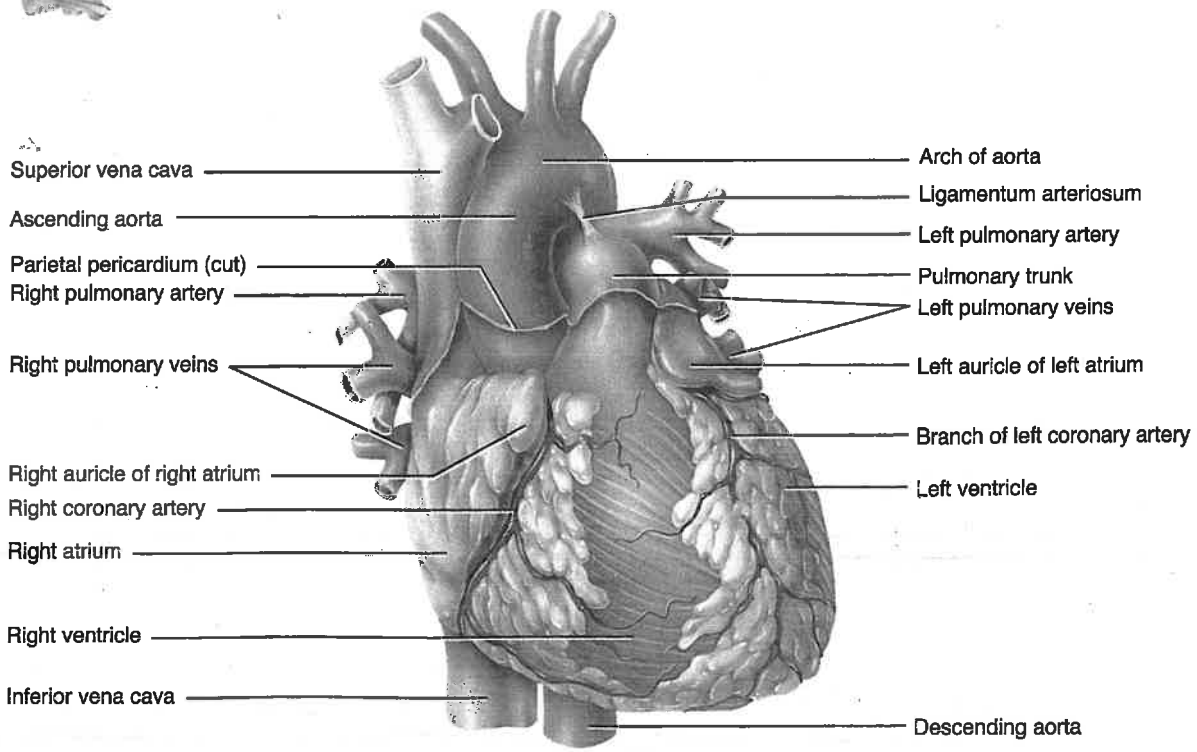
The heart of a heart attack survivor often has regions of infarcted (dead) cardiac muscle tissue that typically are replaced with noncontractile fibrous scar tissue over time. Our inability to repair damage from a heart attack has been attributed to a lack of stem cells in cardiac muscle and to the absence of mitosis in mature cardiac muscle fibers. A recent study of heart transplant recipients by American and Italian scientists, however, provides evidence for significant **replacement of heart cells**. The researchers studied men who had received a heart from a female, and then looked for the presence of a Y chromosome in heart cells. (All female cells except gametes have two X chromosomes and lack the Y chromosome.) Several years after the transplant surgery, between 7% and 16% of the heart cells in the transplanted tissue, including cardiac muscle fibers and endothelial cells in coronary arterioles and capillaries, had been replaced by the recipient's own cells, as evidenced by the presence of a Y chromosome. The study also revealed cells with some of the characteristics of stem cells in both transplanted hearts and control hearts. Evidently, stem cells can migrate from the blood into the heart and differentiate into functional muscle and endothelial cells. The hope is that researchers can learn how to "turn on" such regeneration of heart cells to treat people with heart failure or cardiomyopathy (diseased heart).

Chambers of the Heart

The heart contains four chambers (Figure 15.3). The two upper chambers are the ***atria*** (= entry halls or chambers), and the two lower chambers are the ***ventricles*** (= little bellies). Between the right atrium and left atrium is a thin partition called the ***interatrial septum*** (*inter-* = between; *septum* = a

Figure 15.3 Structure of the heart.

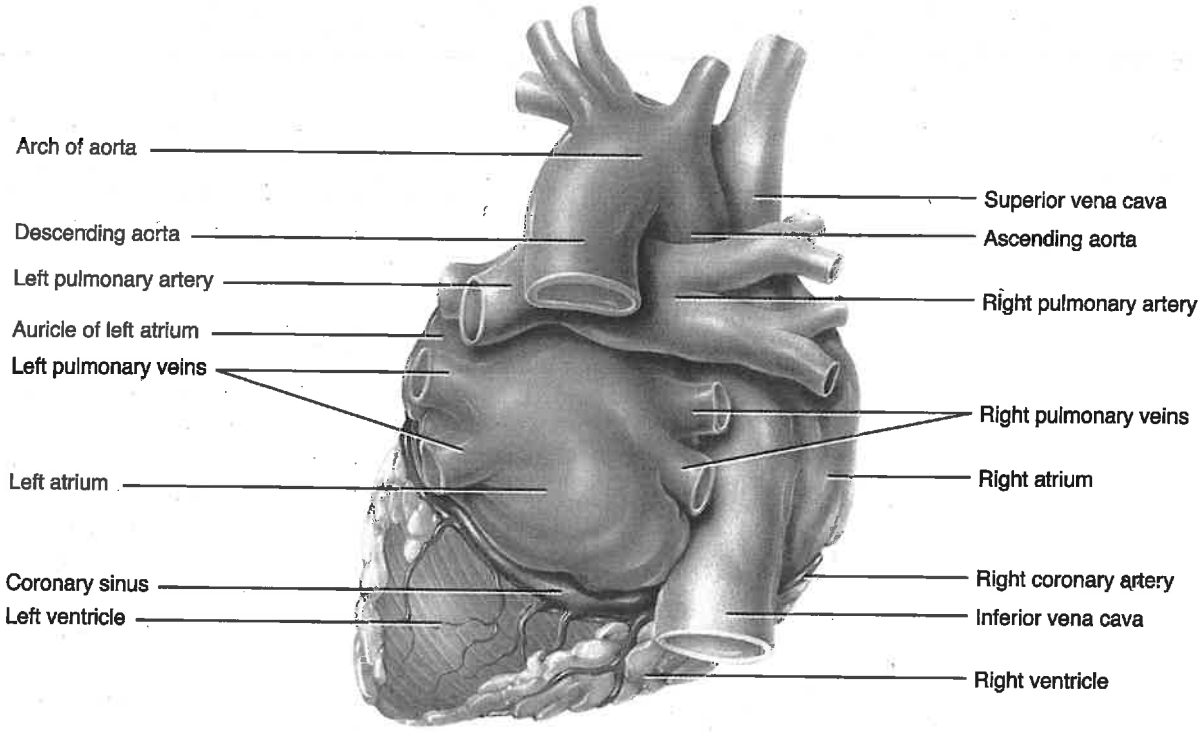
The four chambers of the heart are the two upper atria and two lower ventricles.



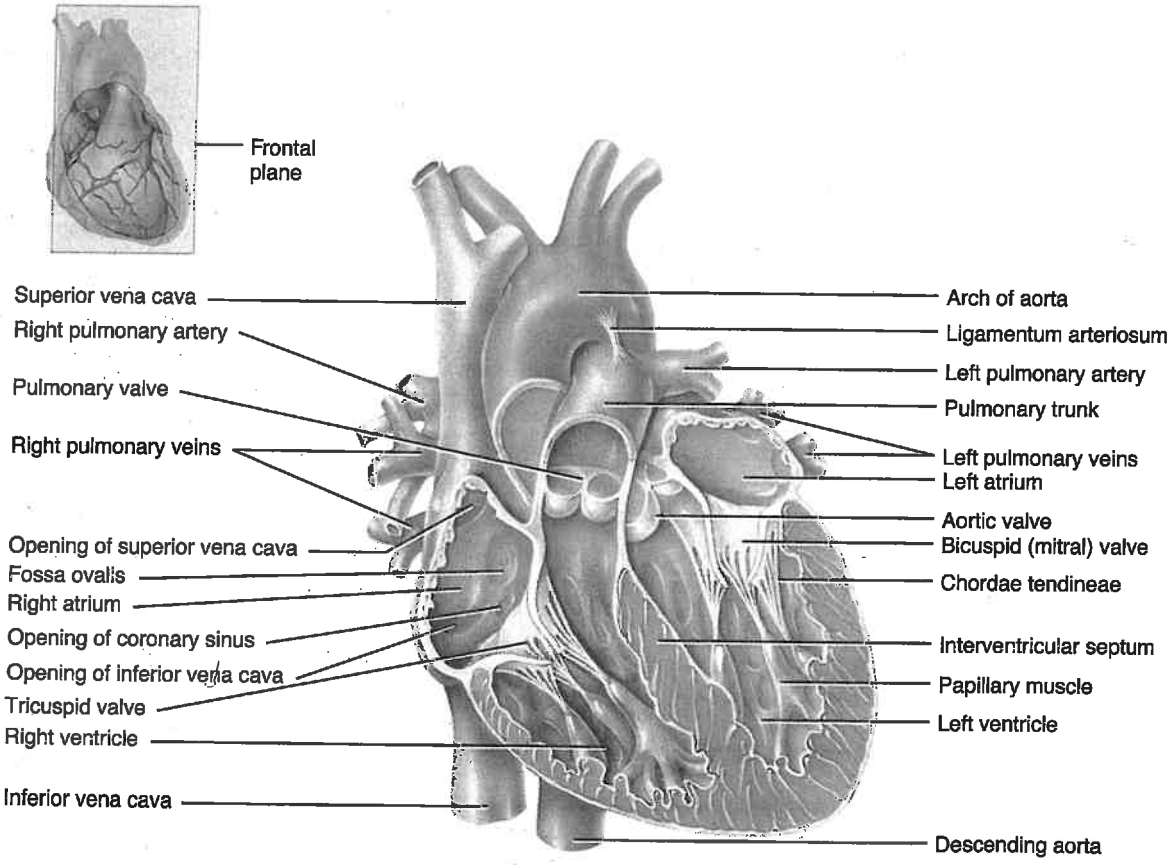
(a) Anterior external view showing surface features

(Continues)

Figure 15.3 *(Continued)*



(b) Posterior external view showing surface features



(c) Anterior view of frontal section showing internal anatomy

Through which type of vessel does blood flow away from the heart?

dividing wall or partition); a prominent feature of this septum is an oval depression called the ***fossa ovalis***. It is the remnant of the ***foramen ovale***, an opening in the fetal heart that directs blood from the right to left atrium in order to bypass the nonfunctioning fetal lungs. The foramen ovale normally closes soon after birth. An ***interventricular septum*** separates the right ventricle from the left ventricle (Figure 15.3c). On the anterior surface of each atrium is a wrinkled pouchlike structure called an ***auricle*** (OR-i-kul; *auri-* = ear), so named because of its resemblance to a dog's ear. Each auricle slightly increases the capacity of an atrium so that it can hold a greater volume of blood.

The thickness of the myocardium of the chambers varies according to the amount of work each chamber has to perform. The walls of the atria are thin compared to those of the ventricles because the atria need only enough cardiac muscle tissue to deliver blood into the ventricles (Figure 15.3c). The right ventricle pumps blood only to the lungs (pulmonary circulation); the left ventricle pumps blood to all other parts of the body (systemic circulation). The left ventricle must work harder than the right ventricle to maintain the same rate of blood flow, so the muscular wall of the left ventricle is considerably thicker than the wall of the right ventricle to overcome the greater pressure.

Great Vessels of the Heart

The right atrium receives ***deoxygenated blood*** (oxygen-poor blood that has given up some of its oxygen to cells) through three ***veins***, blood vessels that return blood to the heart. The ***superior vena cava*** (VĒ-na CĀ-va; *vena* = vein; *cava* = hollow, a cave) brings blood mainly from parts of the body above the heart; the ***inferior vena cava*** brings blood mostly from parts of the body below the heart; and the ***coronary sinus*** drains blood from most of the vessels supplying the wall of the heart (Figure 15.3b, c). The right atrium then delivers the deoxygenated blood into the right ventricle, which pumps it into the ***pulmonary trunk***. The pulmonary trunk divides into a ***right*** and ***left pulmonary artery***, each of which carries blood to the corresponding lung. ***Arteries*** are blood vessels that carry blood away from the heart. In the lungs, the deoxygenated blood unloads carbon dioxide and picks up oxygen. This ***oxygenated blood*** (oxygen-rich blood that has picked up oxygen as it flows through the lungs) then enters the left atrium via four ***pulmonary veins***. The blood then passes into the left ventricle, which pumps the blood into the ***ascending aorta***. From here the oxygenated blood is carried to all parts of the body.

Between the pulmonary trunk and arch of the aorta is a structure called the ***ligamentum arteriosum***. It is the remnant of the ***ductus arteriosus***, a blood vessel in fetal circulation that allows most blood to bypass the nonfunctional fetal lungs (see page 412).

Valves of the Heart

As each chamber of the heart contracts, it pushes a volume of blood into a ventricle or out of the heart into an artery. To prevent the blood from flowing backward, the heart has four ***valves*** composed of dense connective tissue covered by endothelium. These valves open and close in response to pressure changes as the heart contracts and relaxes.

As their names imply, ***atrioventricular (AV) valves*** lie between the atria and ventricles (Figure 15.3c). The atrioventricular valve between the right atrium and right ventricle is called the ***tricuspid valve*** because it consists of three cusps (leaflets). The pointed ends of the cusps project into the ventricle. Tendonlike cords, called ***chordae tendineae*** (KOR-dē ten-DIN-ē-ē; *chord-* = cord; *tend-* = tendon), connect the pointed ends to ***papillary muscles*** (*papill-* = nipple), cardiac muscle projections located on the inner surface of the ventricles. The chordae tendineae prevent the valve cusps from pushing up into the atria when the ventricles contract.

The atrioventricular valve between the left atrium and left ventricle is called the ***bicuspid (mitral) valve***. It has two cusps that work in the same way as the cusps of the tricuspid valve. For blood to pass from an atrium to a ventricle, an atrioventricular valve must open.

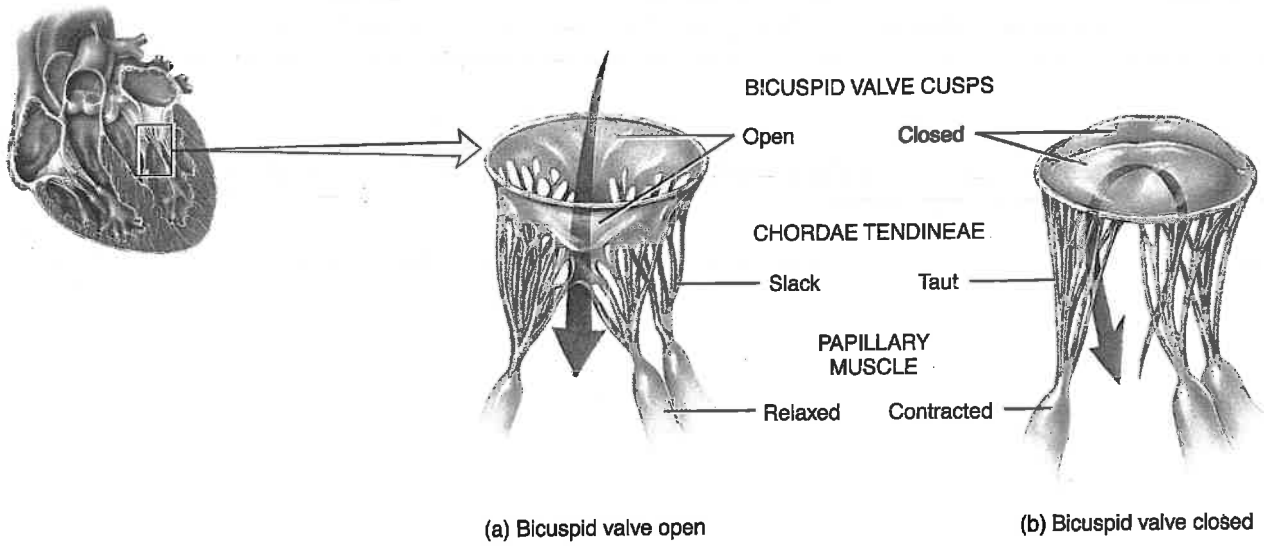
The opening and closing of the valves are due to pressure differences across the valves. When blood moves from an atrium to a ventricle, the valve is pushed open, the papillary muscles relax, and the chordae tendineae slacken (Figure 15.4a). When a ventricle contracts, the pressure of the ventricular blood drives the cusps upward until their edges meet and close the opening (Figure 15.4b). At the same time, contraction of the papillary muscles and tightening of the chordae tendineae help prevent the cusps from swinging upward into the atrium.

Near the origin of the pulmonary trunk and aorta are ***semilunar valves*** called the ***pulmonary valve*** and the ***aortic valve*** that prevent blood from flowing back into the heart (see Figure 15.3c). The pulmonary valve lies in the opening where the pulmonary trunk leaves the right ventricle. The aortic valve is situated at the opening between the left ventricle and the aorta. Each valve consists of three semilunar (half-moon-shaped) cusps that attach to the artery wall. Like the atrioventricular valves, the semilunar valves permit blood to flow in one direction only—in this case, from the ventricles into the arteries.

When the ventricles contract, pressure builds up within them. The semilunar valves open when pressure in the ventricles exceeds the pressure in the arteries, permitting ejection of blood from the ventricles into the pulmonary trunk and aorta (see Figure 15.4d). As the ventricles relax, blood starts to flow back toward the heart. This back-flowing blood fills the valve cusps, which tightly closes the semilunar valves (see Figure 15.4c).

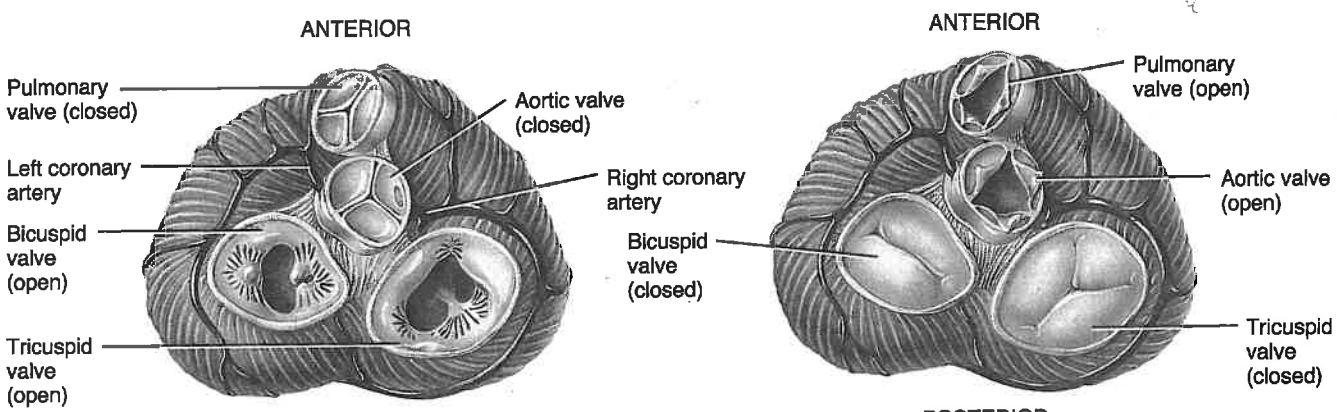
Figure 15.4 Atrioventricular (AV) valves. The bicuspid and tricuspid valves operate in a similar manner.

Heart valves open and close in response to pressure changes as the heart contracts and relaxes.



(a) Bicuspid valve open

(b) Bicuspid valve closed



(c) Superior view with atria removed: pulmonary and aortic valves closed, bicuspid and tricuspid valves open

(d) Superior view with atria removed: pulmonary and aortic valves open, bicuspid and tricuspid valves closed

What is the function of heart valves?

When heart valves operate normally, they open fully and close completely at the proper times. A narrowing of a heart valve opening that restricts blood flow is known as **stenosis** (ste-NŌ-sis = a narrowing); failure of a valve to close completely is termed **insufficiency** or **incompetence**. In **mitral stenosis**, scar formation or a congenital defect causes narrowing of the mitral valve. One cause of **mitral insufficiency**, in which there is backflow of blood from the left ventricle into the left atrium, is **mitral valve prolapse (MVP)**. In MVP, one or both cusps of the mitral valve protrude into the left atrium during ventricular contraction. Mitral valve prolapse is one of the most common valvular disorders, affecting as much as 30% of the population. It is more prevalent in women than in men, and does not always pose a serious threat. In **aortic stenosis**, the aortic valve is narrowed, and in **aortic insufficiency**, there is backflow of blood from the aorta into the left ventricle.

If a heart valve cannot be repaired surgically, then the valve must be replaced. Tissue (biologic) valves may be provided by human donors or pigs; sometimes mechanical (artificial) valves made of plastic or metal are used. The aortic valve is the most commonly replaced heart valve.

■ CHECKPOINT

1. Identify the location of the heart.
2. Describe the various layers of the pericardium and the heart wall.
3. How do atria and ventricles differ in structure and function?
4. Which blood vessels that enter and exit the heart carry oxygenated blood? Which carry deoxygenated blood?
5. In correct sequence, which heart chambers, heart valves, and blood vessels would a drop of blood encounter from the time it flows out of the right atrium until it reaches the aorta?

BLOOD FLOW AND BLOOD SUPPLY OF THE HEART

OBJECTIVES • Explain how blood flows through the heart.

• Describe the clinical importance of the blood supply of the heart.

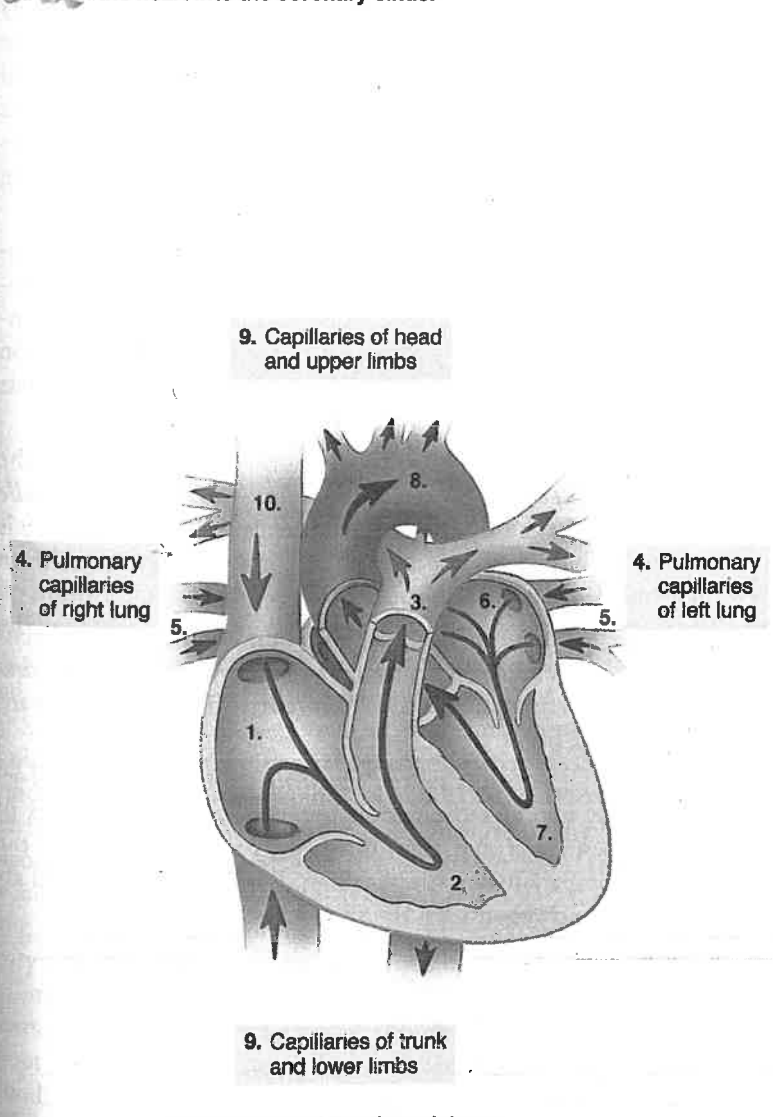
Blood Flow Through the Heart

Blood flows through the heart from areas of higher blood pressure to areas of lower blood pressure. As the walls of the atria contract, the pressure of the blood within them increases. This increased blood pressure forces the AV valves open, allowing atrial blood to flow through the AV valves into the ventricles.

After the atria are finished contracting, the walls of the ventricles contract, increasing ventricular blood pressure and pushing blood through the semilunar valves into the pulmonary trunk and aorta. At the same time, the shape of the AV valve cusps causes them to be pushed shut, preventing backflow of ventricular blood into the atria. Figure 15.5 summarizes the flow of blood through the heart.

Figure 15.5 Blood flow through the heart.

The right and left coronary arteries deliver blood to the heart; the coronary veins drain blood from the heart into the coronary sinus.



Which veins deliver deoxygenated blood into the right atrium?

Blood Supply of the Heart

The wall of the heart, like any other tissue, has its own blood vessels. The flow of blood through the numerous vessels in the myocardium is called ***coronary (cardiac) circulation***. The principal coronary vessels are the ***left*** and ***right coronary arteries***, which originate as branches of the ascending aorta (see Figure 15.3a). Each artery branches and then branches again to deliver oxygen and nutrients throughout the heart muscle. Most of the deoxygenated blood, which carries carbon dioxide and wastes, is collected by a large vein on the posterior surface of the heart, the ***coronary sinus*** (see Figure 15.3b), which empties into the right atrium.

Most parts of the body receive blood from branches of more than one artery, and where two or more arteries supply the same region, they usually connect. These connections, called ***anastomoses*** (a-nas′-tō-MŌ-sēs), provide alternate routes for blood to reach a particular organ or tissue. The myocardium contains many anastomoses that connect branches of a given coronary artery or extend between branches of different coronary arteries. They provide detours for arterial blood if a main route becomes obstructed. Thus, heart muscle may receive sufficient oxygen even if one of its coronary arteries is partially blocked.

When blockage of a coronary artery deprives the heart muscle of oxygen, **reperfusion**, the reestablishment of blood flow, may damage the tissue further. This surprising effect is due to the formation of oxygen **free radicals** from the reintroduced oxygen. Free radicals are electrically charged molecules that have an unpaired electron. Such molecules are unstable and highly reactive. They cause chain reactions that lead to cellular damage and death. To counter the effects of oxygen free radicals, body cells produce enzymes that convert free radicals to less reactive substances. In addition, some nutrients, such as vitamin E, vitamin C, beta-carotene, zinc, and selenium, are antioxidants, which remove oxygen free radicals. Drugs that lessen reperfusion damage after a heart attack or stroke are currently under development.

■ CHECKPOINT

6. Describe the main force that causes blood to flow through the heart.
7. Why is it that blood flowing through the chambers within the heart cannot supply sufficient oxygen or remove enough carbon dioxide from the myocardium?

CONDUCTION SYSTEM OF THE HEART

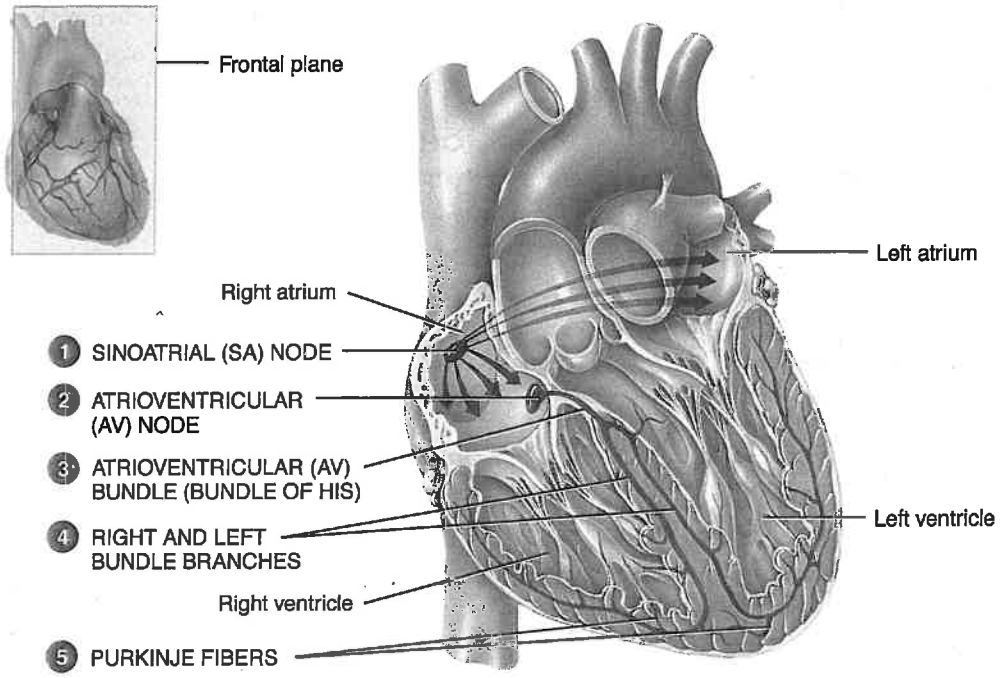
OBJECTIVE ● **Explain how each heartbeat is initiated and maintained.**

About 1% of the cardiac muscle fibers are different from all others because they can generate action potentials over and over and do so in a rhythmical pattern. These cells have two important functions: They act as a ***pacemaker***, setting the rhythm for the entire heart, and they form the ***conduction system***, the route for action potentials throughout the heart muscle. The conduction system ensures that cardiac chambers are stimulated to contract in a coordinated manner, which makes the heart an effective pump. Cardiac action potentials pass through the following components of the conduction system (Figure 15.6):

1. Normally, cardiac excitation begins in the ***sinoatrial (SA) node***, located in the right atrial wall just inferior to the opening of the superior vena cava. An action potential spontaneously arises in the SA node and then conducts throughout both atria via gap junctions in the intercalated discs of atrial fibers (see Figure 15.2b). Following the action potential, the atria contract.
2. By conducting along atrial muscle fibers, the action potential also reaches the ***atrioventricular (AV) node***, located in the interatrial septum, just anterior to the opening of the coronary sinus. At the AV node, the action potential slows considerably, providing time for the atria to empty their blood into the ventricles.
3. From the AV node, the action potential enters the ***atrioventricular (AV) bundle*** (also known as the ***bundle of His***), in the interventricular septum. The AV bundle is the only site where action potentials can conduct from the atria to the ventricles.
4. After conducting along the AV bundle, the action potential then enters both the ***right*** and ***left bundle branches*** that course through the interventricular septum toward the apex of the heart.
5. Finally, large-diameter ***Purkinje fibers*** (pur-KIN-jē) rapidly conduct the action potential, first to the apex of the ventricles and then upward to the remainder of the ventricular myocardium. Then, a fraction of a second after the atria contract, the ventricles contract.

Figure 15.6 Conduction system of the heart. The SA node, located in the right atrial wall, is the heart's pacemaker, initiating cardiac action potentials that cause contraction of the heart's chambers. The arrows indicate the flow of action potentials through the atria. The route of action potentials through the numbered components of the conduction system is described in the text.

The conduction system ensures that cardiac chambers contract in a coordinated manner.



Anterior view of frontal section

Which component of the conduction system provides the only route for action potentials to conduct between the atria and the ventricles?

The SA node initiates action potentials about 100 times per minute, faster than any other region of the conducting system. Thus, the SA node sets the rhythm for contraction of the heart—it is the *pacemaker* of the heart. Various hormones and neurotransmitters can speed or slow pacing of the heart by SA node fibers. In a person at rest, for example, acetylcholine released by the parasympathetic division of the ANS typically slows SA node pacing to about 75 action potentials per minute, causing 75 heartbeats per minute. If the SA node becomes diseased or damaged, the slower AV node fibers can become the pacemaker. With pacing by the AV node, however, heart rate is slower, only 40 to 60 beats/min. If the activity of both nodes is suppressed, the heartbeat may still be maintained by the AV bundle, a bundle branch, or Purkinje fibers. These fibers generate action potentials very slowly, about 20 to 35 times per minute. At such a low heart rate, blood flow to the brain is inadequate.

When the heart rate is too low, normal heart rhythm can be restored and maintained by surgically implanting an **artificial pacemaker**, a device that sends out small electrical currents to stimulate the heart to contract. A pacemaker consists of a battery and impulse generator and is usually implanted beneath the skin just inferior to the clavicle. The pacemaker is connected to one or two flexible wires (leads) that are threaded through the superior vena cava and then passed into the right atrium and right ventricle. Many of the newer pacemakers, called *activity-adjusted pacemakers*, automatically speed up the heartbeat during exercise.

■ CHECKPOINT

8. Describe the path of an action potential through the conduction system.

ELECTROCARDIOGRAM

OBJECTIVE • Describe the meaning and diagnostic value of an electrocardiogram.

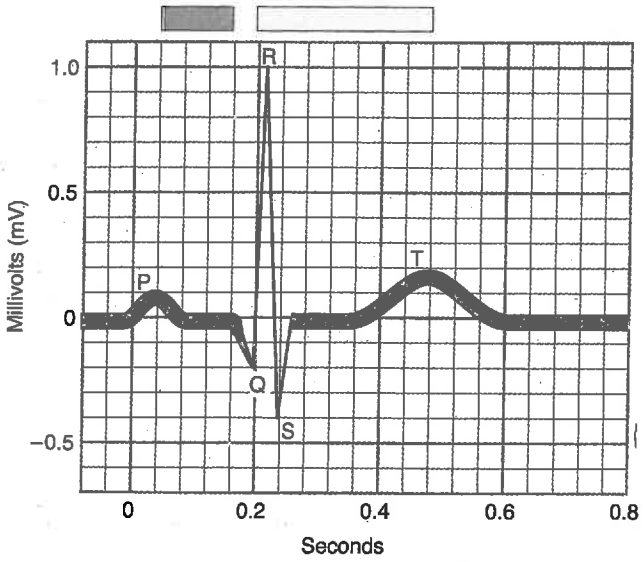
Conduction of action potentials through the heart generates electrical currents that can be picked up by electrodes placed on the skin. A recording of the electrical changes that accompany the heartbeat is called an ***electrocardiogram*** (e-lek′-trō-KAR-dē-ō-gram), which is abbreviated as either ***ECG*** or ***EKG***.

Three clearly recognizable waves accompany each heartbeat. The first, called the ***P wave***, is a small upward deflection on the ECG (Figure 15.7); it represents atrial depolarization, the depolarizing phase of the cardiac action potential as it spreads from the SA node throughout both atria. Depolarization causes contraction. Thus, a fraction of a second after the P wave begins, the atria contract. The second wave, called the ***QRS complex***, begins as a downward deflection (Q); continues as a large, upright, triangular wave (R); and ends as a downward wave (S). The QRS complex represents the onset of ventricular depolarization, as the cardiac action potential spreads through the ventricles. Shortly after the QRS complex begins, the ventricles start to contract. The third wave is the ***T wave***, a dome-shaped upward deflection that indicates ventricular repolarization and occurs just before the ventricles start to relax. Repolarization of the atria is not usually evident in an ECG because it is masked by the larger QRS complex.

Variations in the size and duration of the waves of an ECG are useful in diagnosing abnormal cardiac rhythms and conduction patterns and in following the course of recovery from a heart attack. An ECG can also reveal the presence of a living fetus.

Figure 15.7 Normal electrocardiogram (ECG) of a single heartbeat. P wave = atrial depolarization; QRS complex = onset of ventricular depolarization; T wave = ventricular repolarization.

An electrocardiogram is a recording of the electrical activity that initiates each heartbeat.



What event occurs in response to atrial depolarization?

■ CHECKPOINT

9. What is the significance of the P wave, QRS complex, and T wave?

THE CARDIAC CYCLE

OBJECTIVE • Describe the phases of the cardiac cycle.

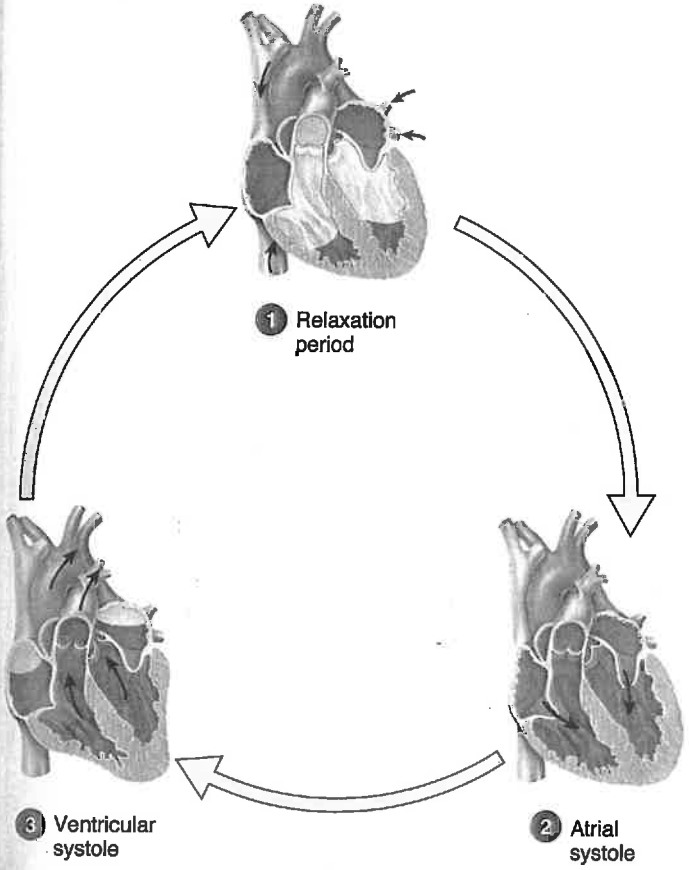
A single ***cardiac cycle*** includes all the events associated with one heartbeat. In a normal cardiac cycle, the two atria contract while the two ventricles relax; then, while the two ventricles contract, the two atria relax. The term ***systole*** (SIS-tō-lē = contraction) refers to the phase of contraction; ***diastole*** (dī-AS-tō-lē = dilation or expansion) refers to the phase of relaxation. A cardiac cycle consists of systole and diastole of both atria plus systole and diastole of both ventricles.

For the purposes of our discussion, we will divide the ***cardiac cycle*** into three phases (Figure 15.8):

1. ***Relaxation period.*** The relaxation period begins at the end of a cardiac cycle when the ventricles start to relax and all four chambers are in diastole. Repolarization of the ventricular muscle fibers (T wave in the ECG) initiates relaxation. As the ventricles relax, pressure within them drops. When ventricular pressure drops below atrial pressure, the AV valves open and ventricular filling begins. About 75% of the ventricular filling occurs after the AV valves open and before the atria contract.
2. ***Atrial systole (contraction).*** An action potential from the SA node causes atrial depolarization, noted as the P wave in the ECG. Atrial systole follows the P wave, which marks the end of the relaxation period. As the atria contract, they force the last 25% of the blood into the ventricles. At the end of atrial systole, each ventricle contains about 130 mL of blood. The AV valves are still open and the semilunar valves are still closed.
3. ***Ventricular systole (contraction).*** The QRS complex in the ECG indicates ventricular depolarization, which leads to contraction of the ventricles. Ventricular contraction pushes blood against the AV valves, forcing them shut. As ventricular contraction continues, pressure inside the chambers quickly rises. When left ventricular

Figure 15.8 Cardiac cycle.

A cardiac cycle is composed of all the events associated with one heartbeat.



What is the term used for the contraction phase of the cardiac cycle? The relaxation phase?

pressure surpasses aortic pressure and right ventricular pressure rises above the pressure in the pulmonary trunk, both semilunar valves open, and ejection of blood from the heart begins. Ejection continues until the ventricles start to relax. At rest, the volume of blood ejected from each ventricle during ventricular systole is about 70 mL (a little more than 2 oz.). When the ventricles begin to relax, ventricular pressure drops, the semilunar valves close, and another relaxation period begins.

At rest, each cardiac cycle lasts about 0.8 sec. In one complete cycle, the first 0.4 sec of the cycle is the relaxation period, when all four chambers are in diastole. Then, the atria are in systole for 0.1 sec and in diastole for the next 0.7 sec. After atrial systole, the ventricles are in systole for 0.3 sec and in diastole for 0.5 sec. When the heart beats faster, for instance during exercise, the relaxation period is shorter.

Heart Sounds

The sound of the heartbeat comes primarily from turbulence in blood flow created by the closure of the valves, not from the contraction of the heart muscle. The first sound, ***lubb***, is a long, booming sound from the AV valves closing after ventricular systole begins. The second sound, a short, sharp sound, ***dupp***, is from the semilunar valves closing at the end of ventricular systole. There is a pause during the relaxation period. Thus, the cardiac cycle is heard as: lubb, dupp, pause; lubb, dupp, pause; lubb, dupp, pause.

Heart sounds provide valuable information about the mechanical operation of the heart. A **heart murmur** is an abnormal sound consisting of a clicking, rushing, or gurgling noise that is heard before, between, or after the normal heart sounds, or that may mask the normal heart sounds. Heart murmurs in children are extremely common and usually do not represent a health condition. These types of heart murmurs often subside or disappear with growth. Although some heart murmurs in adults are innocent, most often a murmur indicates a valve disorder.

■ CHECKPOINT

10. Explain the events that occur during each of the three phases of the cardiac cycle.

11. What causes the heart sounds?

CARDIAC OUTPUT

OBJECTIVE • Define cardiac output, explain how it is calculated, and describe how it is regulated.

The volume of blood ejected per minute from the left ventricle into the aorta is called the ***cardiac output (CO)***. (Note that the same amount of blood is also ejected from the right ventricle into the pulmonary trunk.) Cardiac output is determined by (1) the ***stroke volume (SV)***, the amount of blood ejected by the left ventricle during each beat (contraction), and (2) ***heart rate (HR)***, the number of heartbeats per minute. In a resting adult, stroke volume averages 70 mL, and heart rate is about 75 beats per minute. Thus the average cardiac output in a resting adult is

$$\begin{aligned}\text{Cardiac output} &= \text{stroke volume} \times \text{heart rate}\\ &= 70\ \text{mL/beat} \times 75\ \text{beats/min}\\ &= 5250\ \text{mL/min or } 5.25\ \text{liters/min}\end{aligned}$$

Factors that increase stroke volume or heart rate, such as exercise, increase cardiac output.

Regulation of Stroke Volume

Although some blood is always left in the ventricles at the end of their contraction, a healthy heart pumps out the blood that has entered its chambers during the previous diastole.

Focus on Wellness

Sudden Cardiac Death During Exercise — What's the Risk?

Regular physical activity helps keep hearts and arteries healthy. But very rarely, strenuous activity can precipitate a heart attack. In adults of middle age and older, a heart attack, or myocardial infarction, typically occurs because a blood clot lodges in an artery of the heart already narrowed by atherosclerotic plaque. During exercise, heart rate and blood pressure increase. Under this stress, an unstable plaque may rupture, stimulating the clotting process as the body tries to repair the damaged artery.

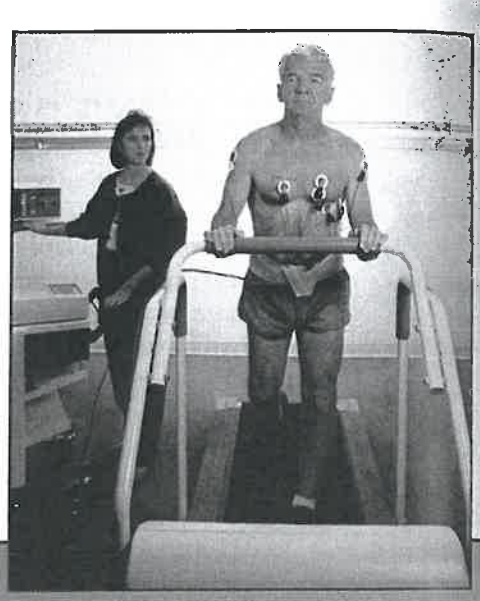
How Risky Is Exercise?

Many studies have been conducted in an attempt to quantify the risk imposed by strenuous exercise. Researchers have concluded that, in general, risk of heart attack is about two to six times higher during strenuous exercise than during light physical activity or rest. The statistical risk of heart attack varies considerably depending on a person's exercise history. Risk is lowest for those who exercise regularly and highest for people unaccustomed to exercise. Risk during exercise also rises with the number and severity of other cardiovascular risk factors. For example, people already diagnosed with heart disease are 10 times as likely to have a heart attack during exercise as apparently healthy individuals. Though this may sound discouraging, the risk can be seen from another point of view. Overall, the incidence of death during physical activity is very low, about 6 deaths per 100,000 middle-aged men per year.

Exercise is also safe for most people recovering from heart attacks. In 167 supervised cardiac rehabilitation exercise programs, the incidence of heart attack in 51,000 patients was 1 in 294,000 person-hours (number of people multiplied by number of hours each exercised). Incidence of death was only 1 in 784,000 person-hours.

Who Is at Risk?

Although these figures illustrate that risk of heart attack and death are quite low, if the death occurs to someone you love, it happens 100% and is still a tragic loss. People with diagnosed or suspected artery disease are most at risk and should check with their physicians before starting an exercise program. Risk can be reduced by exercising regularly (several times per week) at a low to moderate intensity, and by heeding any warning signs of cardiovascular disease, such as chest pain or pressure, abnormal heart rhythms, or dizziness.



▶ **Think It Over . . .**

▶ *Why do you think exercise stress tests are used to help diagnose coronary artery disease?*

The more blood that returns to the heart during diastole, the more blood that is ejected during the next systole. Three factors regulate stroke volume and ensure that the left and right ventricles pump equal volumes of blood:

1. **The degree of stretch in the heart before it contracts.** Within limits, the more the heart is stretched as it fills during diastole, the greater the force of contraction during systole, a relationship known as the ***Frank–Starling law of the heart.*** The situation is somewhat like stretching a rubber band: The more you stretch the heart, the more forcefully it contracts. In other words, within physiological limits, the heart pumps all the blood it receives. If the left side of the heart pumps a little more blood than the right side, a larger volume of blood returns to the right ventricle. On the next beat the right ventricle contracts more forcefully, and the two sides are again in balance.
2. **The forcefulness of contraction of individual ventricular muscle fibers.** Even at a constant degree of stretch, the heart can contract more or less forcefully when certain substances are present. Stimulation of the sympathetic division of the autonomic nervous system (ANS), hormones such as epinephrine and norepinephrine, increased Ca^{2+} level in the interstitial fluid, and the drug digitalis all increase the force of contraction of cardiac muscle fibers. In contrast, inhibition of the sympathetic division of the ANS, anoxia, acidosis, some anesthetics, and increased K^+ level in the extracellular fluid decrease contraction force.
3. **The pressure required to eject blood from the ventricles.** The semilunar valves open and ejection of blood from the heart begins when pressure in the right ventricle exceeds the pressure in the pulmonary trunk and

when the pressure in the left ventricle exceeds the pressure in the aorta. When the required pressure is higher than normal, the valves open later than normal, stroke volume decreases, and more blood remains in the ventricles at the end of systole.

In **congestive heart failure (CHF),** the heart is a failing pump. It pumps blood less and less effectively, leaving more blood in the ventricles at the end of each cycle. The result is a positive feedback cycle. Less-effective pumping leads to even lower pumping capability. Often, one side of the heart starts to fail before the other. If the left ventricle fails first, it can't pump out all the blood it receives, and blood backs up in the lungs. The result is *pulmonary edema*, fluid accumulation in the lungs that can lead to suffocation. If the right ventricle fails first, blood backs up in the systemic blood vessels. In this case, the resulting *peripheral edema* is usually most noticeable as swelling in the feet and ankles. Common causes of CHF are coronary artery disease (see page 379), long-term high blood pressure, myocardial infarctions, and valve disorders.

Regulation of Heart Rate

Adjustments to the heart rate are important in the short-term control of cardiac output and blood pressure. If left to itself, the sinoatrial node would set a constant heart rate of abou 100 beats/min. However, tissues require different volumes c blood flow under different conditions. During exercise, fc example, cardiac output rises to supply working tissues wit increased amounts of oxygen and nutrients. The most impor tant factors in the regulation of heart rate are the autonomi nervous system and the hormones epinephrine and norep nephrine, released by the adrenal glands.

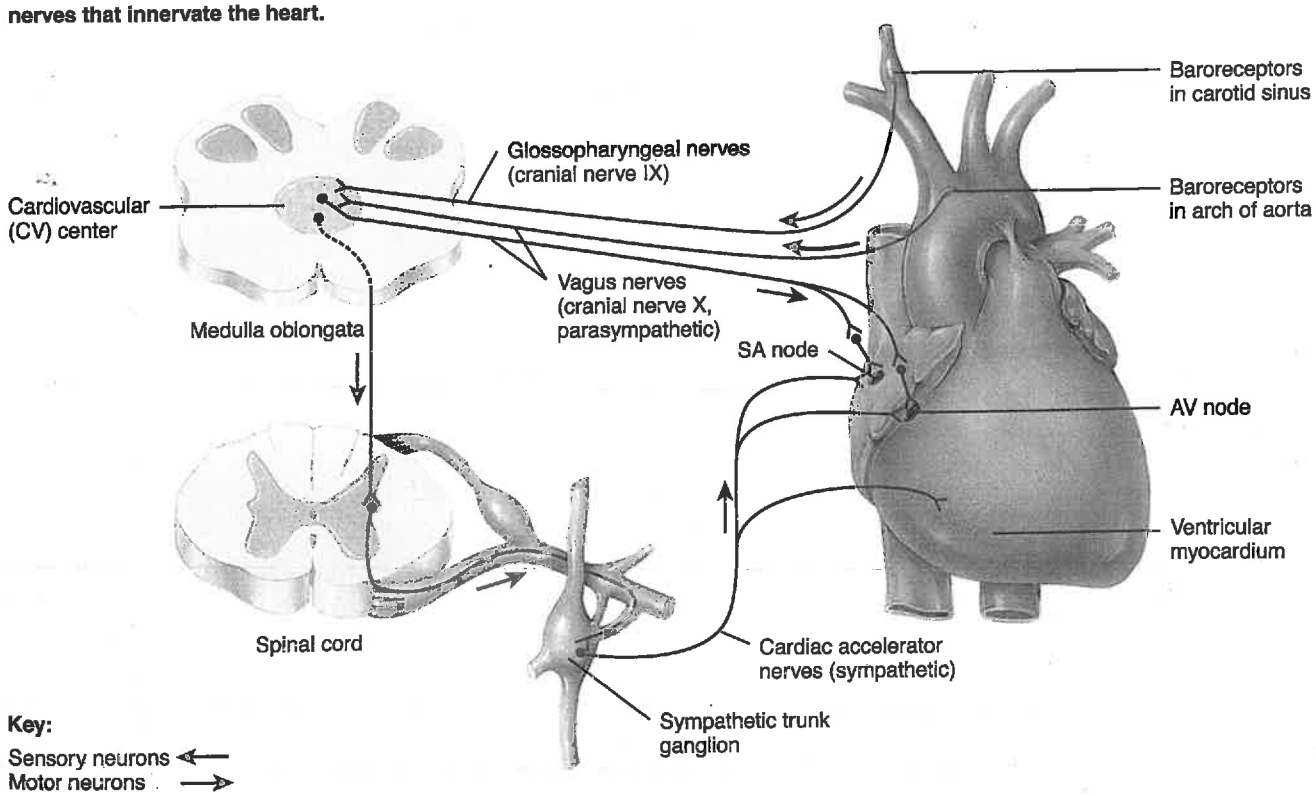
Autonomic Regulation of Heart Rate

The nervous system regulation of the heart originates in th ***cardiovascular (CV) center*** in the medulla oblongata. Th region of the brain stem receives input from a variety c sensory receptors and from higher brain centers, such as th limbic system and cerebral cortex. The cardiovascular cent then directs appropriate output by increasing or decreasing th frequency of nerve impulses sent out to both the sympathet and parasympathetic branches of the ANS (Figure 15.9).

Arising from the CV center are sympathetic neurons th reach the heart via ***cardiac accelerator nerves***. They inne vate the conduction system, atria, and ventricles. The norep nephrine released by cardiac accelerator nerves increases th heart rate. Also arising from the CV center are parasymp thetic neurons that reach the heart via the ***vagus (X) nerve***. These parasympathetic neurons extend to the conductic system and atria. The neurotransmitter they release—acety

Figure 15.9 Autonomic nervous system regulation of heart rate.

The cardiovascular center in the medulla oblongata controls both sympathetic and parasympathetic nerves that innervate the heart.



What effect does acetylcholine, released by parasympathetic nerves, have on heart rate?

choline (ACh)—decreases the heart rate by slowing the pacemaking activity of the SA node.

Several types of sensory receptors provide input to the cardiovascular center. For example, ***baroreceptors*** (*baro-* = pressure), neurons sensitive to blood pressure changes, are strategically located in the arch of the aorta and carotid arteries (arteries in the neck that supply blood to the brain). If there is an increase in blood pressure, the baroreceptors send nerve impulses along sensory neurons that are part of the glossopharyngeal (IX) and vagus (X) nerves to the CV center (Figure 15.9). The cardiovascular center responds by putting out more nerve impulses along the parasympathetic (motor) neurons that are also part of the vagus (X) nerves. The resulting decrease in heart rate lowers cardiac output and thus lowers blood pressure. If blood pressure falls, baroreceptors do not stimulate the cardiovascular center. As a result of this lack of stimulation, heart rate increases, cardiac output increases, and blood pressure increases to the normal level. ***Chemoreceptors***, neurons sensitive to chemical changes in the blood, detect changes in blood levels of chemicals such as O_2, CO_2, and H^+. Their relationship to the cardiovascular center is considered in Chapter 16 with regard to blood pressure.

Chemical Regulation of Heart Rate

Certain chemicals influence both the basic physiology of cardiac muscle and its rate of contraction. Chemicals with major effects on the heart fall into one of two categories:

1. **Hormones.** Epinephrine and norepinephrine (from the adrenal medullae) enhance the heart's pumping effectiveness by increasing both heart rate and contraction force. Exercise, stress, and excitement cause the adrenal medullae to release more hormones. Thyroid hormones also increase heart rate. One sign of hyperthyroidism (excessive levels of thyroid hormone) is tachycardia (elevated resting heart rate).
2. **Ions.** Elevated blood levels of K^+ or Na^+ decrease heart rate and contraction force. A moderate increase in extracellular and intracellular Ca^{2+} level increases heart rate and contraction force.

Other Factors in Heart Rate Regulation

Age, gender, physical fitness, and body temperature also influence resting heart rate. A newborn baby is likely to have a resting heart rate over 120 beats per minute; the rate then declines throughout childhood to the adult level of 75 beats per minute. Adult females generally have slightly higher resting heart rates than adult males, although regular exercise tends to bring resting heart rate down in both sexes. As adults age, their heart rates may increase.

Increased body temperature, such as occurs during fever or strenuous exercise, increases heart rate by causing the SA node to discharge more rapidly. Decreased body temperature decreases heart rate and force of contraction. During surgical repair of certain heart abnormalities, it is helpful to slow a patient's heart rate by deliberately cooling the body.

■ CHECKPOINT

12. Describe how stroke volume is regulated.
13. How does the autonomic nervous system help regulate heart rate?

EXERCISE AND THE HEART

OBJECTIVE • Explain the relationship between exercise and the heart.

Regardless of the current level, a person's cardiovascular fitness can be improved at any age with regular exercise. Some types of exercise are more effective than others for improving the health of the cardiovascular system. ***Aerobics***, any activity that works large body muscles for at least 20 minutes, elevates cardiac output and accelerates metabolic rate. Three to five such sessions a week are usually recommended for improving the health of the cardiovascular system. Brisk walking, running, bicycling, cross-country skiing, and swimming are examples of aerobic activities.

Sustained exercise increases the oxygen demand of the muscles. Whether the demand is met depends mainly on the adequacy of cardiac output and proper functioning of the respiratory system. After several weeks of training, a healthy person increases maximal cardiac output, thereby increasing the maximal rate of oxygen delivery to the tissues. Oxygen delivery also rises because skeletal muscles develop more capillary networks in response to long-term training.

During strenuous activity, a well-trained athlete can achieve a cardiac output double that of a sedentary person, in part because training causes hypertrophy (enlargement) of the heart. Even though the heart of a well-trained athlete is larger, *resting* cardiac output is about the same as in a healthy untrained person, because stroke volume is increased while heart rate is decreased. The resting heart rate of a trained athlete often is only 40–60 beats per minute (*resting bradycardia*). Regular exercise also helps to reduce blood pressure, anxiety, and depression; control weight; and increase the body's ability to dissolve blood clots by increasing fibrinolytic activity.

■ CHECKPOINT

14. What is aerobic exercise? Why are aerobic exercises beneficial?

• • •

The heart is the blood pump for the cardiovascular system, but it is the blood vessels that distribute blood to all parts of the body and collect blood from them. In the next chapter we will see how blood vessels accomplish this.

COMMON DISORDERS

Coronary Artery Disease

Coronary artery disease (CAD) affects about 7 million people and causes nearly 750,000 deaths in the United States each year. CAD is defined as the effects of the accumulation of atherosclerotic plaques (described shortly) in coronary arteries that lead to a reduction in blood flow to the myocardium. Some individuals have no signs or symptoms, others experience angina pectoris (chest pain), and still others suffer a heart attack.

People who possess combinations of certain risk factors are more likely to develop CAD. *Risk factors* (characteristics, symptoms, or signs that are statistically associated with a greater chance of developing a disease) include smoking, high blood pressure, diabetes, high cholesterol levels, obesity, "type A" personality, sedentary lifestyle, and a family history of CAD. Most of these can be modified by changing diet and other habits or can be controlled by taking medications. However, other risk factors are unmodifiable—that is, beyond our control—including genetic predisposition (family history of CAD at an early age), age, and gender. For example, adult males are more likely than adult females to develop CAD; after age 70 the risks are roughly equal. Smoking is undoubtedly the number-one risk factor in all CAD-associated diseases, roughly doubling the risk of morbidity and mortality.

In recent years, a number of new risk factors (all modifiable) have been identified as significant predictors of CAD. *C-reactive proteins (CRPs)* are proteins produced by the liver or present in blood in an inactive form that are converted to an active form during inflammation. CRPs may play a direct role in the development of atherosclerosis by promoting the uptake of LDLs by macrophages. *Lipoprotein (a)* is an LDL-like particle that binds to endothelial cells, macrophages, and blood platelets, may promote the proliferation of smooth muscle fibers, and inhibits the breakdown of blood clots. *Fibrinogen* is a glycoprotein involved in blood clotting that may help regulate cellular proliferation, vasoconstriction, and platelet aggregation. *Homocysteine* is an amino acid that may induce blood vessel damage by promoting platelet aggregation and smooth muscle fiber proliferation.

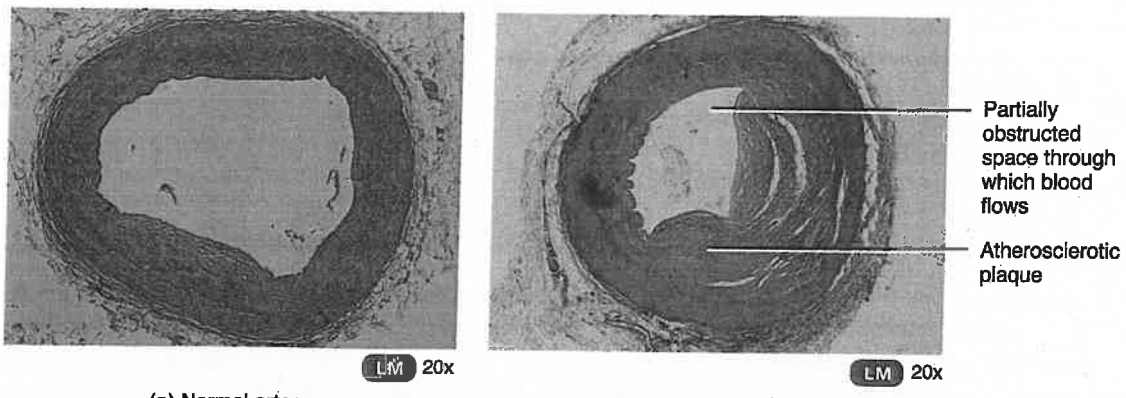
Atherosclerosis (ath'-er-ō-skler-ō-sis) is a progressive disease characterized by the formation in the walls of large- and medium-sized arteries of lesions called ***atherosclerotic plaques*** (Figure 15.10).

To understand how atherosclerotic plaques develop, you will need to know about molecules produced by the liver and small intestine called ***lipoproteins***. These spherical particles consist of an inner core of triglycerides and other lipids and an outer shell of proteins, phospholipids, and cholesterol. Two major lipoproteins are ***low-density lipoproteins*** or ***LDLs*** and ***high-density lipoproteins*** or ***HDLs***. LDLs transport cholesterol from the liver to body cells for use in cell membrane repair and the production of steroid hormones and bile salts. However, excessive amounts of LDLs promote atherosclerosis, so the cholesterol in these particles is known as "bad cholesterol." HDLs, on the other hand, remove excess cholesterol from body cells and transport it to the liver for elimination. Because HDLs decrease blood cholesterol level, the cholesterol in HDLs is known as "good cholesterol." Basically, you want your LDL to be low and your HDL to be high.

It has recently been learned that inflammation, a defensive response of the body to tissue damage, plays a key role in the development of atherosclerotic plaques. As a result of the damage, blood

Figure 15.10 Photomicrographs of a transverse section of (a) a normal artery and (b) one partially obstructed by an atherosclerotic plaque.

Atherosclerosis is a progressive disease caused by the formation of atherosclerotic plaques.



(a) Normal artery

(b) Obstructed artery

What substances are part of an atherosclerotic plaque?