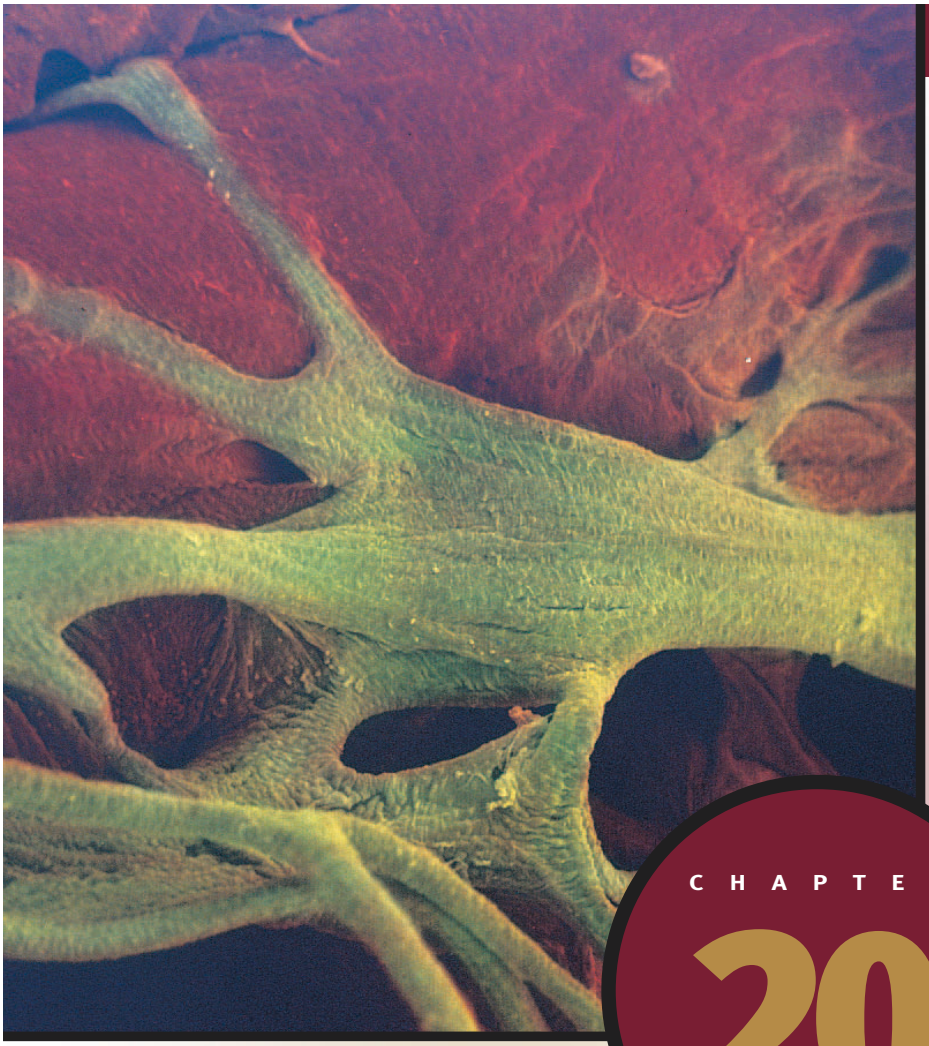


Colorized SEM of Purkinje fibers of the heart.

Cardiovascular System

The Heart

CHAPTER 20

Approximately 370 years ago, it was established that the heart's pumping action is essential to maintain the continuous circulation of blood throughout the body. Our current understanding of the detailed function of this amazing pump, its regulation, and modern treatments for heart disease is, in comparison, very recent.

The heart is actually two pumps in one. The right side of the heart receives blood from the body and pumps blood through the **pulmonary** (pŭl′mō-nār-ē) **circulation,** which carries blood to the lungs and returns it to the left side of the heart. In the lungs, carbon dioxide diffuses from the blood into the lungs, and oxygen diffuses from the lungs into the blood. The left side of the heart pumps blood through the **systemic circulation,** which delivers oxygen and nutrients to all remaining tissues of the body. From those tissues carbon dioxide and other waste products are carried back to the right side of the heart (figure 20.1).

The heart of a healthy 70 kg person pumps approximately 7200 L (approximately 1900 gallons) of blood each day at a rate of 5 L/min. For most people, the heart continues to pump for more than 75 years. During periods of vigorous exercise, the amount of blood pumped per minute increases severalfold. The life of the individual is in danger if the heart loses its ability to pump blood for even a few minutes. **Cardiology** (kar-dē-ol′ō-jē) is a medical specialty concerned with the diagnosis and treatment of heart disease.

This chapter describes the *functions of the heart* (668), *size, shape, and location of the heart* (668), the *anatomy of the heart* (670), the *route of blood flow through the heart* (677), and its *histology* (679) and *electrical properties* (681). The *cardiac cycle* (685), *mean arterial blood pressure* (692), *regulation of the heart* (693), and the *heart and homeostasis* (696) are described. The chapter ends with the *effects of aging on the heart* (699).

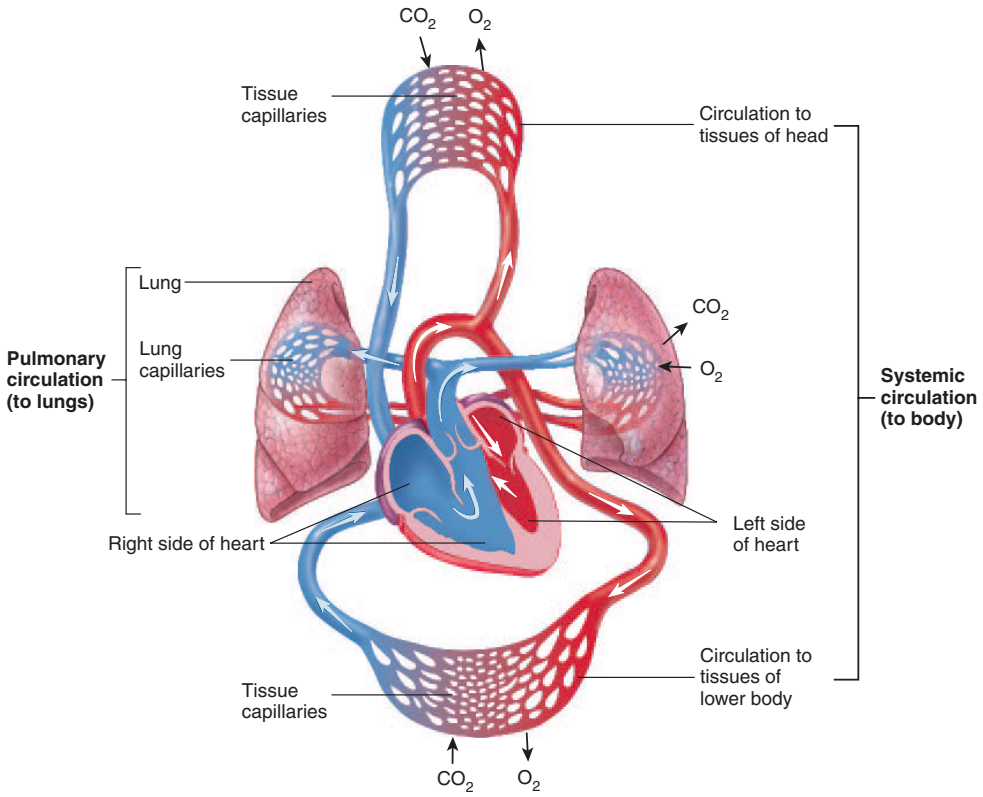


Figure 20.1 Systemic and Pulmonary Circulation

The right side of the heart receives deoxygenated blood (*blue*) from the body and pumps it to the lungs through the pulmonary circulation. The left side of the heart receives oxygenated blood (*red*) from the lungs and pumps it to the body through the systemic circulation to deliver oxygen to the tissues. After passing through the tissues, deoxygenated blood is returned to the right side of the heart.

Functions of the Heart

Objective

- ***Explain the functions of the heart***

The functions of the heart include:

1. *Generating blood pressure.* Contractions of the heart generate blood pressure, which is responsible for blood movement through the blood vessels.
2. *Routing blood.* The heart separates the pulmonary and systemic circulations and ensures better oxygenation of blood flowing to tissues.
3. *Ensuring one-way blood flow.* The valves of the heart ensure a one-way flow of blood though the heart and blood vessels.
4. *Regulating blood supply.* Changes in the rate and force of contraction match blood delivery to the changing metabolic needs of the tissues, such as during rest, exercise, and changes in body position.

1. List four major functions of the heart.

Size, Shape, and Location of the Heart

Objective

- ***Describe the size, shape, and location of the heart.***

The adult heart is shaped like a blunt cone and is approximately the size of a closed fist. The blunt, rounded point of the cone is the **apex;** and the larger, flat part at the opposite end of the cone is the **base.**

The heart is located in the thoracic cavity between the lungs. The heart, trachea, esophagus, and associated structures form a midline partition, the **mediastinum** (mē′dē-as-tī′nŭm; see figure 1.14).

It's important for clinical reasons to know the location of the heart in the thoracic cavity. Positioning a stethoscope to hear the heart sounds and positioning electrodes to record an **electrocardiogram** (ē-lek-trō-kar′dē-ō-gram; **ECG** or **EKG**) from chest leads depend on this knowledge. Effective cardiopulmonary resuscitation (kar′dē-ō-pŭl′mo-nār-ē rē-sŭs′i-tā-shŭn; **CPR**)

also depends on a reasonable knowledge of the position and shape of the heart. The heart lies obliquely in the mediastinum, with its base directed posteriorly and slightly superiorly and the apex directed anteriorly and slightly inferiorly. The apex is also directed to the left so that approximately two-thirds of the heart's mass lies to the left of the midline of the sternum (figure 20.2). The base of the heart is located deep to the sternum and extends to the second intercostal space. The apex is approximately 9 centimeters (cm) to the left of the sternum and is deep to the fifth intercostal space.

2. *Give the approximate size and shape of the heart. Where is it located?*

Cardiopulmonary Resuscitation (CPR)

In cases in which the heart suddenly stops beating, CPR can save lives. CPR involves rhythmic compression of the chest combined with artificial ventilation of the lungs. Applying pressure to the sternum compresses the chest wall, which also compresses the heart and causes it to pump blood. In many cases, CPR can provide an adequate blood supply to the heart wall and brain until emergency medical assistance arrives.

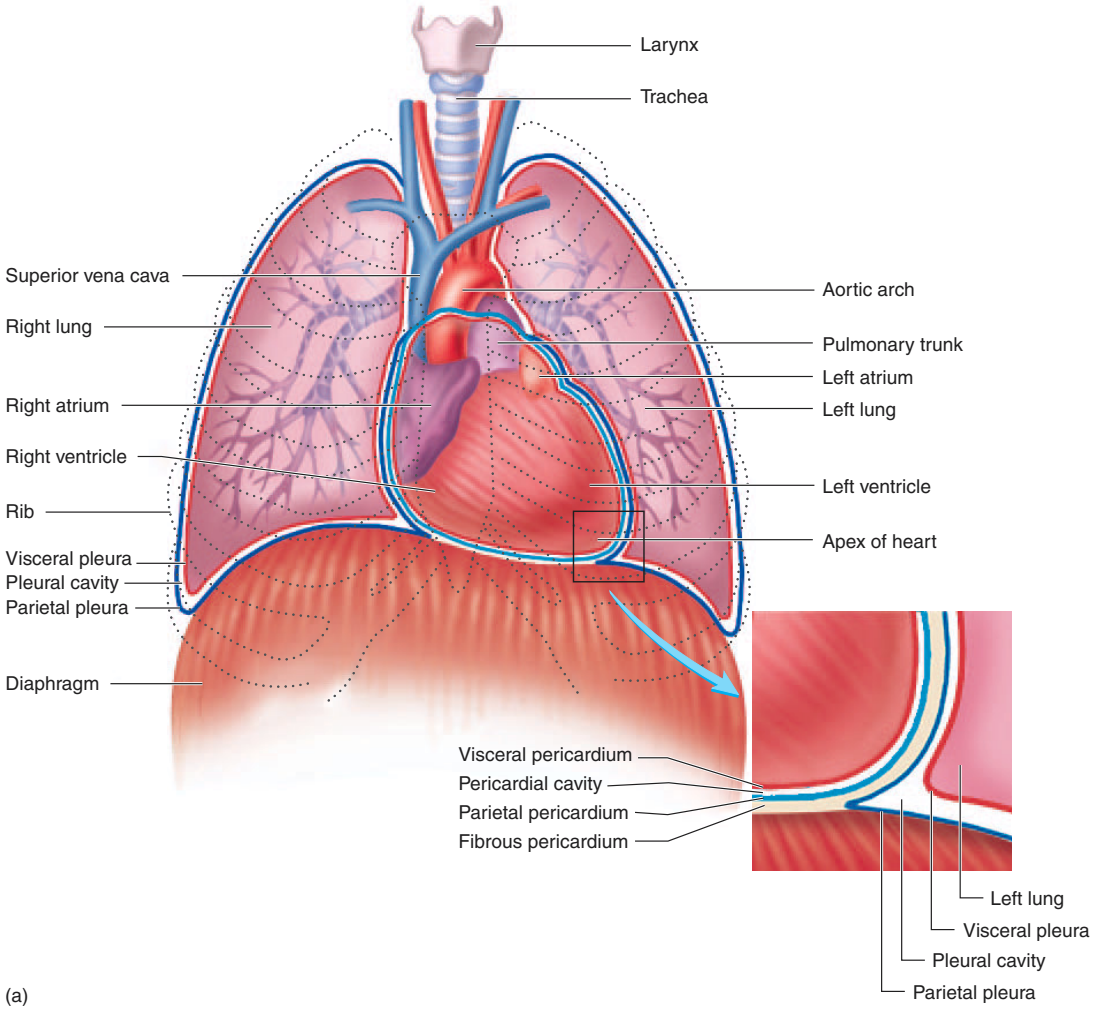


Figure 20.2 Location of the Heart in the Thorax

(*a*) The heart lies deep and slightly to the left of the sternum. The base of the heart, located deep to the sternum, extends to the second intercostal space, and the apex of the heart is in the fifth intercostal space, approximately 9 cm to the left of the midline.

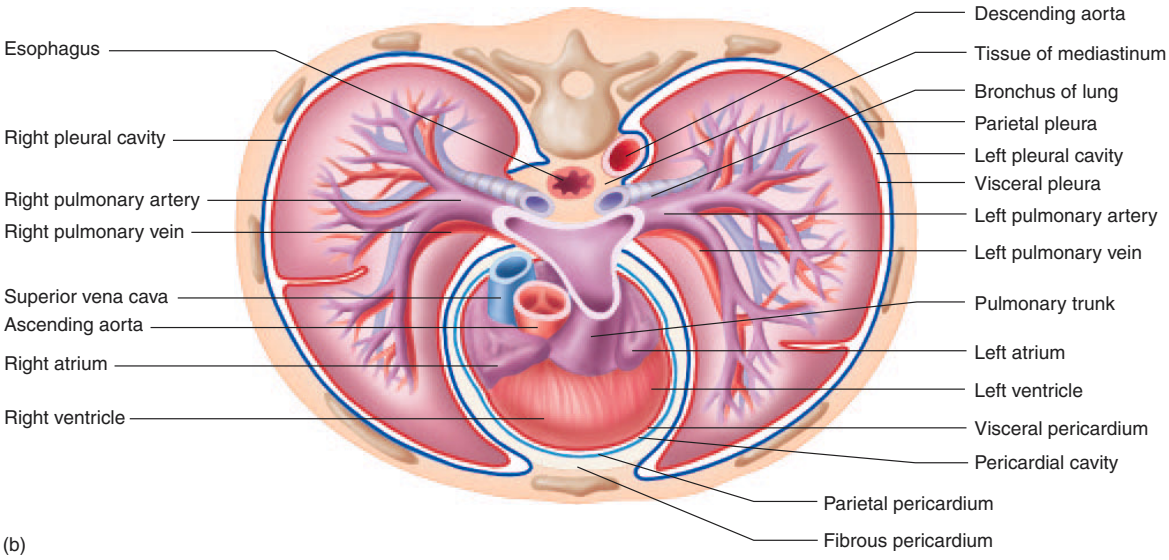


Figure 20.2 *(continued)*

(*b*) Cross section of the thorax showing the position of the heart in the mediastinum and its relationship to other structures.

Anatomy of the Heart

Objectives

- ***Describe the structure and function of the pericardium.***
- ***Describe the histology of the three major layers of the heart.***
- ***Describe the external and internal anatomy of the heart.***

Pericardium

The **pericardium** (per-i-kar′dē-ŭm), or **pericardial sac,** is a double-layered closed sac that surrounds the heart (figure 20.3). It consists of a tough, fibrous connective tissue outer layer called the **fibrous pericardium** and a thin, transparent inner layer of simple squamous epithelium called the **serous pericardium.** The fibrous pericardium prevents overdistention of the heart and anchors it within the mediastinum. Superiorly, the fibrous pericardium is continuous with the connective tissue coverings of the great vessels, and inferiorly it is attached to the surface of the diaphragm.

The part of the serous pericardium lining the fibrous pericardium is the **parietal pericardium,** and that part covering the heart surface is the **visceral pericardium,** or epicardium (see figure 20.3). The parietal and visceral portions of the serous pericardium are continuous with each other where the great vessels enter or leave the heart. The **pericardial cavity,** between the visceral and parietal pericardia, is filled with a thin layer of serous **pericardial fluid,** which helps reduce friction as the heart moves within the pericardial sac.

Pericarditis and Cardiac Tamponade

Pericarditis (per′i-kar-dī′tis) is an inflammation of the serous pericardium. The cause is frequently unknown, but it can result from infection, diseases of connective tissue, or damage due to radiation treatment for cancer. It can be extremely painful, with sensations of pain referred to the back and chest, which can be confused with the pain of a myocardial infarction (heart attack). Pericarditis can result in a small amount of fluid accumulation within the pericardial sac.

Cardiac tamponade (tam-pŏ-nād′) is a potentially fatal condition in which a large volume of fluid or blood accumulates in the pericardial sac. The fluid compresses the heart from the outside. Although the heart is a powerful muscle, it relaxes passively. When it is compressed by fluid within the pericardial sac, it cannot dilate when the cardiac muscle relaxes. Consequently, it cannot fill with blood during relaxation, which makes it impossible for it to pump blood. Cardiac tamponade can cause a person to die quickly unless the fluid is removed. Causes of cardiac tamponade include rupture of the heart wall following a myocardial infarction, rupture of blood vessels in the pericardium after a malignant tumor invades the area, damage to the pericardium resulting from radiation therapy, and trauma (e.g., a traffic accident).

Heart Wall

The heart wall is composed of three layers of tissue: the epicardium, the myocardium, and the endocardium (figure 20.4). The **epicardium** (ep-i-kar′dē-ŭm) is a thin serous membrane that constitutes the smooth outer surface of the heart. The epicardium and

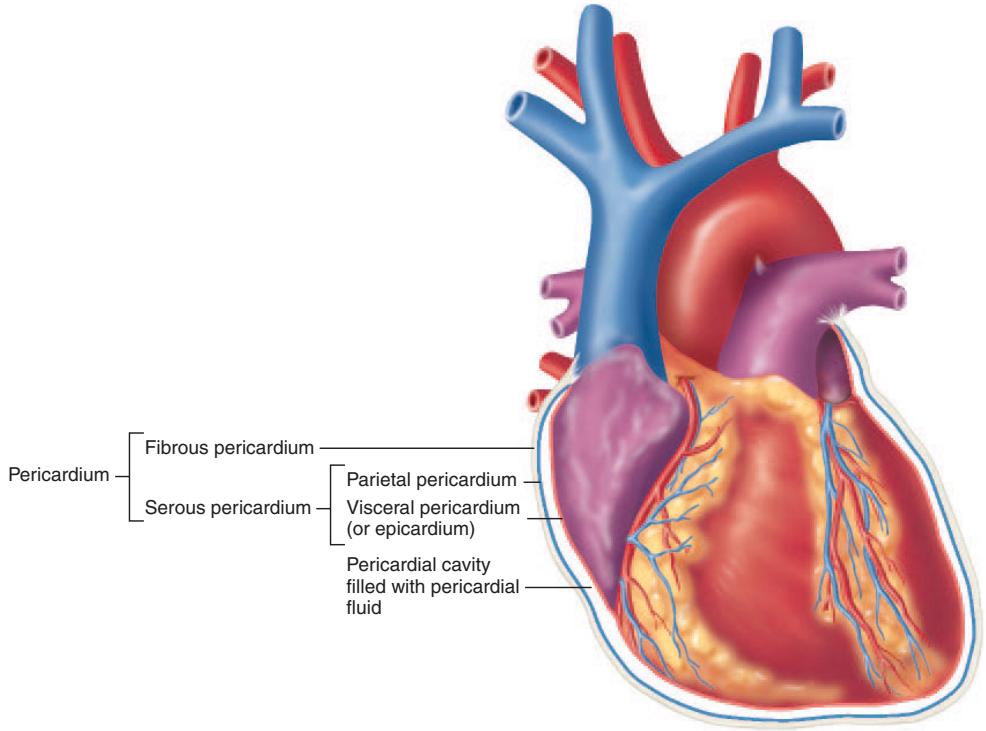


Figure 20.3 Heart in the Pericardium

The heart is located in the pericardium, which consists of an outer fibrous pericardium and an inner serous pericardium. The serous pericardium has two parts: the parietal pericardium lines the fibrous pericardium, and the visceral pericardium (epicardium) covers the surface of the heart. The pericardial cavity, between the parietal and visceral pericardium, is filled with a small amount of pericardial fluid.

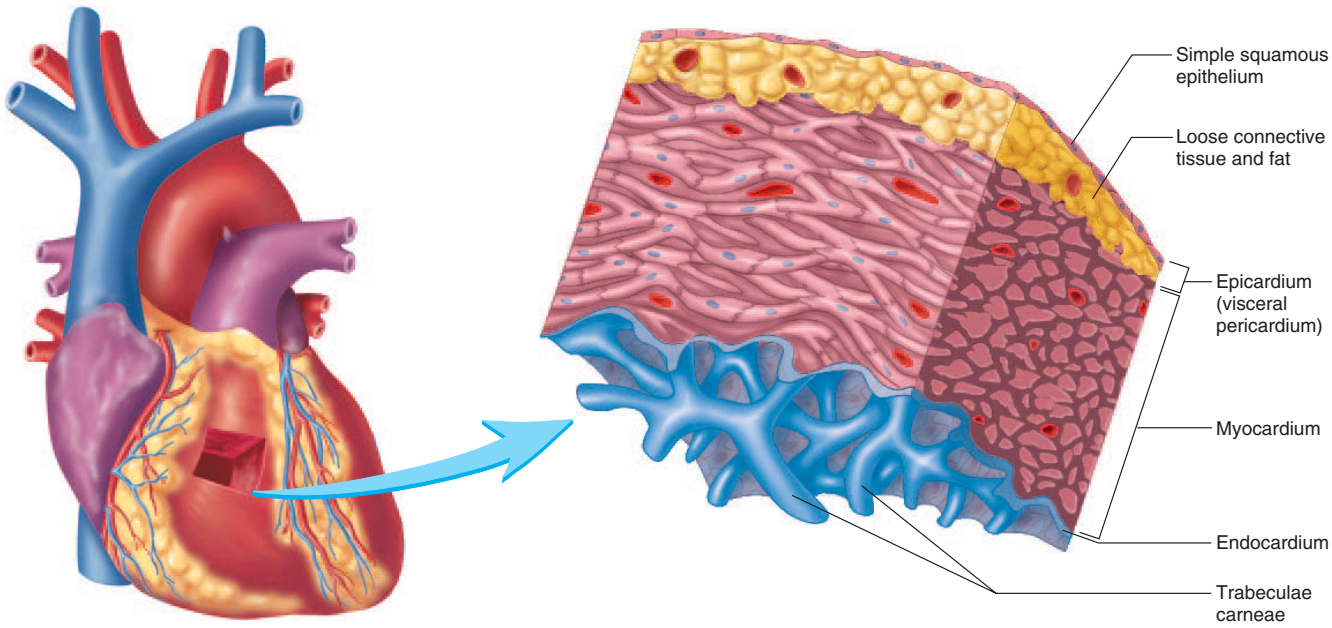


Figure 20.4 Heart Wall

Part of the wall of the heart has been removed to show its structure. The enlarged section illustrates the epicardium, the myocardium, and the endocardium.

the visceral pericardium are two names for the same structure. The serous pericardium is called the epicardium when considered a part of the heart and the visceral pericardium when considered a part of the pericardium. The thick middle layer of the heart, the **myocardium** (mī-ō-kar′dē-ŭm), is composed of cardiac muscle cells and is responsible for the ability of the heart to contract. The smooth inner surface of the heart chambers is the **endocardium** (en-dō-kar′dē-ŭm), which consists of simple squamous epithelium over a layer of connective tissue. The smooth inner surface allows blood to move easily through the heart. The heart valves result from a fold in the endocardium, thus making a double layer of endocardium with connective tissue in between.

The interior surfaces of the atria are mainly flat, but the interior of both auricles and a part of the right atrial wall contain muscular ridges called **musculi pectinati** (pek′ti-nah′tĕ; hair comb). The musculi pectinati of the right atrium are separated from the larger, smooth portions of the atrial wall by a ridge called the **crista terminalis** (kris′tă ter′mi-nal′is; terminal crest). The interior walls of the ventricles contain larger muscular ridges and columns called **trabeculae** (tră-bek′ū-lē; beams) **carneae** (kar′nē-ē; flesh).

External Anatomy and Coronary Circulation

The heart consists of four chambers: two **atria** (ā′trē-ă; entrance chamber) and two **ventricles** (ven′tri-klz; belly). The thin-walled atria form the superior and posterior parts of the heart, and the thick-walled ventricles form the anterior and inferior portions (figure 20.5). Flaplike **auricles** (aw′ri-klz; ears) are extensions of the atria that can be seen anteriorly between each atrium and ventricle. The entire atrium used to be called the auricle, and some medical personnel still refer to it as such.

Several large veins carry blood to the heart. The **superior vena cava** (vē′nă kā′vă) and the **inferior vena cava** carry blood from the body to the right atrium, and four **pulmonary veins** carry blood from the lungs to the left atrium. In addition, the smaller coronary sinus carries blood from the walls of the heart to the right atrium.

Two arteries, the **aorta** and the **pulmonary trunk,** exit the heart. The aorta carries blood from the left ventricle to the body, and the pulmonary trunk carries blood from the right ventricle to the lungs.

A large **coronary** (kōr′o-nār-ē; circling like a crown) **sulcus** (sool′kŭs; ditch) runs obliquely around the heart, separating the atria from the ventricles. Two more sulci extend inferiorly from the coronary sulcus, indicating the division between the right and left ventricles. The **anterior interventricular sulcus,** or **groove,** is on the anterior surface of the heart, and the **posterior interventricular sulcus,** or **groove,** is on the posterior surface of the heart. In a healthy, intact heart the sulci are covered by fat, and only after this fat is removed can the actual sulci be seen.

The major arteries supplying blood to the tissue of the heart lie within the coronary sulcus and interventricular sulci on the surface of the heart. The **right** and **left coronary arteries** exit the

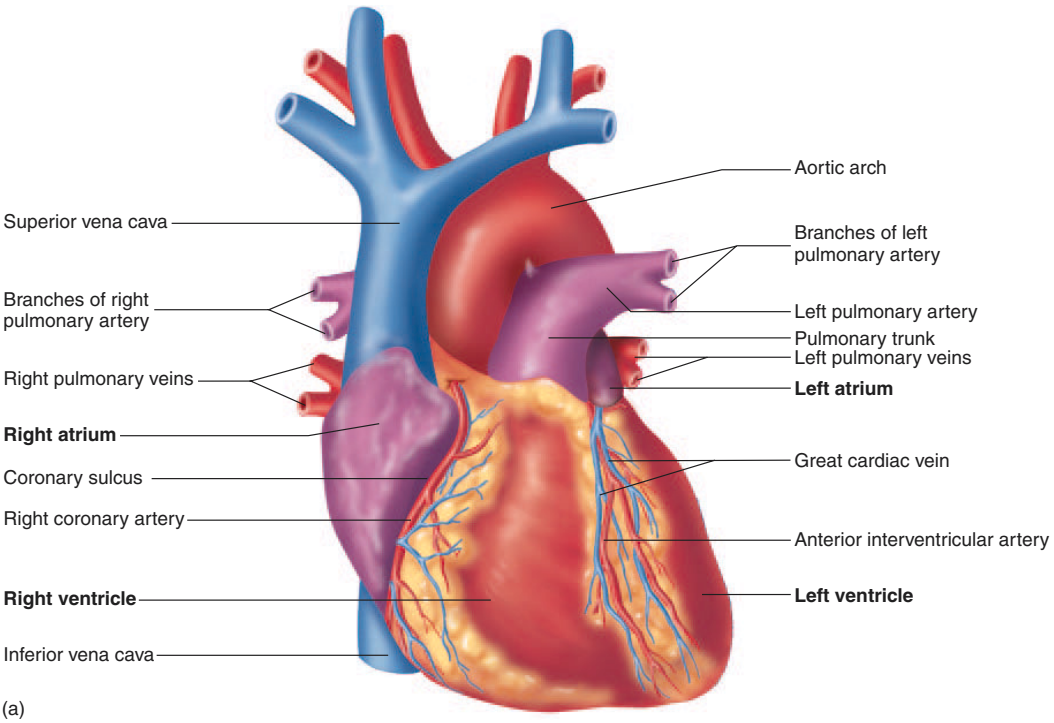


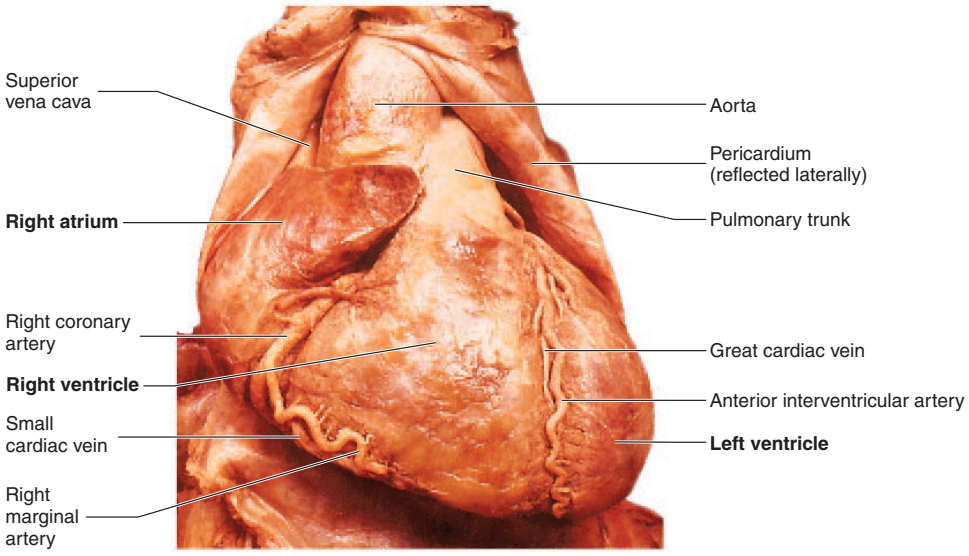
Figure 20.5 Surface of the Heart

(*a*) View of the anterior (sternocostal) surface.

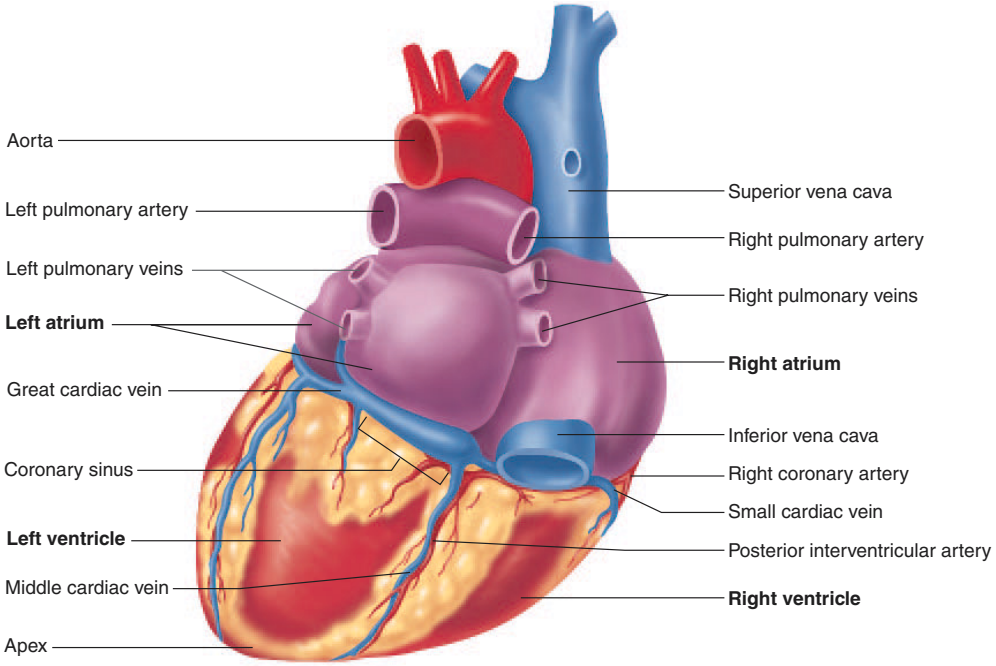
aorta just above the point where the aorta leaves the heart and lie within the coronary sulcus (figure 20.6*a*). The right coronary artery is usually smaller than the left one, and it doesn't supply as much of the heart with blood.

A major branch of the left coronary artery, called the **anterior interventricular artery,** or the **left anterior descending artery,** extends inferiorly in the anterior interventricular sulcus and supplies blood to most of the anterior part of the heart. The **left marginal artery** branches from the left coronary artery to supply blood to the lateral wall of the left ventricle. The **circumflex** (ser′kŭm-fleks) **artery** branches from the left coronary artery and extends around to the posterior side of the heart in the coronary sulcus. Its branches supply blood to much of the posterior wall of the heart.

The right coronary artery lies within the coronary sulcus and extends from the aorta around to the posterior part of the heart. A



(b)



(c)

Figure 20.5 *(continued)*

(*b*) Photograph of the anterior surface. (*c*) View of the posterior (base) and inferior (diaphragmatic) surfaces of the heart.

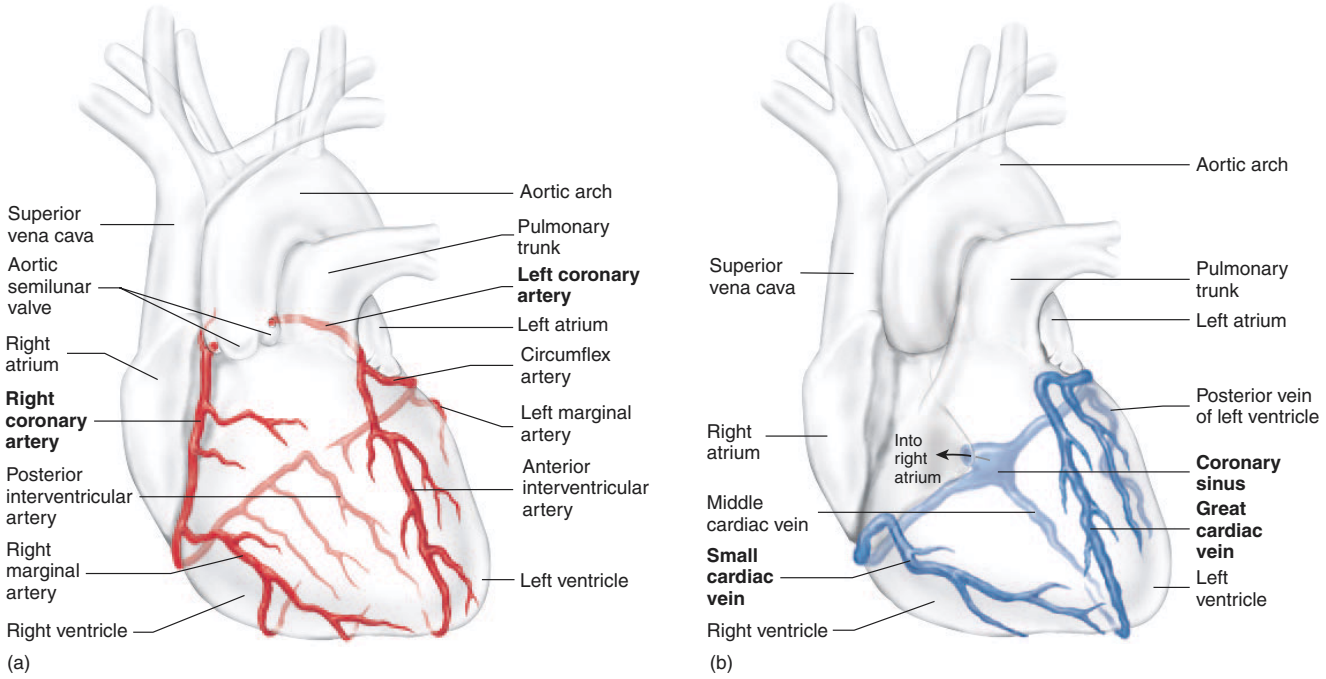


Figure 20.6 Coronary Circulation

(*a*) Arteries supplying blood to the heart. The arteries of the anterior surface are seen directly and are darker in color; the arteries of the posterior surface are seen through the heart and are lighter in color. (*b*) Veins draining blood from the heart. The veins of the anterior surface are seen directly and are darker in color; the veins of the posterior surface are seen through the heart and are lighter in color.

larger branch of the right coronary artery, called the **right marginal artery,** and other branches supply blood to the lateral wall of the right ventricle. A branch of the right coronary artery called the **posterior interventricular artery** lies in the posterior interventricular sulcus and supplies blood to the posterior and inferior part of the heart.

P R E D I C T 1

Predict the effect on the heart if blood flow through a coronary artery, such as the anterior interventricular artery, is restricted or completely blocked.

Most of the myocardium receives blood from more than one arterial branch. Furthermore, there are many anastamoses, or direct connections, between the arterial branches. The anastamoses are either between branches of a given artery or between branches of different arteries. In the event that one artery is blocked, the areas primarily supplied by that artery may still receive some blood through other arterial branches and through anastamoses with other branches. Aerobic exercise tends to increase the density of blood vessels supplying blood to the myocardium and the number and extent of the anastamoses increase. Consequently, aerobic exercise increases the chance that a person will survive the blockage of a small coronary artery. Blockage of larger coronary blood vessels still have the potential to permanently damage large areas of the heart wall.

The major vein draining the tissue on the left side of the heart is the **great cardiac vein,** and a **small cardiac vein** drains the right margin of the heart (figure 20.6*b*). These veins converge toward the posterior part of the coronary sulcus and empty into a large venous cavity called the **coronary sinus,** which in turn empties into the right atrium. A number of smaller veins empty into the cardiac veins, into the coronary sinus, or directly into the right atrium.

Blood flow through the coronary blood vessels is not continuous. When the cardiac muscle contracts, blood vessels in the wall of the heart are compressed and blood does not readily flow through them. When the cardiac muscle is relaxing, the blood vessels are not compressed and blood flow through the coronary blood vessels resumes.

Heart Chambers and Valves

Right and Left Atria

The **right atrium** has three major openings: the openings from the superior vena cava and the inferior vena cava receive blood from the body, and the opening of the coronary sinus receives blood from the heart itself (figure 20.7). The **left atrium** has four relatively uniform openings that receive the four pulmonary veins from the lungs. The two atria are separated from each other by the **interatrial septum.** A slight oval depression, the **fossa ovalis** (fos′ă ō-va′lis), on the right side of the septum marks the

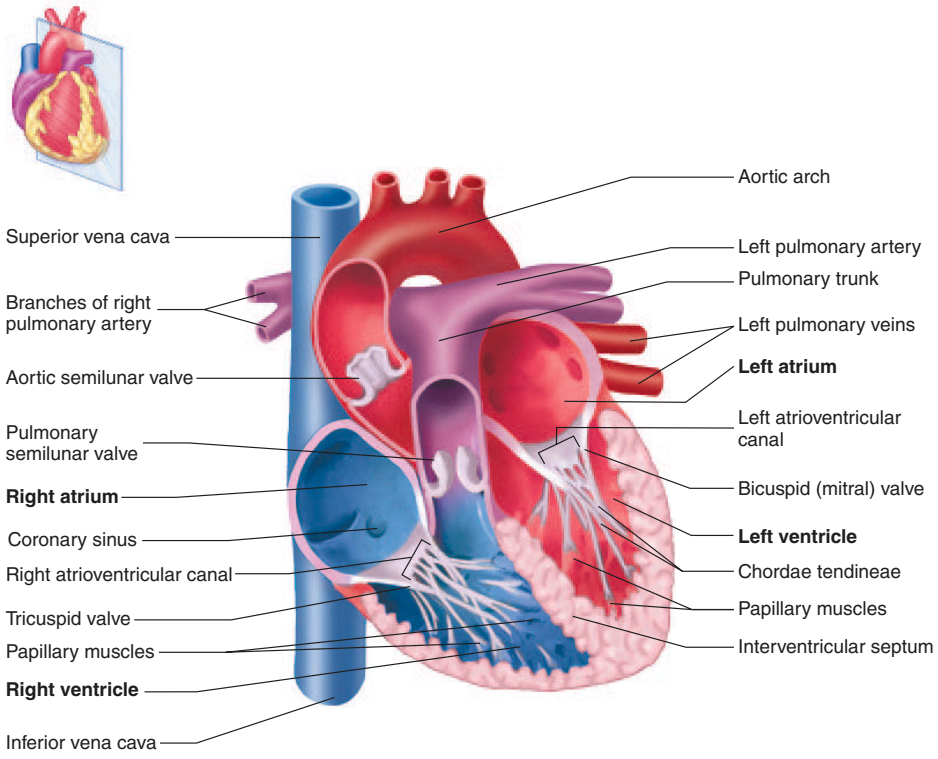


Figure 20.7 Internal Anatomy of the Heart

The heart is cut in a frontal plane to show the internal anatomy.

former location of the **foramen ovale** (ō-va′lē), an opening between the right and left atria in the embryo and the fetus (see chapter 29).

Right and Left Ventricles

The atria open into the ventricles through **atrioventricular canals** (see figure 20.7). Each ventricle has one large, superiorly placed outflow route near the midline of the heart. The **right ventricle** opens into the pulmonary trunk, and the **left ventricle** opens into the aorta. The two ventricles are separated from each other by the **interventricular septum,** which has a thick muscular part toward the apex and a thin membranous part toward the atria.

Atrioventricular Valves

An **atrioventricular valve** is in each atrioventricular canal and is composed of cusps, or flaps. These valves allow blood to flow from the atria into the ventricles but prevent blood from flowing back into the atria. The atrioventricular valve between the right atrium and the right ventricle has three cusps and is therefore called the **tricuspid** (trī-kŭs′pid) **valve.** The atrioventricular valve between the left atrium and left ventricle has two cusps and is therefore called the **bicuspid** (bī-kŭs′pid), or **mitral** (mī′trăl; resembling a bishop's miter, a two-pointed hat), **valve.**

Each ventricle contains cone-shaped muscular pillars called **papillary** (pap′i-lār-ē; nipple, or pimple-shaped) **muscles.** These muscles are attached by thin, strong connective tissue strings called **chordae tendineae** (kōr′dē ten′di-nē-ē; heart strings) to the cusps of the atrioventricular valves (see figure 20.7 and figure 20.8*a*). The papillary muscles contract when the ventricles contract and prevent the valves from opening into the atria by pulling on the chordae tendineae attached to the valve cusps. Blood flowing from the atrium into the ventricle pushes the valve open into the ventricle, but, when the ventricle contracts, blood pushes the valve back toward the atrium. The atrioventricular canal is closed as the valve cusps meet (figure 20.9).

Semilunar Valves

Within the aorta and pulmonary trunk are **aortic** and **pulmonary semilunar** (sem-ē-loo′năr; half-moon-shaped) **valves.** Each valve consists of three pocketlike semilunar cusps, the free inner borders of which meet in the center of the artery to block blood flow (see figures 20.7 and 20.8*b*). Blood flowing out of the ventricles pushes against each valve, forcing it open, but when blood flows back from the aorta or pulmonary trunk toward the ventricles, it enters the pockets of the cusps, causing them to meet in the center of the aorta or pulmonary trunk, thus closing them and keeping blood from flowing back into the ventricles (see figure 20.9).

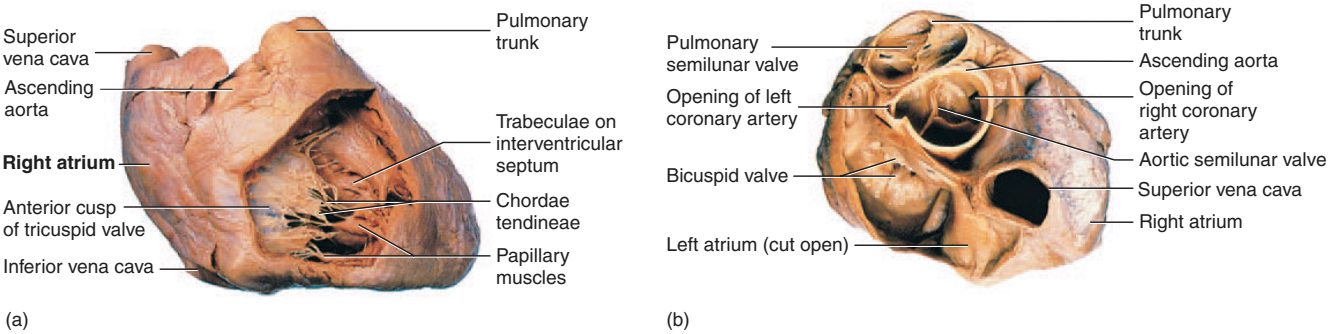
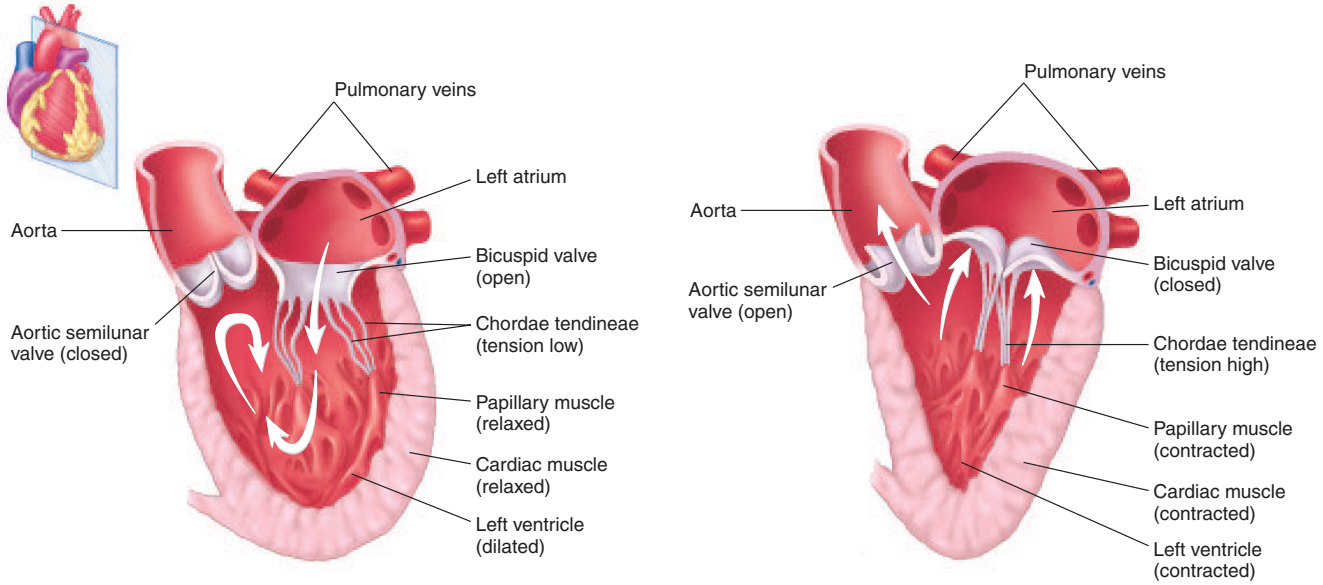


Figure 20.8 Heart Valves

(*a*) View of the tricuspid valve, the chordae tendineae, and the papillary muscles. (*b*) A superior view of the heart valves. Note the three cusps of each semilunar valve meeting to prevent the backflow of blood.



(a) When the bicuspid valve is open, the cusps of the valve are pushed by blood into the ventricle. Papillary muscles are relaxed and tension on the chordae tendineae is low. Blood flows from the left atrium into the left ventricle. When the aortic semilunar valve is closed, the cusps of the valve overlap as they are pushed by the blood in the aorta toward the ventricle. There is no blood flow from the aorta into the ventricle.

(b) When the bicuspid valve is closed, the cusps of the valves overlap as they are pushed by the blood toward the left atrium. There is no blood flow from the ventricle into the atrium. Papillary muscles are contracted and tension on the chordae tendineae is increased. When the aortic semilunar valve is open, the cusps of the valve are pushed by the blood toward the aorta. Blood then flows from the left ventricle into the aorta.

Figure 20.9 Function of the Heart Valves

(*a*) Valve positions when blood is flowing into the left ventricle. (*b*) Valve positions when blood is flowing out of the left ventricle.

3. *What is the pericardium? Name its parts and their functions.*
4. *Describe the three layers of the heart, and state their functions. Name the muscular ridges found on the interior of the auricles. Name the ridges and columns found on the interior walls of the ventricles.*
5. *Name the major blood vessels that enter and leave the heart. Which chambers of the heart do they enter or exit? Is blood flow through the coronary vessels continuous?*
6. *What structure separates the atria from each other? What structure separates the ventricles from each other?*
7. *Name the valves that separate the right atrium from the right ventricle and the left atrium from the left ventricle. What are the functions of the papillary muscles and the chordae tendineae?*
8. *Name the valves found in the aorta and pulmonary trunk.*

Clinical Focus Angina, Infarctions, and Treatment of Blocked Coronary Arteries

Angina pectoris (an′ji-nă, an-jī′nă pek′tō-ris) is pain that results from a reduction in blood supply to cardiac muscle. The pain is temporary and, if blood flow is restored, little permanent change or damage results. Angina pectoris is characterized by chest discomfort deep to the sternum, often described as heaviness, pressure, or moderately severe pain. It is often mistaken for indigestion. The pain can also be referred to the neck, lower jaw, left arm, and left shoulder (see chapter 14, p. 477).

Most often, angina pectoris results from narrowed and hardened coronary arterial walls. The reduced blood flow results in a reduced supply of oxygen to cardiac muscle cells. As a consequence, the limited anaerobic metabolism of cardiac muscle results in a buildup of lactic acid and reduced pH in affected areas of the heart. Pain receptors are stimulated by the lactic acid. The pain is predictably associated with exercise because the increased pumping activity of the heart requires more oxygen, and the narrowed blood vessels cannot supply it. Rest and drugs like nitroglycerin frequently relieve angina pectoris. Nitroglycerin dilates the blood vessels, including the coronary arteries. Consequently, the drug increases the oxygen supply to cardiac muscle and reduces the workload of the heart. Because peripheral arteries are dilated, the heart has to pump blood against a smaller pressure, and the need for oxygen decreases. The heart also pumps less blood because blood tends to remain in the dilated blood vessels and less blood is returned to the heart.

Myocardial infarction (mī-ō-kar′dē-ăl in-fark′shŭn) results from a prolonged lack of blood flow to a part of the cardiac muscle, resulting in a lack of oxygen and ultimately cellular death. Myocardial infarctions vary with the amount of cardiac muscle and the part of the heart that is affected. If blood supply to cardiac muscle is reestablished within 20 minutes, no permanent damage occurs. If the lack of oxygen lasts longer, cell death results. Within 30–60 seconds after blockage of a coronary blood vessel, however, functional changes are obvious. The electrical properties of the cardiac muscle are altered, and the ability of the heart to function properly is lost. The most common cause of myocardial infarction is thrombus formation that blocks a coronary artery. Coronary arteries narrowed by **atherosclerotic** (ath′er-ō-skler-ot′ik) **lesions** provide one of the conditions that increase the chances of myocardial infarction. Atherosclerotic lesions partially block blood vessels, resulting in turbulent blood flow, and the surfaces of the lesions are rough. These changes increase the probability of thrombus formation.

Angioplasty (an′jē-ō-plas-tē) is a process whereby a small balloon is threaded through the aorta and into a coronary artery. After the balloon has entered the partially occluded coronary artery, it is inflated, thereby flattening the atherosclerotic deposits against the vessel walls and opening the occluded blood vessel. This technique improves the function of cardiac muscle in patients suffering from an inadequate blood flow to the cardiac muscle through the coronary arteries. Some controversy exists about its effectiveness. At least in some patients, dilation of the coronary arteries can be reversed within a few weeks or months and blood clots can form in coronary arteries following angioplasty. To help prevent future blockage, a metal-mesh tube called a **stent** is inserted into the vessel. Although the stent is better able to hold the vessel open, it too can eventually become blocked. Small rotating blades and lasers are also used to remove lesions from coronary vessels.

A **coronary bypass** is a surgical procedure that relieves the effects of obstructions in the coronary arteries. The technique involves taking healthy segments of blood vessels from other parts of the patient's body and using them to bypass obstructions in the coronary arteries. The technique is common for those who suffer from severe occlusion in specific parts of coronary arteries.

Special enzymes are used to break down blood clots that form in the coronary arteries and cause heart attacks. The major enzymes used are **streptokinase** (strep-tō-kī′nās), **tissue plasminogen** (plaz-min′ō-jen) **activator (t-PA),** or, sometimes, **urokinase** (ūr-ō-kī′nās). These enzymes function to activate plasminogen, which is an inactive form of an enzyme in the body that breaks down the fibrin of clots. The strategy is to administer these drugs to people suffering from myocardial infarctions as soon as possible following the onset of symptoms. Removal of the occlusions produced by clots reestablishes blood flow to the cardiac muscle and reduces the amount of cardiac muscle permanently damaged by the occlusion.

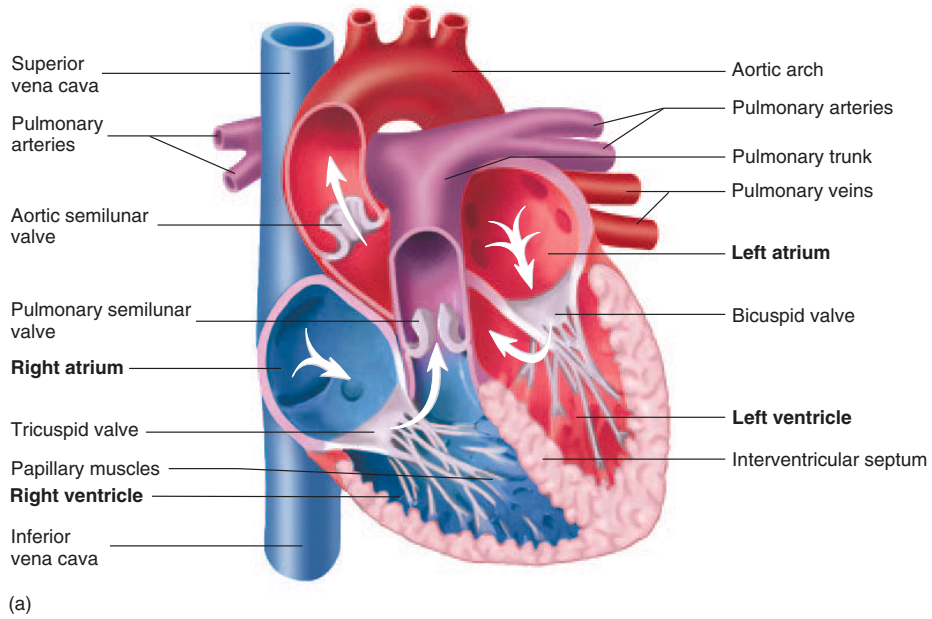
Route of Blood Flow Through the Heart

Objective

- ***Describe the flow of blood through the heart.***

Blood flow through the heart is depicted in figure 20.10. Even though it's more convenient to discuss blood flow through the heart one side at a time, it's important to understand that both atria contract at about the same time and both ventricles contract at about the same time. This concept is particularly important when considering electrical activity, pressure changes, and heart sounds.

Blood enters the right atrium from the systemic circulation, which returns blood from all the tissues of the body. Blood flows from an area of higher pressure in the systemic circulation to the right atrium, which has a lower pressure. Most of the blood in the right atrium then passes into the right ventricle as the ventricle relaxes following the previous contraction. The right atrium then contracts, and most of the blood remaining in the atrium is pushed into the ventricle to complete right ventricular filling.



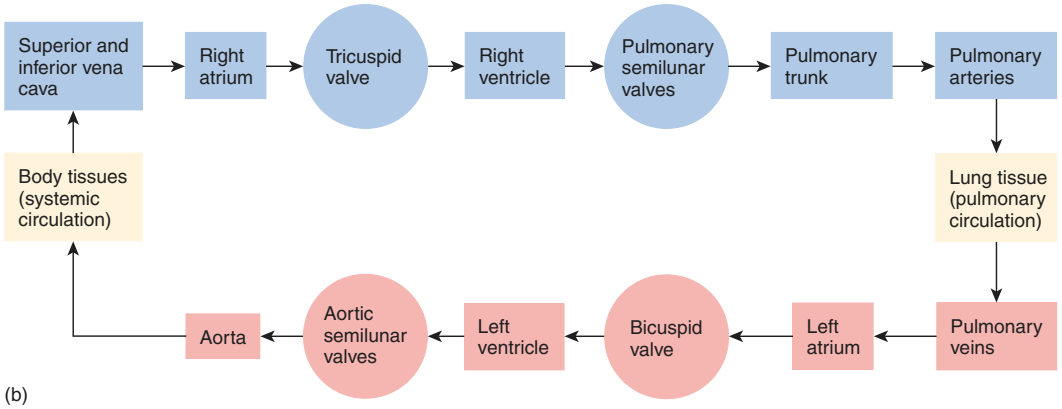


Figure 20.10 Blood Flow Through the Heart

(*a*) Frontal section of the heart revealing the four chambers and the direction of blood flow through the heart. (*b*) Diagram listing in order the structures through which blood flows in the systemic and pulmonary circulations. The heart valves are indicated by *circles:* deoxygenated blood (*blue*); oxygenated blood (*red*).

Contraction of the right ventricle pushes blood against the tricuspid valve, forcing it closed, and against the pulmonary semilunar valve, forcing it open, thus allowing blood to enter the pulmonary trunk.

The pulmonary trunk branches to form the **pulmonary arteries** (see figure 20.5), which carry blood to the lungs, where carbon dioxide is released and oxygen is picked up (see chapters 21 and 23). Blood returning from the lungs enters the left atrium through the four pulmonary veins. The blood passing from the left atrium to the left ventricle opens the bicuspid valve, and contraction of the left atrium completes left ventricular filling.

Contraction of the left ventricle pushes blood against the bicuspid valve, closing it, and against the aortic semilunar valve, opening it and allowing blood to enter the aorta. Blood flowing through the aorta is distributed to all parts of the body except to the parts of the lungs supplied by the pulmonary blood vessels (see chapter 23).

9. ***Starting at the venae cavae and ending at the aorta, describe the flow of blood through the heart.***

Histology

Objectives

- *List the characteristics of cardiac muscle.*
- *Describe the conducting system of the heart.*

Heart Skeleton

The **heart skeleton** consists of a plate of fibrous connective tissue between the atria and ventricles. This connective tissue plate forms **fibrous rings** around the atrioventricular and semilunar valves and provides a solid support for them (figure 20.11). The fibrous connective tissue plate also serves as electrical insulation between the atria and the ventricles and provides a rigid site for attachment of the cardiac muscles.

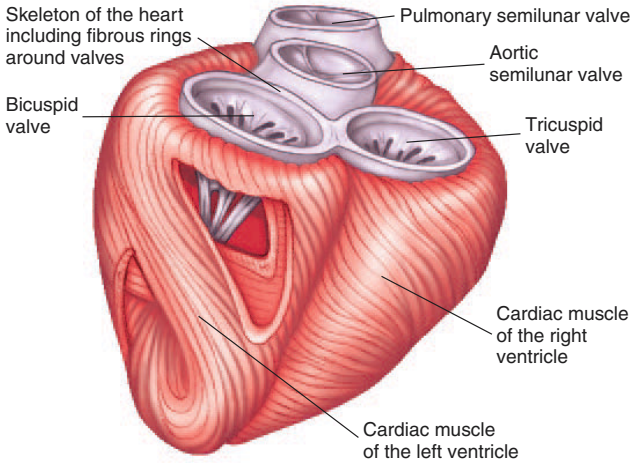


Figure 20.11 Skeleton of the Heart

The skeleton of the heart consists of fibrous connective tissue rings that surround the heart valves and separate the atria from the ventricles. Cardiac muscle attaches to the fibrous connective tissue. The muscle fibers are arranged so that when the ventricles contract a wringing motion is produced and the distance between the apex and base of the heart shortens.

Cardiac Muscle

Cardiac muscle cells are elongated, branching cells that contain one or occasionally two centrally located nuclei. Cardiac muscle cells contain actin and myosin myofilaments organized to form sarcomeres, which join end to end to form myofibrils (see chapter 4). The actin and myosin myofilaments are responsible for muscle contraction, and their organization gives cardiac muscle a striated (banded) appearance. The striations are less regularly arranged and less numerous than in skeletal muscle (figure 20.12).

Cardiac muscle has a **smooth sarcoplasmic reticulum,** but it is neither as regularly arranged nor as abundant as in skeletal muscle fibers, and no dilated cisternae are present, as occurs in skeletal muscle. The sarcoplasmic reticulum comes into close association at various points with membranes of **transverse tubules (T tubules).** Also, the T tubules of cardiac muscle are less abundant than in skeletal muscle and they are found near the Z disks of the sarcomeres instead of where the actin and myosin overlaps as in skeletal muscle. The loose association between the sarcoplasmic reticulum and the T tubules is partly responsible for the slow onset of contraction and the prolonged contraction phase in cardiac muscle. Depolarizations of the cardiac muscle plasma membrane are not carried from the surface of the cell to the sarcoplasmic reticulum as efficiently as they are in skeletal

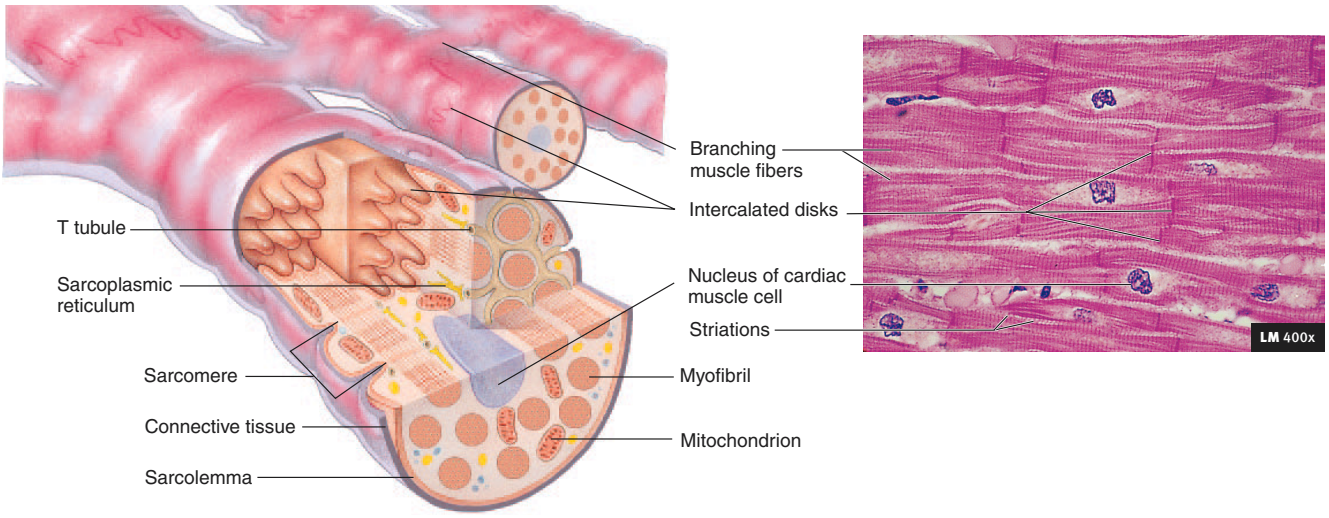


Figure 20.12 Histology of the Heart

(*a*) Heart muscle demonstrating the structure and arrangement of the individual muscle fibers. (*b*) Photomicrograph of heart muscle.

muscles, and calcium must diffuse a greater distance from the sarcoplasmic reticulum to the actin myofilaments. In addition, a substantial number of Ca^{2+} enter the cardiac muscle cells from the extracellular fluid.

Adenosine triphosphate (ATP) provides the energy for cardiac muscle contraction, and, as in other tissues, ATP production depends on oxygen availability. Cardiac muscle, however, cannot develop a large oxygen debt, a characteristic that is consistent with the function of the heart. Development of a large oxygen debt would result in muscular fatigue and cessation of cardiac muscle contraction. Cardiac muscle cells are rich in mitochondria, which perform oxidative metabolism at a rate rapid enough to sustain normal myocardial energy requirements. The extensive capillary network provides an adequate oxygen supply to the cardiac muscle cells.

PREDICT 2

Under resting conditions, most ATP produced in cardiac muscle is derived from the metabolism of fatty acids. During periods of heavy exercise, however, cardiac muscle cells use lactic acid as an energy source. Explain why this arrangement is an advantage.

Cardiac muscle cells are organized in spiral bundles or sheets. The cells are bound end to end and laterally to adjacent cells by specialized cell–cell contacts called **intercalated** (inter′kă-lā-ted) **disks** (see figure 20.12). The membranes of the intercalated disks have folds, and the adjacent cells fit together, thus greatly increasing contact between them. Specialized plasma membrane structures called **desmosomes** (dez′mō-sōmz) hold the cells together, and **gap junctions** function as areas of low electric resistance between the cells, allowing action potentials to pass from one cell to adjacent cells (see figure 4.3). Electrically, the cardiac muscle cells behave as a single unit, and the highly coordinated contractions of the heart depend on this functional characteristic.

Conducting System

The conducting system of the heart, which relays electric action potentials through the heart, consists of modified cardiac muscle cells that form two nodes (meaning a knot or lump) and a conducting bundle (figure 20.13). The two nodes are contained within the walls of the right atrium and are named according to their position in the atrium. The **sinoatrial (SA) node** is medial to the opening of the superior vena cava, and the **atrioventricular (AV) node** is medial to the right atrioventricular valve. The AV node gives rise to a conducting bundle of the heart, the **atrioventricular bundle.** This bundle passes through a small opening in the fibrous skeleton to reach the interventricular septum, where it divides to form the **right** and **left bundle branches,** which extend beneath the endocardium on either side of the interventricular septum to the apices of the right and left ventricles, respectively.

The inferior terminal branches of the bundle branches are called **Purkinje** (per-kin′jē) **fibers,** which are large-diameter cardiac muscle fibers. They have fewer myofibrils than most cardiac muscle cells and don't contract as forcefully. Intercalated disks are well developed between the Purkinje fibers and contain numerous gap junctions. As a result of these structural modifications, action potentials travel along the Purkinje fibers much more rapidly than through other cardiac muscle tissue.

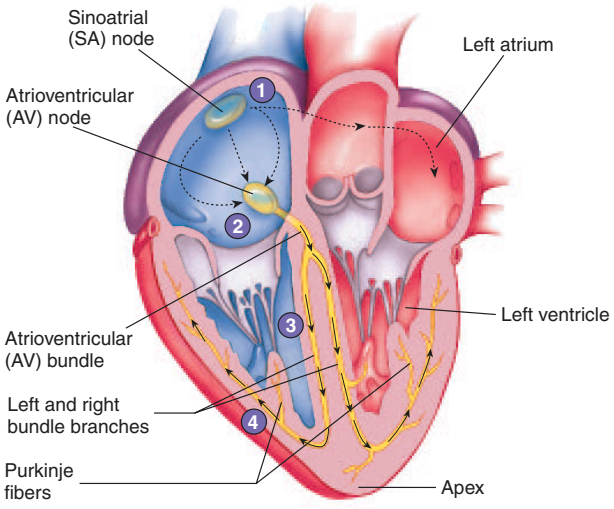
Cardiac muscle cells have the capacity to generate spontaneous action potentials, but cells of the SA node do so at a greater frequency. As a result, the SA node is called the **pacemaker** of the heart. Thus, the heart contracts spontaneously and rhythmically. Once action potentials are produced, they spread from the SA node to adjacent cardiac muscle fibers of the atrium. Preferential pathways conduct action potentials from the SA node to the AV node at a greater velocity than they are transmitted in the remainder of the atrial muscle fibers, although such pathways cannot be distinguished structurally from the remainder of the atrium.

1. Action potentials originate in the sinoatrial (SA) node and travel across the wall of the atrium (*arrows*) from the SA node to the atrioventricular (AV) node.

2. Action potentials pass through the AV node and along the atrioventricular (AV) bundle, which extends from the AV node, through the fibrous skeleton, into the interventricular septum.

3. The AV bundle divides into right and left bundle branches, and action potentials descend to the apex of each ventricle along the bundle branches.

4. Action potentials are carried by the Purkinje fibers from the bundle branches to the ventricular walls.



Process Figure 20.13 Conducting System of the Heart

When the heart beats under resting conditions, approximately 0.04 second is required for action potentials to travel from the SA node to the AV node. Within the AV node, action potentials are propagated slowly compared to the remainder of the conducting system. As a consequence, a delay occurs of 0.11 second from the time action potentials reach the AV node until they pass to the AV bundle. The total delay of 0.15 second allows completion of the atrial contraction before ventricular contraction begins.

After action potentials pass from the AV node to the highly specialized conducting bundles, the velocity of conduction increases dramatically. The action potentials pass through the left and right bundle branches and through the individual Purkinje fibers that penetrate into the myocardium of the ventricles (see figure 20.13).

Because of the arrangement of the conducting system, the first part of the myocardium that is stimulated is the inner wall of the ventricles near the apex. Thus ventricular contraction begins at the apex and progresses throughout the ventricles. Once stimulated, the spiral arrangement of muscle layers in the wall of the heart results in a wringing action that proceeds from the apex toward the base of the heart. During the process, the distance between the apex and the base of the heart decreases.

10. *Describe and list the functions of the skeleton of the heart.*
11. *Describe the similarities and differences between cardiac muscle and skeletal muscle.*
12. *Why does cardiac muscle have a slow onset of contraction and a prolonged contraction?*
13. *What substances do cardiac muscle cells use as an energy source? Do cardiac muscle cells develop an oxygen debt?*
14. *What anatomic features are responsible for the ability of cardiac muscle cells to contract as a unit?*
15. *List the parts of the conducting system of the heart. Explain how the conducting system coordinates contraction of the atria and ventricles. Explain why Purkinje fibers conduct action potentials more rapidly than other cardiac muscle cells.*

P R E D I C T 3

Explain why it's more efficient for contraction of the ventricles to begin at the apex of the heart than at the base.

Electrical Properties

Objectives

- *Describe action potentials in cardiac muscle cells.*
- *Define the term autorhythmic, and explain how the SA node functions as the pacemaker.*
- *Explain the features of an electrocardiogram and the events that those features represent.*

Cardiac muscle cells, like other electrically excitable cells such as neurons and skeletal muscle fibers, have a **resting membrane potential (RMP).** The RMP depends on a low permeability of the plasma membrane to Na^+ and Ca^{2+} and a higher permeability to K^+. When neurons, skeletal muscle cells, and cardiac muscle cells are depolarized to their threshold level, action potentials result (see chapter 11).

Action Potentials

Like action potentials in skeletal muscle, those in cardiac muscle exhibit depolarization followed by repolarization of the RMP. Alterations in membrane channels are responsible for the changes in the permeability of the plasma membrane that produce the action potentials. Action potentials in cardiac muscle last longer than those in skeletal muscle, and the membrane channels differ from those in skeletal muscle. In contrast to action potentials in skeletal muscle, which take less than 2 milliseconds (ms) to complete, action potentials in cardiac muscle take approximately 200–500 ms to complete.

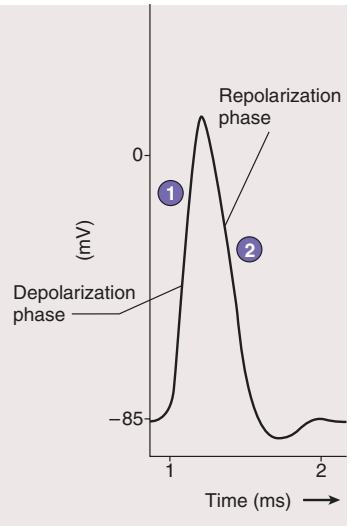
In cardiac muscle, the action potential consists of a rapid **depolarization phase,** followed by rapid, but partial, **early repolarization.** Then a prolonged period of slow repolarization occurs, called the **plateau phase.** At the end of the plateau, a more rapid **final repolarization phase** takes place, during which the membrane potential returns to its resting level (figure 20.14).

Membrane channels, called **voltage-gated Na^+ channels,** or **sodium fast channels** (or **fast channels**), open bringing about the depolarization phase of the action potential. As the voltage-gated Na^+ channels open, Na^+ diffuses into the cell, causing rapid depolarization until the cell is depolarized to approximately +20 millivolts (mV).

The voltage change occurring during depolarization affects other ion channels in the plasma membrane. Several different types of **voltage-gated K^+ channels** exist, each of which opens and closes at different membrane potentials, causing changes in membrane permeability to K^+. For example, at rest, the movement of K^+ through open voltage-gated K^+ channels is primarily responsible for establishing the resting membrane potential in cardiac muscle cells. Depolarization causes these voltage-gated K^+ channels to close, thereby decreasing membrane permeability to K^+. Depolarization also causes **voltage-gated Ca^{2+},** or **calcium slow channels** (or **slow channels**) to begin to open. Compared to sodium fast channels, the calcium slow channels open and close slowly.

Repolarization is the result of changes in membrane permeability to Na^+, K^+, and Ca^{2+}. Early repolarization occurs when the voltage-gated Na^+ channels close and a small number of voltage-gated K^+ channels open. Na^+ movement into the cell stops, and K^+ move out of the cell. The plateau phase occurs as voltage-gated Ca^{2+} channels continue to open, and the movement of Ca^{2+} into the cell counteracts the potential change produced by the movement of K^+ out of the cell. The plateau phase ends and final repolarization begins as the voltage-gated Ca^{2+} channels close and many more voltage-gated K^+ channels open. Thus Ca^{2+} stops diffusing into the cell, and the tendency for K^+ to diffuse out of the cell increases. These permeability changes cause the membrane potential to return to its resting level.

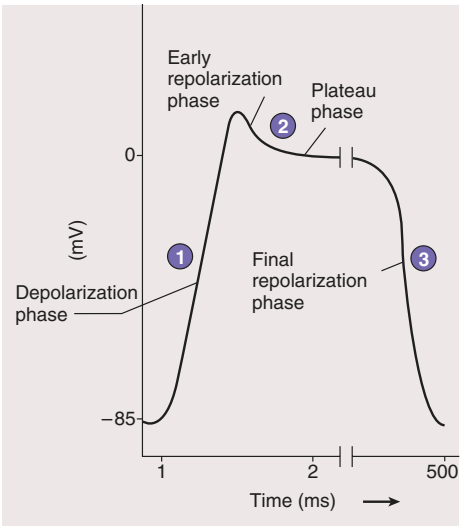
Action potentials in cardiac muscle are conducted from cell to cell, whereas action potentials in skeletal muscle fibers are



(a)

Permeability changes during an action potential in skeletal muscle:

1. **Depolarization phase**
   - Voltage-gated Na^+ channels open.
   - Voltage-gated K^+ channels begin to open.
2. **Repolarization phase**
   - Voltage-gated Na^+ channels close.
   - Voltage-gated K^+ channels continue to open.
   - Voltage-gated K^+ channels close at the end of repolarization and return the membrane potential to its resting value.



(b)

Permeability changes during an action potential in cardiac muscle:

1. **Depolarization phase**
   - Voltage-gated Na^+ channels open.
   - Voltage-gated K^+ channels close.
   - Voltage-gated Ca^{2+} channels begin to open.
2. **Early repolarization and plateau phases**
   - Voltage-gated Na^+ channels close.
   - Some voltage-gated K^+ channels open, causing early repolarization.
   - Voltage-gated Ca^{2+} channels are open, producing the plateau by slowing further repolarization.
3. **Final repolarization phase**
   - Voltage-gated Ca^{2+} channels close.
   - Many voltage-gated K^+ channels open.

Figure 20.14 Comparison of Action Potentials in Skeletal and Cardiac Muscle

(*a*) An action potential in skeletal muscle consists of depolarization and repolarization phases. (*b*) An action potential in cardiac muscle consists of depolarization, early repolarization, plateau, and final repolarization phases. Cardiac muscle does not repolarize as rapidly as skeletal muscle (*indicated by the break in the curve*) because of the plateau phase.

conducted along the length of a single muscle fiber, but not from fiber to fiber. Also, the rate of action potential propagation is slower in cardiac muscle than in skeletal muscle because cardiac muscle cells are smaller in diameter and much shorter than skeletal muscle fibers. Although the gap junctions of intercalated disks allow transfer of action potentials between cardiac muscle cells, they do slow the rate of action potential conduction between the cardiac muscle cells.

Autorhythmicity of Cardiac Muscle

The heart is said to be **autorhythmic** (aw′tō-rith′mik) because it stimulates itself *(auto)* to contract at regular intervals *(rhythmic)*. If the heart is removed from the body and maintained under physiologic conditions with the proper nutrients and temperature, it will continue to beat autorhythmically for a long time.

In the SA node, pacemaker cells generate action potentials spontaneously and at regular intervals. These action potentials spread through the conducting system of the heart to other cardiac muscle cells, causing voltage-gated Na^+ channels to open. As a result, action potentials are produced and the cardiac muscle cells contract.

The generation of action potentials in the SA node results when a spontaneously developing local potential, called the **prepotential,** reaches threshold (figure 20.15). Changes in ion movement into and out of the pacemaker cells cause the prepotential. Na^+ cause depolarization by moving into the cells through specialized non-gated Na^+ channels. A decreasing permeability to K^+ also causes depolarization as fewer K^+ move out of the cells. As a result of the depolarization, voltage-gated Ca^{2+} channels open, and the movement of Ca^{2+} into the pacemaker cells causes further depolarization. When the prepotential reaches threshold, many voltage-gated Ca^{2+} channels open. Unlike other cardiac muscle cells, the movement of Ca^{2+} into the pacemaker cells is primarily responsible for the depolarization phase of the action potential. Repolarization occurs, as in other cardiac muscle cells, when the voltage-gated Ca^{2+} channels close and the voltage-gated

Permeability changes in pacemaker cells:

1. **Prepotential**
   - A small number of Na^+ channels are open.
   - Voltage-gated K^+ channels that opened in the repolarization phase of the previous action potential are closing.
   - Voltage-gated Ca^{2+} channels begin to open.
2. **Depolarization phase**
   - Voltage-gated Ca^{2+} channels are open.
   - Voltage-gated K^+ channels are closed.
3. **Repolarization phase**
   - Voltage-gated Ca^{2+} channels close.
   - Voltage-gated K^+ channels open.

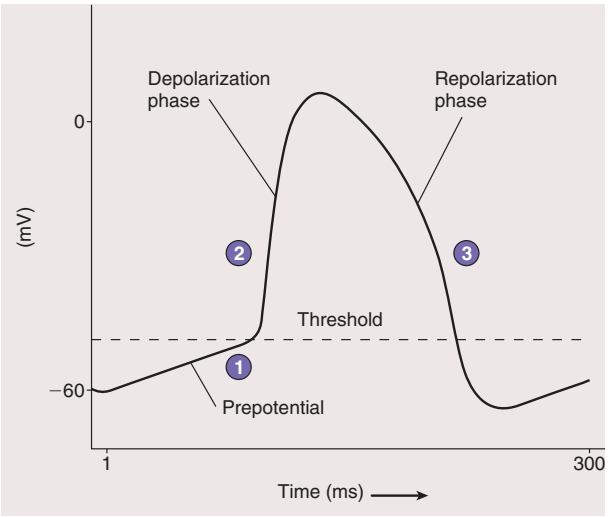


Figure 20.15 SA Node Action Potential

The production of action potentials by the SA node is responsible for the autorhythmicity of the heart.

K^+ channels open. After the RMP is reestablished, production of another prepotential starts the generation of the next action potential.

Drugs that Block Calcium Channels

Various chemical agents like manganese ions (Mn^{2+}) and verapamil (ver-ap′ă-mil) block voltage-gated Ca^{2+} channels. Voltage-gated Ca^{2+} channel-blocking agents prevent the movement of Ca^{2+} through voltage-gated Ca^{2+} channels into the cell and, for that reason, are called **calcium channel blockers.** Some calcium channel blockers are widely used clinically in the treatment of various cardiac disorders, including tachycardia and certain arrhythmias. Calcium channel blockers slow the development of the prepotential and thus reduce the heart rate. If action potentials arise prematurely within the SA node or other areas of the heart, calcium channel blockers reduce that tendency. Calcium channel blockers also reduce the amount of work performed by the heart because less calcium enters cardiac muscle cells to activate the contractile mechanism. On the other hand, epinephrine and norepinephrine increase the heart rate and its force of contraction by opening voltage-gated Ca^{2+} channels.

Although most cardiac muscle cells respond to action potentials produced by the SA node, some cardiac muscle cells in the conducting system can generate spontaneous action potentials. Normally, the SA node controls the rhythm of the heart because its pacemaker cells generate action potentials at a faster rate than other potential pacemaker cells to produce a heart rate of 70–80 beats per minute (bpm). An **ectopic focus** (ek-top′ik fō′kŭs; pl., foci, fō′sī) is any part of the heart other than the SA node that generates a heartbeat. For example, if the SA node doesn't function properly, the part of the heart to produce action potentials at the next highest frequency is the AV node, which produces a heart rate of 40–60 bpm. Another cause of an ectopic focus is blockage of the conducting pathways between the SA node and other parts of the heart. For example, if action potentials do not pass through the AV node, an ectopic focus can develop in an AV bundle, resulting in a heart rate of 30 bpm.

Ectopic foci can also appear when the rate of action potential generation in the ectopic focus becomes enhanced. For example, when cells are injured their plasma membranes become more permeable, resulting in depolarization. These injured cells can be the source of ectopic action potentials.

PREDICT 4

Predict the consequences for the pumping effectiveness of the heart if numerous ectopic foci in the ventricles produce action potentials at the same time.

Refractory Period of Cardiac Muscle

Cardiac muscle, like skeletal muscle, has **refractory** (rē-frak′tōr-ē) **periods** associated with its action potentials. During the **absolute refractory period,** the cardiac muscle cell is completely insensitive to further stimulation, and during the **relative refractory period** the cell exhibits reduced sensitivity to additional stimulation. Because the plateau phase of the action potential in cardiac muscle delays repolarization to the RMP, the refractory period is prolonged. The long refractory period ensures that, after contraction, relaxation is nearly complete before another action potential can be initiated, thus preventing tetanic contractions in cardiac muscle.

PREDICT 5

Predict the consequences if cardiac muscle could undergo tetanic contraction.

Electrocardiogram

The conduction of action potentials through the myocardium during the cardiac cycle produces electric currents that can be measured at the surface of the body. Electrodes placed on the surface of the body and attached to an appropriate recording device can

Table 20.1 Major Cardiac Arrhythmias

Conditions	Symptoms	Possible Causes
Abnormal Heart Rhythms		
Tachycardia	Heart rate in excess of 100 bpm	Elevated body temperature; excessive sympathetic stimulation; toxic conditions
Paroxysmal atrial tachycardia	Sudden increase in heart rate to 95–150 bpm for a few seconds or even for several hours; P wave precedes every QRS complex; P wave inverted and superimposed on T wave	Excessive sympathetic stimulation; abnormally elevated permeability of slow channels
Ventricular tachycardia	Frequently causes fibrillation	Often associated with damage to AV node or ventricular muscle
Abnormal Rhythms Resulting from Ectopic Action Potentials		
Atrial flutter	300 P waves/min; 125 QRS complexes/min resulting in two or three P waves (atrial contraction) for evry QRS complex (ventricular contraction)	Ectopic action potentials in the atria
Atrial fibrillation	No P waves; normal QRS complexes; irregular timing; ventricles constantly stimulated by atria; reduced pumping effectiveness and filling time	Ectopic action potentials in the atria
Ventricular fibrillation	No QRS complexes; no rhythmic contraction of the myocardium; many patches of asynchronously contracting ventricular muscle	Ectopic action potentials in the ventricles
Bradycardia	Heart rate less than 60 bpm	Elevated stroke volume in athletes; excessive vagal stimulation; carotid sinus syndrome
Sinus Arrhythmia	Heart rate varies 5% during respiratory cycle and up to 30% during deep respiration	Cause not always known; occasionally caused by ischemia or inflammation or associated with cardiac failure
SA Node Block	Cessation of P wave; new low heart rate due to AV node acting as pacemaker; normal QRS complex and T wave	Ischemia; tissue damage due to infarction; causes unknown
AV Node Block		
First-degree	PR interval greater than 0.2 second	Inflammation of AV bundle
Second-degree	PR interval 0.25–0.45 second; some P waves trigger QRS complexes and others do not; 2:1, 3:1, and 3:2 P wave/QRS complex ratios may occur	Excessive vagal stimulation
Complete heart block	P wave dissociated from QRS complex; atrial rhythm approximately 100 bpm; ventricular rhythm less than 40 bpm	Ischemia of AV nodal fibers or compression of AV bundle
Premature Atrial Contractions	Occasional shortened ntervals between one contraction and the succeeding contraction; frequently occurs in healthy people P wave superimposed on QRS complex	Excessive smoking; lack of sleep; too much caffeine; alcoholism
Premature Ventricular Contractions (PVCs)	Prolonged QRS complex; exaggerated voltage because only one ventricle may depolarize; inverted T wave; increased probability of fibrillation	Ectopic foci in ventricles; lack of sleep; too much caffeine, irritability; occasionally occurs with coronary thrombosis

Abbreviations: SA = sinoatrial; AV = atrioventricular.

detect small voltage changes resulting from action potentials in the cardiac muscle. The electrodes detect a summation of all the action potentials that are transmitted through the heart at a given time. Electrodes do not detect individual action potentials. The summated record of the cardiac action potentials is an electrocardiogram (ECG or EKG).

The ECG is not a direct measurement of mechanical events in the heart, and neither the force of contraction nor blood pressure can be determined from it. Each deflection in the ECG record, however, indicates an electrical event within the heart and correlates with a subsequent mechanical event. Consequently, it's an extremely valuable diagnostic tool in identifying a number of cardiac abnormalities (table 20.1), particularly because it is painless, easy to record, and noninvasive (meaning that it doesn't require surgical procedures). Abnormal heart rates or rhythms, abnormal conduction pathways, hypertrophy or atrophy of portions of the heart, and the approximate location of damaged cardiac muscle can be determined from analysis of an ECG.

The normal ECG consists of a P wave, a QRS complex, and a T wave (figure 20.16). The **P wave,** which is the result of action potentials that cause depolarization of the atrial myocardium, signals the onset of atrial contraction. The **QRS complex** is composed of three individual waves: the Q, R, and S waves. The QRS complex results from ventricular depolarization and signals the onset of ventricular contraction. The **T wave** represents repolarization of the ventricles and precedes ventricular relaxation. A wave representing repolarization of the atria cannot be seen because it occurs during the QRS complex.

The time between the beginning of the P wave and the beginning of the QRS complex is the PQ interval, commonly called the PR interval because the Q wave is often very small. During the PR interval, which lasts approximately 0.16 second, the atria contract and begin to relax. The ventricles begin to depolarize at the end of the PR interval. The QT interval extends from the beginning of the QRS complex to the end of the T wave, lasts approximately 0.36 second, and represents the approximate length of time required for the ventricles to contract and begin to relax.

Alterations in the Electrocardiogram

Elongation of the PR interval can result from (1) a delay in action potential conduction through the atrial muscle because of damage, such as that caused by **ischemia** (is-kē′mē-ă), which is the obstruction of the blood supply to the walls of the heart, (2) a delay of action potential conduction through atrial muscle because of a dilated atrium, or (3) a delay of action potential conduction through the AV node and bundle because of ischemia, compression, or necrosis of the AV node or bundle. These conditions result in slow conduction of action potentials through the bundle branches. An unusually long QT interval reflects the abnormal conduction of action potentials through the ventricles, which can result from myocardial infarctions or from an abnormally enlarged left or right ventricle.

Examples of alteration in the form of the electrocardiogram due to cardiac abnormalities are illustrated in figure 20.17. Examples include complete heart block, premature ventricular contraction, bundle branch block, atrial fibrillation, and ventricular fibrillation.

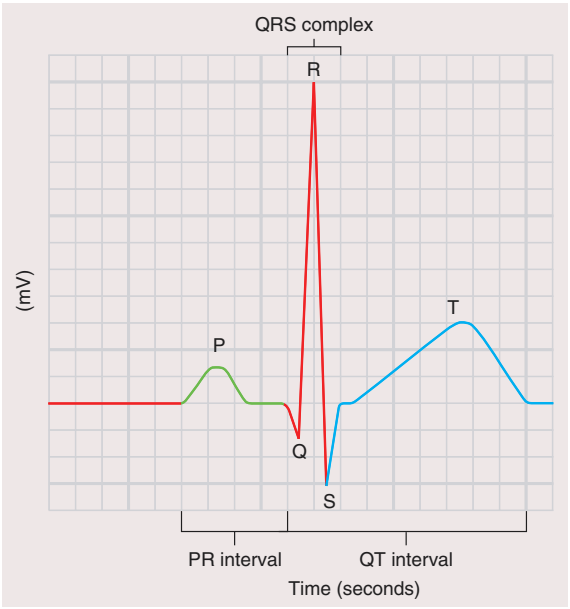


Figure 20.16 Electrocardiogram

The major waves and intervals of an electrocardiogram are labeled. Each thin horizontal line on the ECG recording represents 1 mV, and each thin vertical line represents 0.04 second.

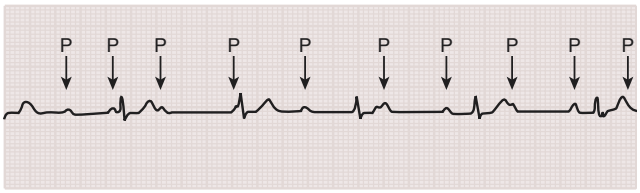
16. *For cardiac muscle action potentials, describe ion movement during the depolarization, early repolarization, plateau, and final repolarization phases. What ions are associated with fast channels and slow channels?*
17. *Why is cardiac muscle referred to as autorhythmic? What are ectopic foci?*
18. *How does the depolarization of pacemaker cells differ from the depolarization of other cardiac muscle cells? What is the prepotential?*
19. *Why does cardiac muscle have a prolonged refractory period? What is the advantage of a prolonged refractory period?*
20. *What does an ECG measure? Name the waves produced by an ECG, and state what events occur during each wave.*

Cardiac Cycle

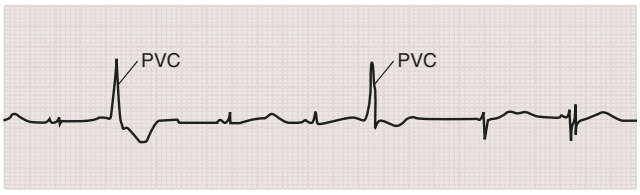
Objectives

- *Describe the five events of the cardiac cycle that occur during ventricular systole and ventricular diastole.*
- *Explain the bases of the major heart sounds.*
- *Describe the aortic pressure curve.*

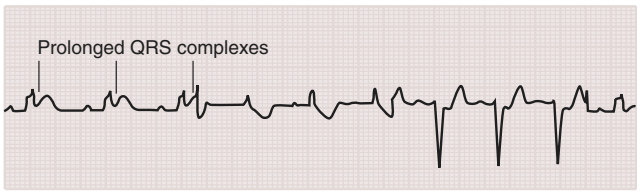
The heart is actually two separate pumps that work together, one in the right half and the other in the left half of the heart. Each pump consists of a primer pump—the atrium—and a power pump—the ventricle. Both atrial primer pumps complete the filling of the ventricles with blood, and both ventricular power pumps



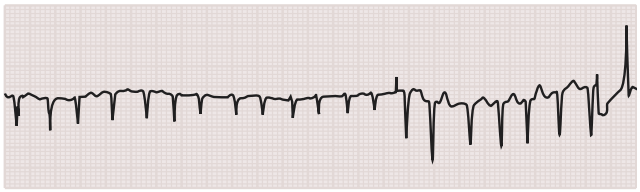
Complete heart block (P waves and QRS complexes are not coordinated)



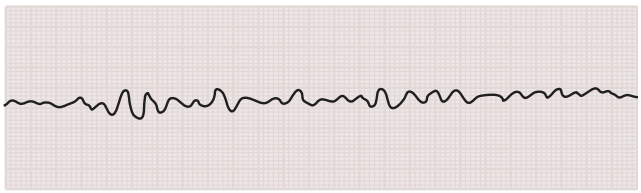
Premature ventricular contraction (PVC) (no P waves precede PVC's)



Bundle branch block



Atrial fibrillation (no clear P waves and rapid QRS complexes)



Ventricular fibrillation (no P, QRS, or T waves)

Figure 20.17 Examples of Alterations in the Electrocardiogram

produce the major force that causes blood to flow through the pulmonary and systemic arteries. The term **cardiac cycle** refers to the repetitive pumping process that begins with the onset of cardiac muscle contraction and ends with the beginning of the next contraction (figures 20.18 and 20.19). Pressure changes produced within the heart chambers as a result of cardiac muscle contraction are responsible for blood movement because blood moves from areas of higher pressure to areas of lower pressure.

The duration of the cardiac cycle varies considerably among humans and also during an individual's lifetime. It can be as short as 0.25–0.3 second in a newborn infant or as long as 1 or more seconds in a well-trained athlete. The normal cardiac cycle of 0.7–0.8 second depends on the capability of cardiac muscle to contract and on the functional integrity of the conducting system.

The term **systole** (sis′tō-lē) means to contract, and **diastole** (dī-as′tō-lē) means to dilate. **Atrial systole** is contraction of the atrial myocardium, and **atrial diastole** is relaxation of the atrial myocardium. Similarly, **ventricular systole** is contraction of the ventricular myocardium, and **ventricular diastole** is relaxation of the ventricular myocardium. When the terms *systole* and *diastole* are used without reference to specific chambers, however, they mean ventricular systole or diastole.

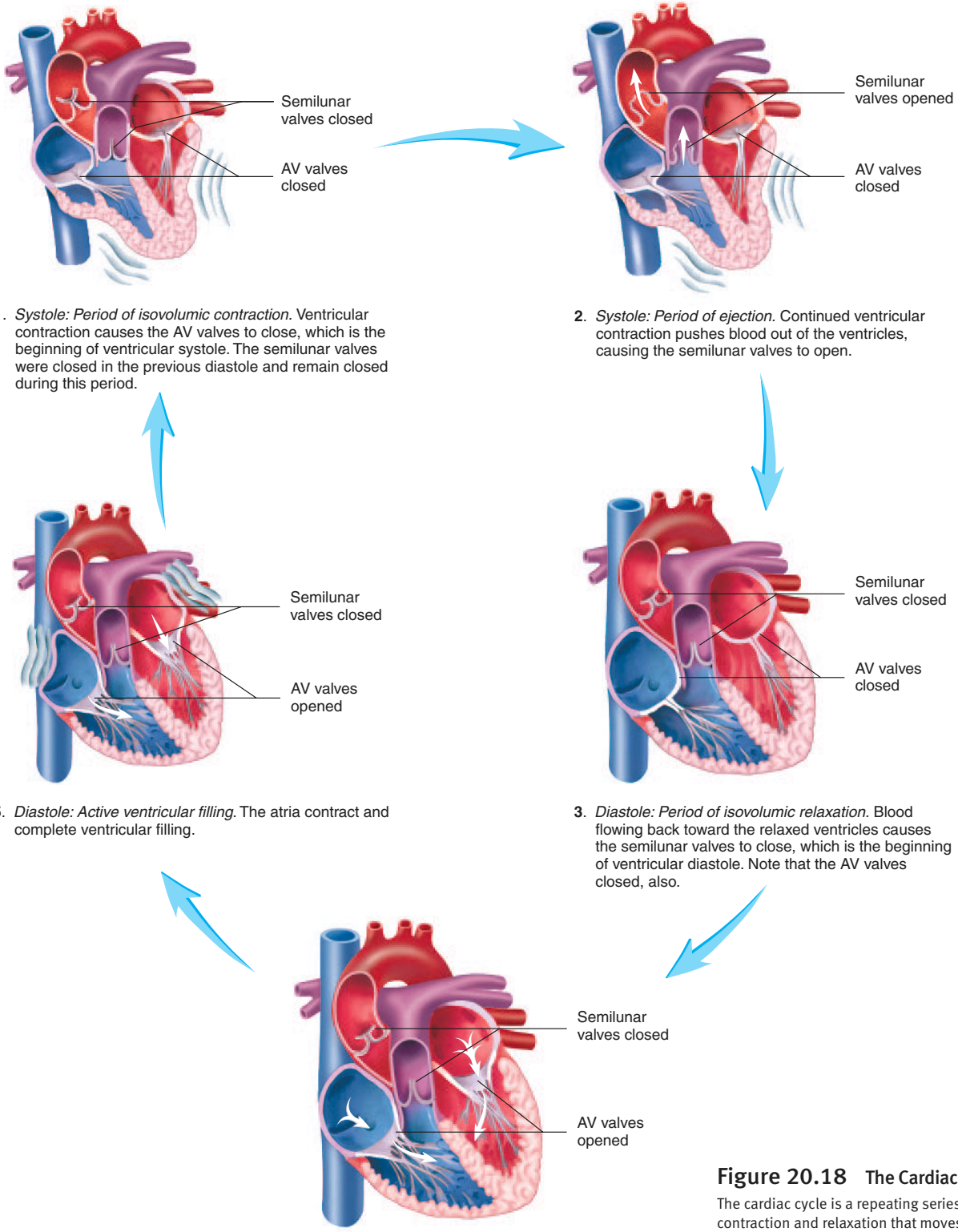
Before considering the details of the cardiac cycle, an overview of the main events is helpful. Just before systole begins, the atria and ventricles are relaxed, the ventricles are filled with blood, the semilunar valves are closed, and the AV valves are open. As systole begins, contraction of the ventricles increases ventricular pressures, causing blood to flow toward the atria and close the AV valves. As contraction proceeds, ventricular pressures continue to rise, but no blood flows from the ventricles because all the valves are closed. This brief interval is called the **period of isovolumic** (ī′sō-vol-ū′mik) **contraction** because the volume of blood in the ventricles does not change, even though the ventricles are contracting (see figure 20.18 *1*). As the ventricles continue to contract, ventricular pressures become greater than the pressures in the pulmonary trunk and aorta. As a result, during the **period of ejection,** the semilunar valves are pushed open and blood flows from the ventricles into those arteries (see figure 20.18 *2*).

As diastole begins, the ventricles relax and ventricular pressures decrease below the pressures in the pulmonary trunk and aorta. Consequently, blood begins to flow back toward the ventricles, causing the semilunar valves to close (see figure 20.18 *3*). With closure of the semilunar valves, all the heart valves are closed and no blood flows into the relaxing ventricles during the **period of isovolumic relaxation.**

Throughout ventricular systole and the period of isovolumic relaxation, the atria relax and blood flows into them from the veins. As the ventricles continue to relax, ventricular pressures become lower than atrial pressures, the AV valves open, and blood flows from the atria into the relaxed ventricles (see figure 20.18 *4*). At rest, most ventricular filling is a passive process resulting from the greater pressure of blood in the veins and atria than in the completely relaxed ventricles. Completion of ventricular filling is an active process resulting from increased atrial pressure produced by contraction of the atria (see figure 20.18 *5*). During exercise, atrial contraction is more important for ventricular filling because, as heart rate increases, less time is available for passive ventricular filling.

Events Occurring During Ventricular Systole

Figure 20.19 displays the main events of the cardiac cycle in graphic form and should be examined from top to bottom for each period of the cardiac cycle. The ECG indicates the electrical events that cause contraction and relaxation of the atria and ventricles. The pressure graph shows the pressure changes within the left atrium, left ventricle, and aorta resulting from atrial and



1. *Systole: Period of isovolumic contraction.* Ventricular contraction causes the AV valves to close, which is the beginning of ventricular systole. The semilunar valves were closed in the previous diastole and remain closed during this period.

2. *Systole: Period of ejection.* Continued ventricular contraction pushes blood out of the ventricles, causing the semilunar valves to open.

3. *Diastole: Period of isovolumic relaxation.* Blood flowing back toward the relaxed ventricles causes the semilunar valves to close, which is the beginning of ventricular diastole. Note that the AV valves closed, also.

4. *Diastole: Passive ventricular filling.* The AV valves open and blood flows into the relaxed ventricles, accounting for most of the ventricular filling.

5. *Diastole: Active ventricular filling.* The atria contract and complete ventricular filling.

Figure 20.18 The Cardiac Cycle

The cardiac cycle is a repeating series of contraction and relaxation that moves blood through the heart. See figure 20.19 and table 20.2 for additional details and explanations. (*AV* = atrioventricular)

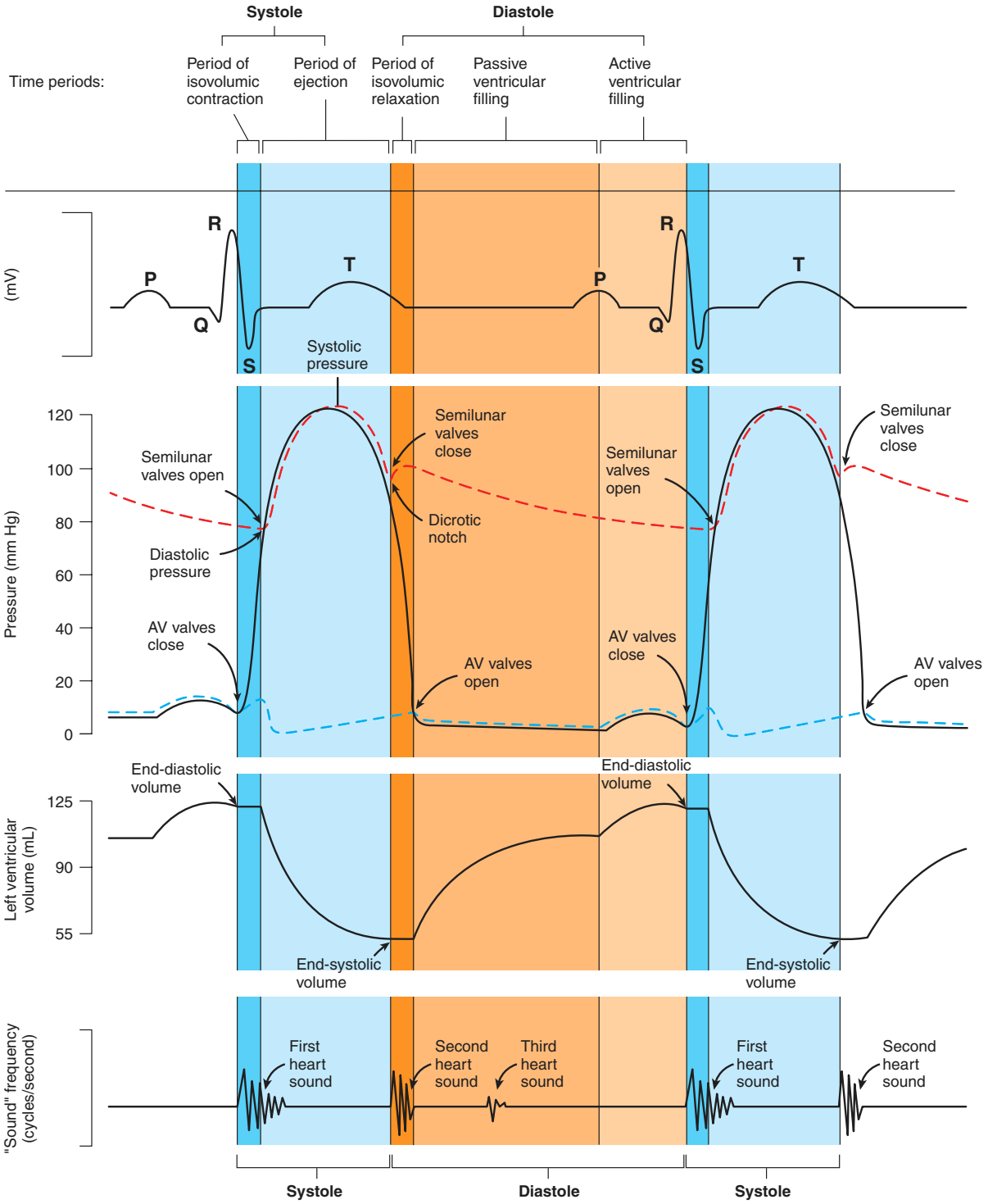


Figure 20.19 Events Occurring During the Cardiac Cycle

The cardiac cycle is divided into five periods (*see top of figure*). Within these periods, four graphs are presented. From *top* to *bottom*, the electrocardiograph; pressure changes for the left atrium (*blue line*), left ventricle (*black line*), and aorta (*red line*); left ventricular volume curve; and heart sounds are illustrated. See table 20.2 for explanations of events during each period and figure 20.18 for illustrations of the valves and blood flow movement.

ventricular contraction and relaxation. Although pressure changes in the right side of the heart are not shown, they are similar to those in the left side, only lower. The volume graph presents the changes in left ventricular volume as blood flows into and out of the left ventricle as a result of the pressure changes. The sound graph records the closing of valves caused by blood flow. See also figure 20.18 for illustrations of the valves and blood flow and table 20.2 for a summary of the events occurring during each period.

Period of Isovolumic Contraction

Completion of the QRS complex initiates contraction of the ventricles. Ventricular pressure rapidly increases, resulting in closure of the AV valves. During the previous ventricular diastole, the ventricles were filled with 120–130 mL of blood, which is called the **end-diastolic volume.** Ventricular volume doesn't change during the period of isovolumic contraction because all the heart valves are closed at this time.

P R E D I C T 6

Is the cardiac muscle contracting isotonically or isometrically during the period of isovolumic contraction?

Period of Ejection

As soon as ventricular pressures exceed the pressures in the aorta and pulmonary trunk, the semilunar valves open. The aortic semilunar valve opens at approximately 80 millimeters of mercury (mm Hg) ventricular pressure, whereas the pulmonary semilunar valve opens at approximately 8 mm Hg. Although the pressures are different, both valves open at nearly the same time.

As blood flows from the ventricles during the period of ejection, the left ventricular pressure continues to climb to approximately 120 mm Hg, and the right ventricular pressure increases to approximately 25 mm Hg. The larger left ventricular pressure causes blood to flow throughout the body (systemic circulation), whereas the lower right ventricle pressure causes blood to flow through the lungs (pulmonary circuit). Even though the pressure generated by the left ventricle is much higher than that of the right ventricle, the amount of blood pumped by each is almost the same.

P R E D I C T 7

Which ventricle has the thickest wall? Why is it important for each ventricle to pump approximately the same volume of blood?

During the first part of ejection, blood flows rapidly out of the ventricles. Toward the end of ejection, very little blood flow occurs, which causes the ventricular pressure to decrease despite continued ventricular contraction. At the end of ejection, the volume has decreased to 50–60 mL, which is called the **end-systolic volume.**

Events Occurring During Ventricular Diastole

Period of Isovolumic Relaxation

Completion of the T wave results in ventricular repolarization and relaxation. The already decreasing ventricular pressure falls very rapidly as the ventricles suddenly relax. When the ventricular pressures fall below the pressures in the aorta and pulmonary trunk, the recoil of the elastic arterial walls, which were stretched during the period of ejection, forces the blood to flow back toward the ventricles, thereby closing the semilunar valves. Ventricular volume doesn't change during the period of isovolumic relaxation because all the heart valves are closed at this time.

Passive Ventricular Filling

During ventricular systole and the period of isovolumic relaxation, the relaxed atria fills with blood. As ventricular pressure drops below atrial pressure, the atrioventricular valves open and allow blood to flow from the atria into the ventricles. Blood flows from the area of higher pressure in the veins and atria toward the area of lower pressure in the relaxed ventricles. Most ventricular filling occurs during the first one-third of ventricular diastole. At the end of passive ventricular filling, the ventricles are approximately 70% filled.

P R E D I C T 8

Fibrillation is abnormal, rapid contractions of different parts of the heart that prevent the heart muscle from contracting as a single unit. Explain why atrial fibrillation does not immediately cause death, but ventricular fibrillation does.

Active Ventricular Filling

Depolarization of the SA node generates action potentials that spread over the atria, producing the P wave and stimulating both atria to contract (atrial systole). The atria contract during the last one-third of ventricular diastole and complete ventricular filling.

Under most conditions, the atria function primarily as reservoirs, and the ventricles can pump sufficient blood to maintain homeostasis even if the atria do not contract at all. During exercise, however, the heart pumps 300%–400% more blood than during resting conditions. It is under these conditions that the pumping action of the atria becomes important in maintaining the pumping efficiency of the heart.

Heart Sounds

Distinct sounds are heard when a stethoscope is used to listen to the heart (figures 20.19 and 20.20). The **first heart sound** is a low-pitched sound, often described as a "lubb" sound. It's caused by vibration of the atrioventricular valves and surrounding fluid as the valves close at the beginning of ventricular systole. The **second heart sound** is a higher-pitched sound often described as a "dupp" sound. It results from closure of the aortic and pulmonary semilunar valves, at the beginning of ventricular diastole. Systole is, therefore, approximately the time between the first and second heart sounds. Diastole, which lasts somewhat longer, is approximately the time between the second heart sound and the next first heart sound.

Occasionally, a **third heart sound,** caused by blood flowing in a turbulent fashion into the ventricles, can be detected near the end of the first one-third of diastole. The third heart sound is normal, although faint, and is detected most easily in thin, young people.

Table 20.2 Summary of the Events of the Cardiac Cycle

	Ventricular Systole	
	Period of Isovolumic Contraction	**Period of Ejection**
Time Period	The ventricles begin to contract, but ventricular volume doesn't change.	The ventricles continue to contract and blood is pumped out of the ventricles.
Condition of Valves	Semilunar valves closed; AV valves closed (see figure 20.18*a*).	Semilunar valves opened; AV valves closed (see figure 20.18*b*).
ECG	The QRS complex is completed and the ventricles are depolarized. As a result, the ventricles begin to contract. Atrial repolarization is masked by the QRS complex. The atria are relaxed (atrial diastole).	The **T wave** results from ventricular repolarization.
Atrial Pressure Graph	Atrial pressure decreases in the relaxed atria. When atrial pressure is less than venous pressure, blood flows into the atria. Atrial pressure increases briefly as the contracting ventricles push blood back toward the atria.	Atrial pressure increases gradually as blood flows from the veins into the relaxed atria.
Ventricular Pressure Graph	Ventricular contraction causes an increase in ventricular pressure, which causes blood to flow toward the atria, closing the AV valves. Ventricular pressure increases rapidly.	Ventricular pressure becomes greater than pressure in the aorta as the ventricles continue to contract. The semilunar valves are pushed open as blood flows out of the ventricles. Ventricular pressure peaks as the ventricles contract maximally; then pressure decreases as blood flow out of the ventricles decreases.
Aortic Pressure Graph	Just before the semilunar valves open, pressure in the aorta decreases to its lowest value, called the **diastolic pressure** (approximately 80 mm Hg).	As ventricular contraction forces blood into the aorta, pressure in the aorta increases to its highest value, called the **systolic pressure** (approximately 120 mm Hg).
Volume Graph	During the **period of isovolumic contraction,** ventricular volume doesn't change because the semilunar and AV valves are closed.	After the semilunar valves open, blood volume decreases as blood flows out of the ventricles during the **period of ejection.** The amount of blood left in a ventricle at the end of the period of ejection is called the **end-systolic volume.**
Sound Graph	Blood flowing from the ventricles toward the atria closes the AV valves. Vibrations of the valves and the turbulent flow of blood produce the **first heart sound,** which marks the beginning of ventricular systole.	

Aortic Pressure Curve

The elastic walls of the aorta are stretched as blood is ejected into the aorta from the left ventricle. Aortic pressure remains slightly below ventricular pressure during this period of ejection. As ventricular pressure drops below that in the aorta, blood flows back toward the ventricle because of the elastic recoil of the aorta. Consequently, the aortic semilunar valve closes, and pressure within the aorta increases slightly, producing a **dicrotic** (dī-krot′ik) **notch** in the aortic pressure curve (see figure 20.19). The term *dicrotic* means double-beating; when increased pressure caused by recoil is large, a double pulse can be felt. The dicrotic notch is also called an **incisura** (in′sī-soo′ră; a cutting into). Aortic pressure then gradually falls throughout the rest of ventricular diastole as blood flows through the peripheral vessels. By the time aortic pressure has fallen to approximately 80 mm Hg, the ventricles again contract, forcing blood once more into the aorta.

Blood pressure measurements performed for clinical purposes reflect the pressure changes that occur in the aorta rather

Ventricular Diastole		
Period of Isovolumic Relaxation	**Passive Ventricular Filling**	**Active Ventricular Filling**
The ventricles relax, but ventricular volume doesn't change.	Blood flows into the ventricles because blood pressure is higher in the veins and atria than in the relaxed ventricles.	Contraction of the atria pumps blood into the ventricles.
Semilunar valves closed; AV valves closed (see figure 20.18*c*).	Semilunar valves closed; AV valves opened (see figure 20.18*d*).	Semilunar valves closed; AV valves opened (see figure 20.18*e*).
The T wave is completed and the ventricles are repolarized. The ventricles relax.	The **P wave** is produced when the SA node generates action potentials and a wave of depolarization begins to propagate across the atria.	The P wave is completed and the atria are stimulated to contract. Action potentials are delayed in the AV node for 0.11 second, allowing time for the atria to contract. The **QRS complex** begins as action potentials are propagated from the AV node to the ventricles.
Atrial pressure continues to increase gradually as blood flows from the veins into the relaxed atria.	After the AV valves open, atrial pressure decreases as blood flows out of the atria into the relaxed ventricles.	Atrial contraction (systole) causes an increase in atrial pressure, and blood is forced to flow from the atria into the ventricles.
Elastic recoil of the aorta pushes blood back toward the heart, causing the semilunar valves to close. After closure of the semilunar valves, the pressure in the relaxing ventricles rapidly decreases.	No significant change occurs in ventricular pressure during this time period.	Atrial contraction (systole) and the movement of blood into the ventricles cause a slight increase in ventricular pressure.
After the semilunar valves close, elastic recoil of the aorta causes a slight increase in aortic pressure, producing the **dicrotic notch,** or **incisura.**	Aortic pressure gradually decreases as blood runs out of the aorta into other systemic blood vessels.	Aortic pressure gradually decreases as blood runs out of the aorta into other systemic blood vessels.
During the **period of isovolumic relaxation,** ventricular volume doesn't change because the semilunar and AV valves are closed.	After the AV valves open, blood flows from the atria and veins into the ventricles because of pressure differences. Most ventricular filling occurs during the first one-third of diastole. Little ventricular filling occurs during the middle one-third of diastole.	Atrial contraction (systole) completes ventricular filling during the last one-third of diastole.
Blood flowing from the ventricles toward the aorta and pulmonary trunk closes the semilunar valves. Vibrations of the valves and the turbulent flow of blood produce the **second heart sound,** which marks the beginning of ventricular diastole.	Sometimes the turbulent flow of blood into the ventricles produces a **third heart sound.**	The amount of blood in a ventricle at the end of ventricular diastole is called the **end-diastolic volume.**

Abbreviation: AV = atrioventricular.

than in the left ventricle (see chapter 21). The blood pressure in the aorta fluctuates between systolic pressure, which is about 120 mm Hg, and diastolic pressure, which is about 80 mm Hg for the average young adult at rest.

21. ***Define systole and diastole.***
22. ***List the five periods of the cardiac cycle, and state whether the AV and semilunar valves are open or closed during each period.***
23. ***Define isovolumic. When does most ventricular filling occur?***
24. ***Define end-diastolic volume and end-systolic volume.***
25. ***What produces the first heart sound, the second heart sound, and the third heart sound?***
26. ***Explain the production in the aorta of systolic pressure, diastolic pressure, and the dicrotic notch, or incisura.***

Clinical Focus Abnormal Heart Sounds

Heart sounds provide important information to clinicians about the normal function of the heart and assist in diagnosing cardiac abnormalities. Abnormal heart sounds are called **murmurs** (mer′merz), and certain murmurs are important indicators of specific cardiac abnormalities. For example, an **incompetent valve** leaks significantly. After an incompetent valve closes, blood flows through it but in a reverse direction. The movement of blood in a direction opposite to normal results in turbulence, which causes a gurgling or swishing sound immediately after the valve closes. An incompetent tricuspid valve or bicuspid valve makes a swish sound immediately after the first heart sound, and the first heart sound may be muffled. An incompetent aortic or pulmonary semilunar valve results in a swish sound immediately after the second heart sound.

Stenosed (sten′ōzd) valves have an abnormally narrow opening and also produce abnormal heart sounds. Blood flows through stenosed valves in a very turbulent fashion and produces a rushing sound before the valve closes. A stenosed atrioventricular valve, therefore, results in a rushing sound immediately before the first heart sound, and a stenosed semilunar valve results in a rushing sound immediately before the second heart sound.

Inflammation of the heart valves, resulting from conditions like rheumatic fever, can cause valves to become either incompetent or stenosed. In addition, myocardial infarctions that make papillary muscles nonfunctional can cause bicuspid or tricuspid valves to be incompetent.

Mean Arterial Blood Pressure

Objective

- ***Describe the factors that determine mean arterial pressure.***

Blood pressure is responsible for blood movement and, therefore, is critical to the maintenance of homeostasis in the body. Blood flows from areas of higher to areas of lower pressure. For example, during one cardiac cycle, blood flows from the higher pressure in the aorta toward the lower pressure in the relaxed left ventricle.

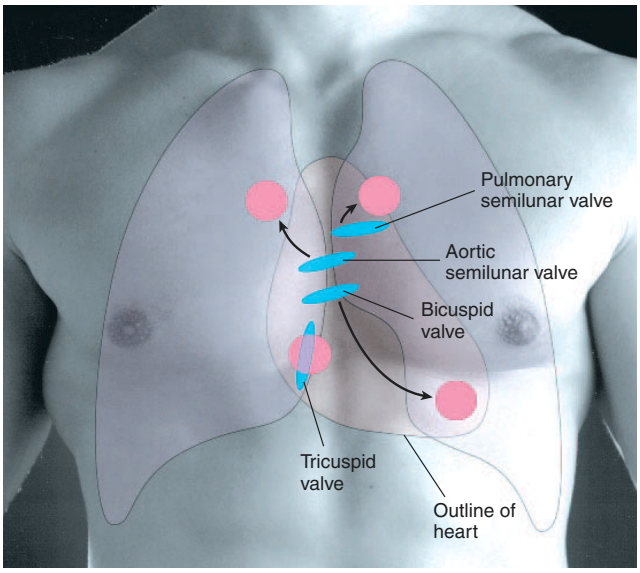


Figure 20.20 Location of the Heart Valves in the Thorax

Surface markings of the heart in the male. The positions of the four heart valves are indicated by *blue ellipses,* and the sites where the sounds of the valves are best heard with the stethoscope are indicated by *pink circles.*

Mean arterial pressure (MAP) is the average blood pressure between systolic and diastolic pressure in the aorta. It's proportional to **cardiac output (CO)** times **peripheral resistance (PR).** Cardiac output, or **minute volume,** is the amount of blood pumped by the heart per minute, and peripheral resistance is the total resistance against which blood must be pumped.

$$MAP = CO \times PR$$

Changes in cardiac output and peripheral resistance (figure 20.21) can alter mean arterial pressure. Cardiac output is discussed in this chapter, and peripheral resistance is explained in chapter 21.

Cardiac output is equal to heart rate times stroke volume. **Heart rate (HR)** is the number of times the heart beats (contracts) per minute. **Stroke volume (SV),** which is the volume of blood pumped during each heartbeat (cardiac cycle), is equal to end-diastolic volume minus end-systolic volume. During diastole, blood flows from the atria into the ventricles, and end-diastolic volume normally increases to approximately 125 mL. After the ventricles partially empty during systole, end-systolic volume decreases to approximately 55 mL. The **stroke volume** is therefore equal to 70 mL (125−55).

To better understand stroke volume, imagine that you're rinsing out a sponge under a running water faucet. As you relax your hand, the sponge fills with water; as your fingers contract, water is squeezed out of the sponge; and, after you have squeezed it, some water is left in the sponge. In this analogy, the amount of water you squeeze out of the sponge (stroke volume) is the difference between the amount of water in the sponge when your hand is relaxed (end-diastolic volume) and the amount that is left in the sponge after you squeeze it (end-systolic volume).

Stroke volume can be increased by increasing end-diastolic volume or by decreasing end-systolic volume (see figure 20.21). During exercise, end-diastolic volume increases because of an increase in **venous return,** which is the amount of blood returning to the heart from the peripheral circulation. End-systolic volume decreases because the heart contracts more forcefully. For example, stroke volume could increase from a resting value of 70 mL to an

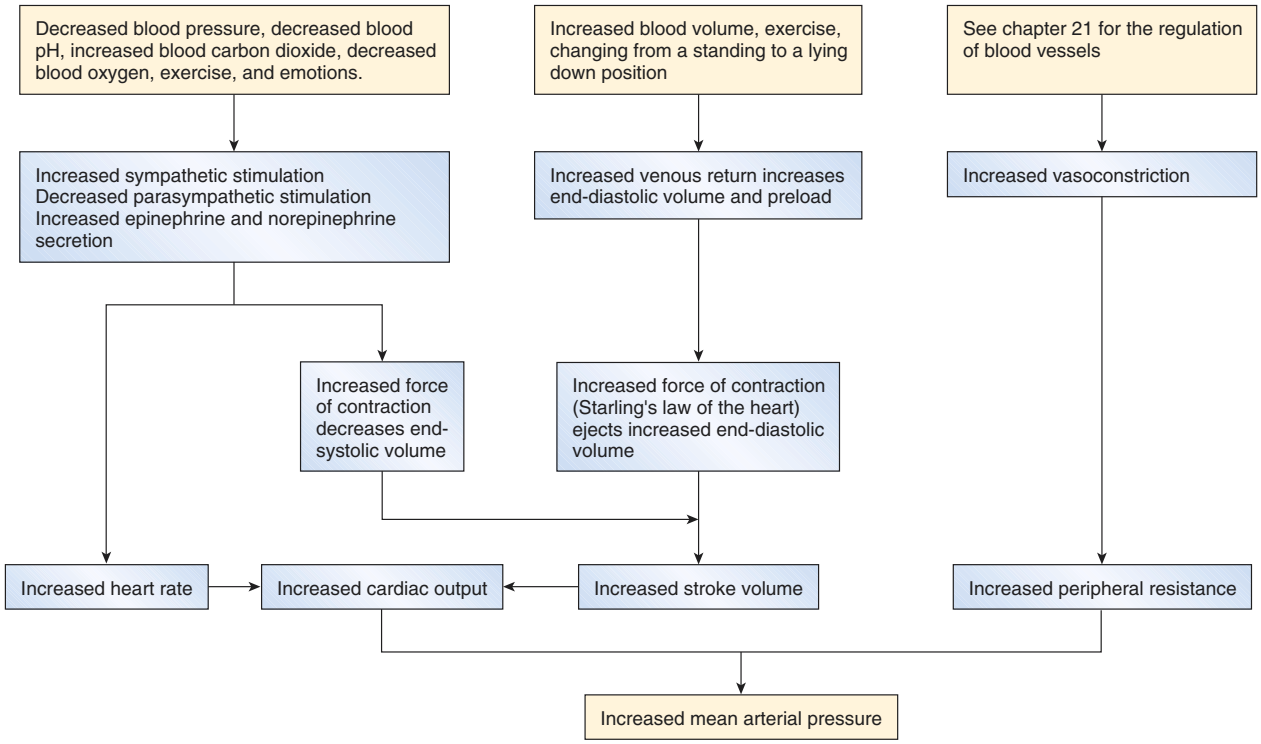


Figure 20.21 Factors Affecting Mean Arterial Pressure

Mean arterial pressure is regulated by controlling cardiac output and peripheral resistance.

exercising value of 115 mL by increasing end-diastolic volume to 145 mL and decreasing end-systolic volume to 30 mL.

Under resting conditions, the heart rate is approximately 72 bpm, and the stroke volume is approximately 70 mL/beat, although these values can vary considerably from person to person. The cardiac output is therefore

$$\begin{aligned} CO &= HR \times SV \\ &= 72 \text{ bpm} \times 70 \text{ mL/beat} \\ &= 5040 \text{ mL/min (approximately 5 L/min)} \end{aligned}$$

During exercise, heart rate can increase to 190 bpm, and the stroke volume can increase to 115 mL. Consequently, cardiac output is

$$\begin{aligned} CO &= 190 \text{ bpm} \times 115 \text{ mL/beat} \\ &= 21{,}850 \text{ mL/min (approximately 22 L/min)} \end{aligned}$$

The difference between cardiac output when a person is at rest and maximum cardiac output is called **cardiac reserve.** The greater a person's cardiac reserve, the greater his or her capacity for doing exercise. Lack of exercise and cardiovascular diseases can reduce cardiac reserve and affect a person's quality of life. Exercise training can greatly increase cardiac reserve by increasing cardiac output. In well-trained athletes, stroke volume during exercise can increase to over 200 mL/beat, resulting in cardiac outputs of 40 L/min or more.

- ***27. Define mean arterial pressure, cardiac output, and peripheral resistance. Explain the role of mean arterial pressure in causing blood flow.***
- ***28. Define stroke volume, and state two ways to increase stroke volume.***
- ***29. What is cardiac reserve? How can exercise training influence cardiac reserve?***

Regulation of the Heart

Objectives

- ***Describe intrinsic regulation of the heart.***
- ***Describe the mechanisms involved in extrinsic regulation of the heart.***

To maintain homeostasis, the amount of blood pumped by the heart must vary dramatically. For example, during exercise cardiac output can increase several times over resting values. Either intrinsic or extrinsic regulatory mechanisms control cardiac output. **Intrinsic regulation** results from the normal functional characteristics of the heart and does not depend on either neural or hormonal regulation. It functions when the heart is in place in the body or is removed and maintained outside the body under proper conditions. On the other hand, **extrinsic regulation**

involves neural and hormonal control. Neural regulation of the heart results from sympathetic and parasympathetic reflexes, and the major hormonal regulation comes from epinephrine and norepinephrine secreted from the adrenal medulla.

Intrinsic Regulation

The amount of blood that flows into the right atrium from the veins during diastole is called the venous return. As venous return increases, end-diastolic volume increases (see figure 20.21). A greater end-diastolic volume increases the stretch of the ventricular walls. The extent to which the ventricular walls are stretched is sometimes called the **preload.** An increased preload causes an increase in cardiac output, and a decreased preload causes a decrease in cardiac output.

Cardiac muscle exhibits a length-versus-tension relationship similar to that of skeletal muscle. Skeletal muscle, however, is stretched to nearly its optimal length before contraction, whereas cardiac muscle fibers are not stretched to the point at which they contract with a maximal force (see chapter 9). An increased preload, therefore, causes the cardiac muscle fibers to contract with a greater force and produce a greater stroke volume. This relationship between preload and stroke volume is commonly referred to as **Starling's law of the heart,** which describes the relationship between changes in the pumping effectiveness of the heart and changes in preload (see figure 20.21). Venous return can decrease to a value as low as 2 L/min or increase to as much as 24 L/min, which has a major effect on the preload.

Afterload is the pressure the contracting ventricles must produce to overcome the pressure in the aorta and move blood into the aorta. Although the pumping effectiveness of the heart is greatly influenced by relatively small changes in the preload, it is very insensitive to large changes in afterload. Aortic blood pressure must increase to more than 170 mm Hg before it hampers the ability of the ventricles to pump blood.

During physical exercise, blood vessels in exercising skeletal muscles dilate and allow increased flow of blood through the vessels. The increased blood flow increases oxygen and nutrient delivery to the exercising muscles. In addition, skeletal muscle contractions repeatedly compress veins and cause an increased rate of blood flow from the skeletal muscles toward the heart. As blood rapidly flows through skeletal muscles and back to the heart, venous return to the heart increases, resulting in an increased preload. The increased preload causes an increased force of cardiac muscle contraction, which increases stroke volume. The increase in stroke volume results in increased cardiac output, and the volume of blood flowing to the exercising muscles increases. When a person rests, venous return to the heart decreases because arteries in the skeletal muscles constrict and because muscular contractions no longer repeatedly compress the veins. As a result blood flow through skeletal muscles decreases, and there is a decrease in preload and cardiac output.

Extrinsic Regulation

The heart is innervated by both **parasympathetic** and **sympathetic** nerve fibers (figure 20.22). They influence the pumping action of the heart by affecting both heart rate and stroke volume. The influence of parasympathetic stimulation on the heart is much less than that of sympathetic stimulation. Sympathetic stimulation can increase cardiac output by 50%–100% over resting values, whereas parasympathetic stimulation can cause only a 10%–20% decrease.

Extrinsic regulation of the heart functions to keep blood pressure, blood oxygen levels, blood carbon dioxide levels, and blood pH within their normal ranges of values. For example, if blood pressure suddenly decreases, extrinsic mechanisms detect the decrease and initiate responses that increase cardiac output to bring blood pressure back to its normal range.

Parasympathetic Control

Parasympathetic nerve fibers are carried to the heart through the **vagus nerves.** Preganglionic fibers of the vagus nerve extend from the brainstem to terminal ganglia within the wall of the heart, and postganglionic fibers extend from the ganglia to the SA node, AV node, coronary vessels, and atrial myocardium.

Parasympathetic stimulation has an inhibitory influence on the heart, primarily by decreasing the heart rate. During resting conditions, continuous parasympathetic stimulation inhibits the heart to a small degree. An increase in heart rate during exercise results, in part, from decreased parasympathetic stimulation. Strong parasympathetic stimulation can decrease the heart rate 20–30 bpm but it has little effect on stroke volume. In fact, if venous return remains constant while the heart is inhibited by parasympathetic stimulation, stroke volume actually can increase. The longer time between heartbeats allows the heart to fill to a greater capacity, resulting in an increased preload, which increases stroke volume because of Starling's law of the heart.

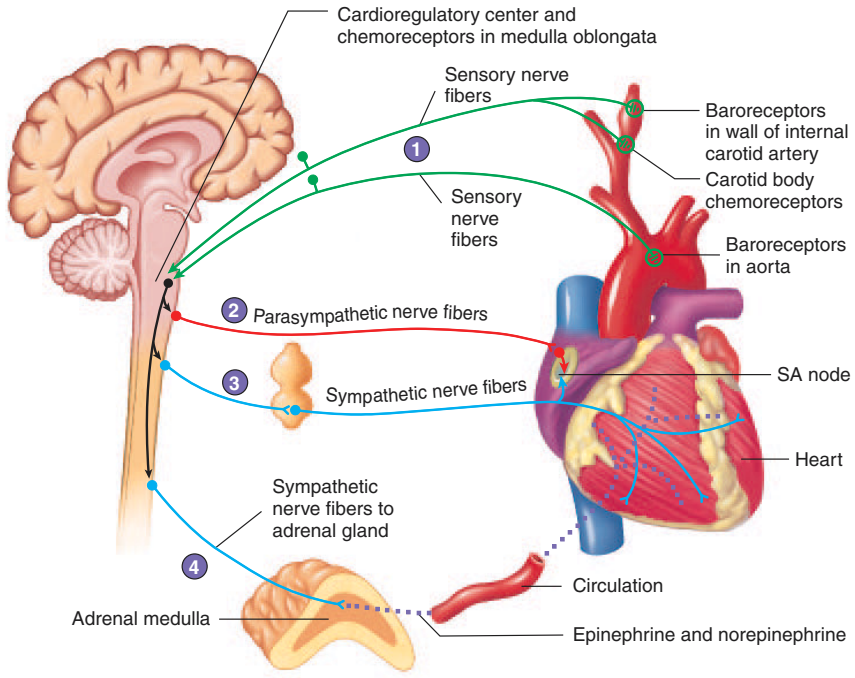
Acetylcholine, the neurotransmitter produced by postganglionic parasympathetic neurons, binds to ligand-gated channels that cause cardiac plasma membranes to become more permeable to K^+. As a consequence, the membrane hyperpolarizes. Heart rate decreases because the hyperpolarized membrane takes longer to depolarize and cause an action potential.

Sympathetic Control

Sympathetic nerve fibers originate in the thoracic region of the spinal cord as preganglionic neurons. These neurons synapse with postganglionic neurons of the inferior **cervical** and upper **thoracic sympathetic chain ganglia,** which project to the heart as **cardiac nerves** (see figure 20.22 and chapter 16). The postganglionic sympathetic nerve fibers innervate the SA and AV nodes, the coronary vessels, and the atrial and ventricular myocardium.

Sympathetic stimulation increases both the heart rate and the force of muscular contraction. In response to strong sympathetic stimulation, the heart rate can increase to 250 or, occasionally, 300 bpm. Stronger contractions also can increase stroke volume. The increased force of contraction resulting from sympathetic stimulation causes a lower end-systolic volume in the heart; therefore, the heart empties to a greater extent (see figure 20.21).

1. Sensory (*green*) neurons carry action potentials from baroreceptors to the cardioregulatory center. Chemoreceptors in the medulla oblongata influence the cardioregulatory center.
2. The cardioregulatory center controls the frequency of action potentials in the parasympathetic (*red*) neurons extending to the heart. The parasympathetic neurons decrease the heart rate.
3. The cardioregulatory center controls the frequency of action potential in the sympathetic (*blue*) neurons extending to the heart. The sympathetic neurons increase the heart rate and the stroke volume.
4. The cardioregulatory center influences the frequency of action potentials in the sympathetic (*blue*) neurons extending to the adrenal medulla. The sympathetic neurons increase the secretion of epinephrine and some norepinephrine into the general circulation. Epinephrine and norepinephrine increase the heart rate and stroke volume.



Process Figure 20.22 Baroreceptor and Chemoreceptor Reflexes

Sensory (*green*) nerves carry action potentials from sensory receptors to the medulla oblongata. Sympathetic (*blue*) and parasympathetic (*red*) nerves exit the spinal cord or medulla oblongata and extend to the heart to regulate its function. Epinephrine and norepinephrine from the adrenal gland also help regulate the heart's action. (*SA* = sinoatrial)

P R E D I C T 9

What effect does sympathetic stimulation have on stroke volume if the venous return remains constant? Sympathetic stimulation of the heart also results in dilation of the coronary blood vessels. Explain the functional advantage of that effect.

Limitations exist, however, to the relationship between increased heart rate and cardiac output. If the heart rate becomes too fast, diastole is not long enough to allow complete ventricular filling, end-diastolic volume decreases, and stroke volume actually decreases. In addition, if heart rate increases beyond a critical level, the strength of contraction decreases, probably as a result of the accumulation of metabolites in cardiac muscle cells. The limit of the heart's ability to increase the volume of blood pumped is 170–250 bpm in response to intense sympathetic stimulation.

Sympathetic stimulation of the ventricular myocardium plays a significant role in regulation of its contraction force during resting conditions. Sympathetic stimulation maintains the strength of ventricular contraction at a level approximately 20% greater than it would be with no sympathetic stimulation.

Norepinephrine, the postganglionic sympathetic neurotransmitter, increases the rate and degree of cardiac muscle depolarization so that both the frequency and amplitude of the action potentials are increased. The effect of norepinephrine on the heart involves the association between norepinephrine and cell surface β-adrenergic receptors. This combination causes a G protein–mediated synthesis and accumulation of cAMP in the cytoplasm of cardiac muscle cells. Cyclic AMP increases the permeability of the plasma membrane to Ca^{2+}, primarily by opening calcium slow channels in the plasma membrane.

Hormonal Control

Epinephrine and norepinephrine released from the adrenal medulla can markedly influence the pumping effectiveness of the heart. Epinephrine has essentially the same effect on cardiac muscle as norepinephrine and, therefore, increases the rate and force of heart contractions (see figure 20.21). The secretion of epinephrine and norepinephrine from the adrenal medulla is controlled by sympathetic stimulation of the medulla and occurs in response to increased physical activity, emotional excitement, or stressful conditions. Many stimuli that increase sympathetic stimulation of the heart also increase release of epinephrine and norepinephrine from the adrenal gland (see chapter 18). Epinephrine and

norepinephrine are transported in the blood through the vessels of the heart to the cardiac muscle cells, where they bind to β-adrenergic receptors and stimulate cAMP synthesis. Epinephrine takes a longer time to act on the heart than sympathetic stimulation does, but the effect lasts longer.

30. *Define the term venous return, and explain how it affects preload. How does preload affect cardiac output? State Starling's law of the heart.*
31. *Define the term afterload, and describe its effect on the pumping effectiveness of the heart.*
32. *What part of the brain regulates the heart? Describe the autonomic nerve supply to the heart.*
33. *What effect do parasympathetic stimulation and sympathetic stimulation have on heart rate, force of contraction, and stroke volume?*
34. *What neurotransmitters are released by the parasympathetic and sympathetic postganglionic neurons of the heart? What effects do they have on membrane permeability and excitablity?*
35. *Name the two main hormones that affect the heart. Where are they produced, what causes their release, and what effects do they have on the heart?*

Heart and Homeostasis

Objective

- *Describe the major factors that help maintain homeostasis by regulating heart activity.*

The pumping efficiency of the heart plays an important role in the maintenance of homeostasis. Blood pressure in the systemic vessels must be maintained at a level which is high enough to achieve nutrient and waste product exchange across the walls of the capillaries that meets metabolic demands. The activity of the heart must be regulated because the metabolic activities of the tissues change under such conditions as exercise and rest.

Effect of Blood Pressure

Baroreceptor (bar′ō-rē-sep′ter, bar′ō-rē-sep′tōr) **reflexes** detect changes in blood pressure and result in changes in heart rate and in the force of contraction. The sensory receptors of the baroreceptor reflexes are stretch receptors. They are in the walls of certain large arteries, such as the internal carotid arteries and the aorta, and they function to measure blood pressure (see figure 20.22). The anatomy of these sensory structures and their afferent pathways are described in chapter 21.

Afferent neurons project primarily through the glossopharyngeal (cranial nerve IX) and vagus (cranial nerve X) nerves from the baroreceptors to an area in the medulla oblongata called the **cardioregulatory center,** where sensory action potentials are integrated (see figure 20.22). The part of the cardioregulatory center that functions to increase heart rate is called the **cardioacceleratory center,** and the part that functions to decrease heart rate is called the **cardioinhibitory center.** Efferent action potentials then are sent from the cardioregulatory center to the heart through both the sympathetic and parasympathetic divisions of the autonomic nervous system.

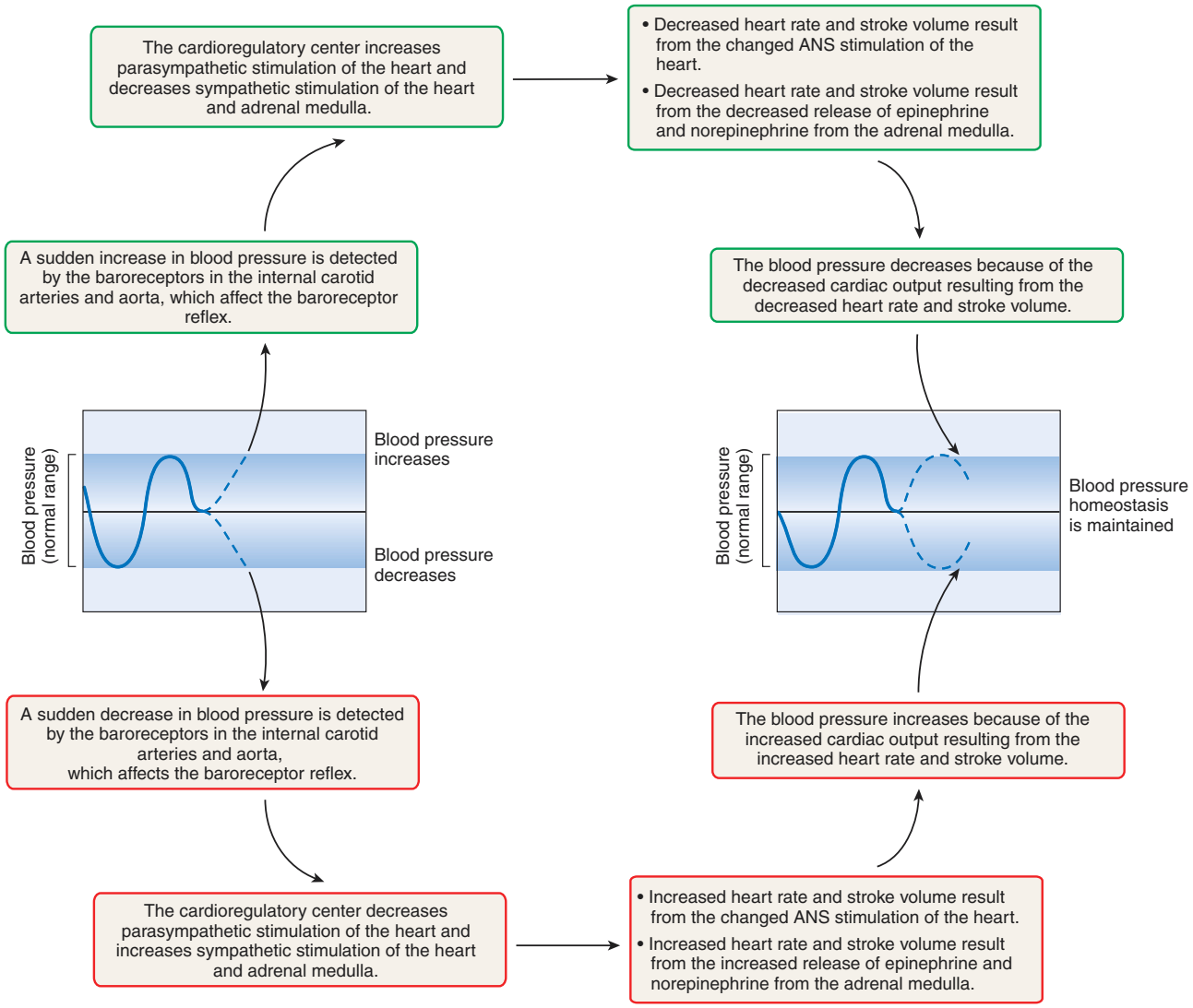
Increased blood pressure within the internal carotid arteries and aorta causes their walls to stretch, thereby stimulating an increase in action potential frequency in the baroreceptors (figure 20.23). At normal blood pressures (80–120 mm Hg), afferent action potentials are sent from the baroreceptors to the medulla oblongata at a relatively constant frequency. When blood pressure increases, the arterial walls are stretched further, and the afferent action potential frequency increases. When blood pressure decreases, the arterial walls are stretched to a lesser extent, and the afferent action potential frequency decreases. In response to increased blood pressure, the baroreceptor reflexes decrease sympathetic stimulation and increase parasympathetic stimulation of the heart, causing the heart rate to decrease. Decreased blood pressure causes decreased parasympathetic and increased sympathetic stimulation of the heart, resulting in an increased heart rate and force of contraction. Withdrawal of parasympathetic stimulation is primarily responsible for increases in heart rate up to approximately 100 bpm. Larger increases in heart rate, especially during exercise, result from sympathetic stimulation. The baroreceptor reflexes are homeostatic because they keep the blood pressure within a narrow range of values, which is adequate to maintain blood flow to the tissues.

Effect of pH, Carbon Dioxide, and Oxygen

Chemoreceptor (kē′mō-rē-sep′tor) **reflexes** help regulate the activity of the heart. Chemoreceptors sensitive to changes in pH and carbon dioxide levels exist within the medulla oblongata. A drop in pH and a rise in carbon dioxide decrease parasympathetic and increase sympathetic stimulation of the heart, resulting in an increased heart rate and force of contraction (figure 20.24).

The increased cardiac output causes greater blood flow through the lungs, where carbon dioxide is eliminated from the body. This helps bring the blood carbon dioxide level down to its normal range of values and helps to increase the blood pH.

Chemoreceptors primarily sensitive to blood oxygen levels are found in the carotid and aortic bodies. These small structures are located near large arteries close to the brain and heart, and they monitor blood flowing to the brain and to the rest of the body. A dramatic decrease in blood oxygen levels, such as during asphyxiation, activates the carotid and aortic body chemoreceptor reflexes. In carefully controlled experiments, it's possible to isolate the effects of the carotid and aortic body chemoreceptor reflexes from other reflexes, such as the medullary chemoreceptor reflexes. These experiments indicate that a decrease in blood oxygen results in a decrease in heart rate and an increase in vasoconstriction. The increased vasoconstriction causes blood pressure to rise, which promotes blood delivery despite the decrease in heart rate. The carotid and aortic body chemoreceptor reflexes may protect the heart for a short time by slowing the heart and thereby reducing its need for oxygen. The carotid and aortic body chemoreceptor reflexes normally don't function independently of other regulatory mechanisms. When all regulatory mechanisms function together, the effect of large, prolonged



Homeostasis Figure 20.23 Baroreceptor Reflex

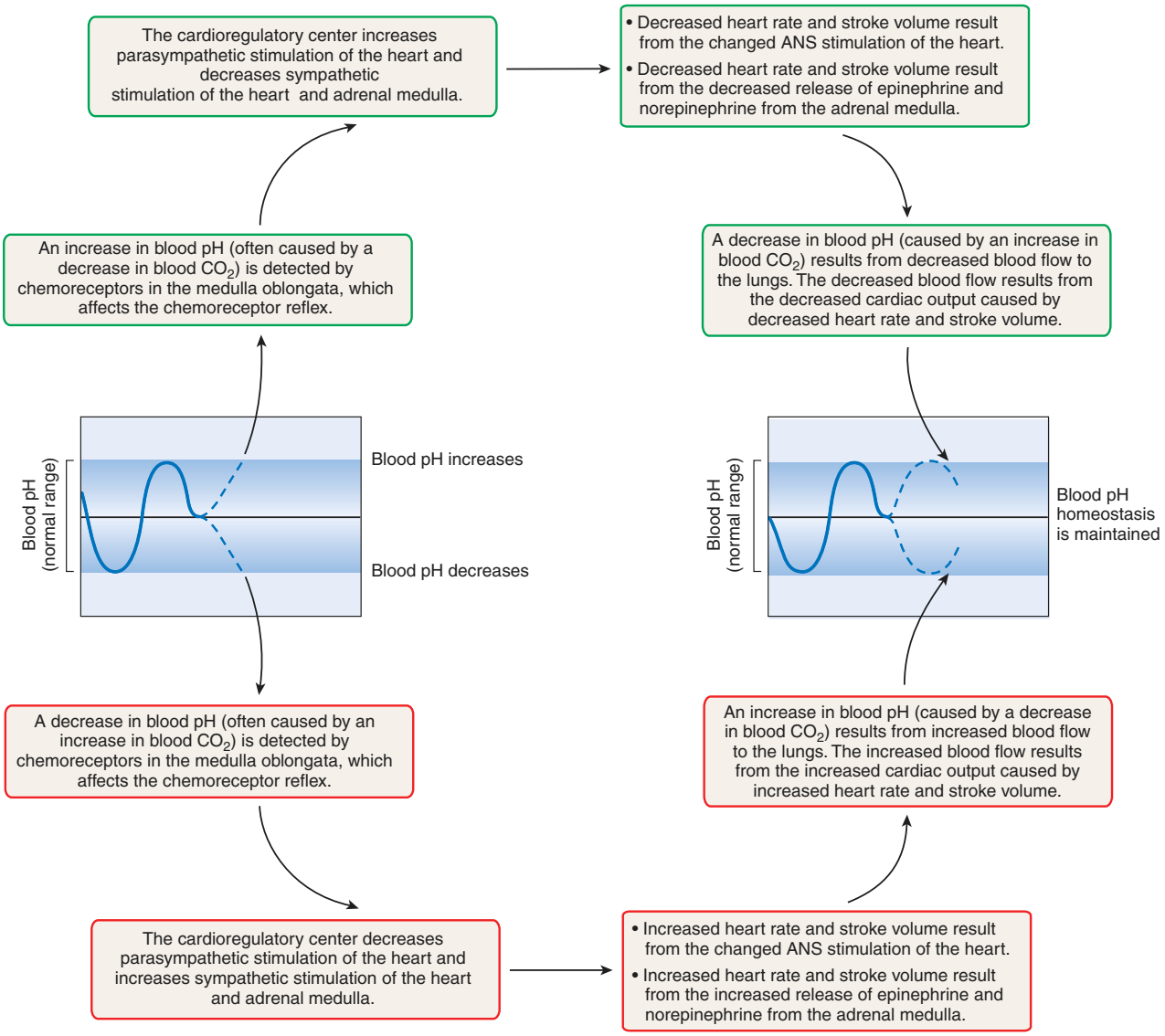
The baroreceptor reflex maintains homeostasis in response to changes in blood pressure. (*ANS* = autonomic nervous system)

decreases in blood oxygen levels is to increase the heart rate. Low blood oxygen levels result in increased stimulation of respiratory movements (see chapter 23). Increased inflation of the lungs stimulates stretch receptors in the lungs. Afferent action potentials from these stretch receptors influence the cardioregulatory center, which causes an increase in heart rate. The reduced oxygen levels that exist at high altitudes can cause an increase in heart rate even when blood carbon dioxide levels remain low. The carotid and aortic body chemoreceptor reflexes are more important in the regulation of respiration (see chapter 23) and blood vessel constriction (see chapter 21) than in the regulation of heart rate.

Effect of Extracellular Ion Concentration

Ions that affect cardiac muscle function are the same ions (potassium, calcium, and sodium) that influence membrane potentials in other electrically excitable tissues. Some differences do exist, however, between the response of cardiac muscle and that of nerve or muscle tissue to these ions. For example, the extracellular levels of Na^+ rarely deviate enough from the normal value to affect the function of cardiac muscle significantly.

Excess K^+ in cardiac tissue causes the heart rate and stroke volume to decrease. A twofold increase in extracellular K^+ results in



Homeostasis Figure 20.24 Chemoreceptor Reflex-pH

The chemoreceptor reflex maintains homeostasis in response to changes in blood concentrations of CO_2 and H^+. (*ANS* = autonomic nervous system)

heart block, which is loss of the functional conduction of action potentials through the conducting system of the heart. The excess K^+ in the extracellular fluid causes partial depolarization of the resting membrane potential, resulting in a decreased amplitude of action potentials and a decreased rate at which action potentials are conducted along muscle fibers. As the conduction rates decrease, ectopic action potentials can occur. The reduced action potential amplitude also results in less calcium entering the sarcoplasm of the cell; thus the strength of cardiac muscle contraction decreases.

Although the extracellular concentration of K^+ normally is small, a decrease in extracellular K^+ results in a decrease in the heart rate because the resting membrane potential is hyperpolarized; as a consequence, it takes longer for the membrane to depolarize to threshold. The force of contraction is not affected, however.

An increase in the extracellular concentration of Ca^{2+} produces an increase in the force of cardiac contraction because of a greater influx of Ca^{2+} into the sarcoplasm during action potential

generation. Elevated plasma Ca^{2+} levels have an indirect effect on heart rate because they reduce the frequency of action potentials in nerve fibers, thus reducing sympathetic and parasympathetic stimulation of the heart (see chapter 11). Generally, elevated blood Ca^{2+} levels reduce the heart rate.

A low blood Ca^{2+} level increases the heart rate, although the effect is imperceptible until blood Ca^{2+} levels are reduced to approximately one-tenth of their normal value. The reduced extracellular Ca^{2+} levels cause Na^{+} channels to open, which allows Na^{+} to diffuse more readily into the cell, resulting in depolarization and action potential generation. Reduced Ca^{2+} levels, however, usually cause death as a result of tetany of skeletal muscles before they decrease enough to markedly influence the heart's function.

Effect of Body Temperature

Under resting conditions, the temperature of cardiac muscle normally doesn't change dramatically in humans, although alterations in temperature influence the heart rate. Small increases in cardiac muscle temperature cause the heart rate to increase, and decreases in temperature cause the heart rate to decrease. For example, during exercise or fever, increased heart rate and force of contraction accompany temperature increases, but the heart rate decreases under conditions of hypothermia. During heart surgery, the body temperature sometimes is reduced dramatically to slow the heart rate and other metabolic functions in the body.

36. *How does the nervous system detect and respond to (a) a decrease in blood pressure, (b) an increase in carbon dioxide levels, (c) a decrease in blood pH, and (d) a decrease in blood oxygen levels?*
37. *Describe the baroreceptor reflex and the response of the heart to an increase in venous return.*
38. *What effect does an increase or decrease in extracellular potassium, calcium, and sodium ions have on heart rate and the force of contraction of the heart?*
39. *What effect does temperature have on heart rate?*

Effects of Aging on the Heart

Objective

- *List the major age-related changes of the heart.*

Aging results in gradual changes in the function of the heart, which are minor under resting conditions, but become more significant in response to exercise and when age-related diseases develop. The mechanisms that regulate the heart effectively compensate for most of the changes under resting conditions.

Hypertrophy of the left ventricle is a common age-related change. This appears to result from a gradual increase in the pressure in the aorta against which the left ventricle must pump blood and a gradual increase in the stiffness of cardiac muscle tissue. The increased pressure in the aorta results from a gradual decrease in arterial elasticity resulting in an increased stiffness of the aorta and other large arteries. Myocardial cells accumulate lipid and collagen fibers increase in cardiac tissue. These changes make the cardiac muscle tissue stiffer and less compliant. The increased volume of the left ventricle can sometimes result in an increase in left atrial pressure and increased pulmonary capillary pressure. This can cause pulmonary edema and a tendency for people to feel out of breath when they exercise strenuously.

There is a gradual decrease in the maximum heart rate. This can be roughly predicted by the following formula: Maximum heart rate = 220 − age of the individual. There is an increase in the rate at which ATP is broken down by cardiac muscle and a decrease in the rate of Ca^{2+} transport. There is a decrease in the maximum rate at which cardiac muscle can carry out aerobic metabolism. In addition, there is a decrease in the degree to which epinephrine and norepinephrine can increase the heart rate. These changes are consistent with longer contraction and relaxation times for cardiac muscle and a decrease in the maximum heart rate. Both the resting and maximum cardiac output slowly decrease as people age and, by 85 years of age, the cardiac output may be decreased by 30%–60%.

Age-related changes in the connective tissue of the heart valves occur. The connective tissue becomes less flexible and Ca^{2+} deposits increase. The result is an increased tendency for heart valves to function abnormally. There is especially an increased tendency for the aortic semilunar valve to become stenosed, but other heart valves, such as the bicuspid valve, may become either stenosed or incompetent.

Atrophy and replacement of cells of the left bundle branch and a decrease in the number of SA node cells alter the electrical conduction system of the heart and lead to a higher rate of cardiac arrhythmias in elderly people.

The enlarged and thickened cardiac muscle, especially in the left ventricle, consumes more oxygen to pump the same amount of blood pumped by a younger heart. This change is not significant except if the coronary circulation is decreased by coronary artery disease. However, the development of coronary artery disease is age-related. Congestive heart disease is also age-related. Approximately 10% of elderly people over 80 have congestive heart failure, and a major contributing factor is coronary artery disease. Because of the age-related changes in the heart, many elderly people are limited in their ability to respond to emergencies, infections, blood loss, or stress.

Exercise has many beneficial effects on the heart. Regular aerobic exercise improves the functional capacity of the heart at all ages, providing no conditions develop which cause the increased workload of the heart to be harmful.

40. *Explain how age-related changes affect the function of the left vetricle.*
41. *Describe the age-related changes in the heart rate.*
42. *Describe how increasing age affects the function of the conduction system and the heart valves.*
43. *Describe the effect of two age-related heart diseases on functions of the aging heart.*

Clinical Focus Conditions and Diseases Affecting the Heart

Inflammation of Heart Tissues

Endocarditis (en′dō-kar-dī′tis) is inflammation of the endocardium. It affects the valves more severely than other areas of the heart and can lead to deposition of scar tissue, causing valves to become stenosed or incompetent.

Myocarditis (mī′ō-kar-dī′tis) is inflammation of the myocardium and can lead to heart failure.

Pericarditis is inflammation of the pericardium. Pericarditis can result from bacterial or viral infections and can be extremely painful.

Rheumatic (roo-mat′ik) **heart disease** can result from a streptococcal infection in young people. Toxin produced by the bacteria can cause an immune reaction called rheumatic fever about 2–4 weeks after the infection. The immune reaction can cause inflammation of the endocardium, called **rheumatic endocarditis.** The inflamed valves, especially the bicuspid valve, can become stenosed or incompetent. The effective treatment of streptococcal infections with antibiotics has reduced the frequency of rheumatic heart disease.

Reduced Blood Flow to Cardiac Muscle

Coronary heart disease reduces the amount of blood that the coronary arteries are able to deliver to the myocardium. The reduction in blood flow damages the myocardium. The degree of damage depends on the size of the arteries involved, whether occlusion (blockage) is partial or complete, and whether occlusion is gradual or sudden. As the walls of the arteries thicken and harden with age, the volume of blood they can supply to the heart muscle declines, and the ability of the heart to pump blood decreases. Inadequate blood flow to the heart muscle can result in angina pectoris, which is a poorly localized sensation of pain in the region of the chest, left arm, and left shoulder.

Degenerative changes in the artery wall can cause the inside surface of the artery to become roughened. The chance of platelet aggregation increases at the rough surface, which increases the chance of **coronary thrombosis** (throm-bō′sis; formation of a blood clot in a coronary vessel). Inadequate blood flow can cause an **infarct** (in′farkt), an area of damaged cardiac tissue. A heart attack is often referred to as a coronary thrombosis or a **myocardial infarct.** The outcome of coronary thrombosis depends on the extent of the damage to heart muscle caused by inadequate blood flow and whether other blood vessels can supply enough blood to maintain the heart's function. Death can occur swiftly if the infarct is large; if the infarct is small, the heart can continue to function. In most cases, scar tissue replaces damaged cardiac muscle in the area of the infarct.

People who survive infarctions often lead fairly normal lives if they take precautions. Most cases call for moderate exercise, adequate rest, a disciplined diet, and reduced stress.

Congenital Conditions Affecting the Heart

Congenital heart disease is the result of abnormal development of the heart. The following conditions are common congenital defects.

Septal defect is a hole in a septum between the left and right sides of the heart. The hole may be in the interatrial or interventricular septum. These defects allow blood to flow from one side of the heart to the other and, as a consequence, greatly reduce the pumping effectiveness of the heart (see chapter 29).

Patent ductus arteriosus (dŭk′tŭs ar-tēr′ē-ō-sŭs) results when a blood vessel called the **ductus arteriosus,** which is present in the fetus, fails to close after birth. The ductus arteriosus extends between the pulmonary trunk and the aorta. It allows blood to pass from the pulmonary trunk to the aorta, thus bypassing the lungs. This is normal before birth because the lungs are not functioning (see chapter 29). If the ductus arteriosus fails to close after birth, blood flows in the opposite direction, from the aorta to the pulmonary trunk. As a consequence, blood flows through the lungs under higher pressure, causing damage to the lungs. In addition, the amount of work required of the left ventricle to maintain adequate systemic blood pressure increases.

Stenosis (ste-nō′sis) **of a heart valve** is a narrowed opening through one of the heart valves. In aortic or pulmonary valve stenosis, the workload of the heart is increased because the ventricles must contract with a much greater force to pump blood from the ventricles. Stenosis of the bicuspid valve prevents the flow of blood into the left ventricle, causing blood to back up in the left atrium and in the lungs, resulting in congestion of the lungs. Stenosis of the tricuspid valve causes blood to back up in the right atrium and systemic veins, causing swelling in the periphery.

An **incompetent heart valve** is one that leaks. Blood, therefore, flows through the valve when it's closed. The workload of the heart is increased because incompetent valves reduce the pumping efficiency of the heart. For example, an incompetent aortic semilunar valve allows blood to flow from the aorta into the left ventricle during diastole. Thus, the left ventricle fills with blood to a greater degree than normal. The increased filling of the left ventricle results in a greater stroke volume because of Starling's law of the heart. The pressure produced by the contracting ventricle and the pressure in the aorta is greater than normal during ventricular systole. The pressure in the aorta, however, decreases very rapidly as blood leaks into the left ventricle during diastole.

An incompetent bicuspid valve allows blood to flow back into the left atrium from the left ventricle during ventricular systole. This increases the pressure in the left atrium and pulmonary veins, which results in pulmonary edema. Also, the stroke volume of the left ventricle is reduced, which causes a decrease in systemic blood pressure. Similarly, an incompetent tricuspid valve allows blood to flow back into the right atrium and systemic veins, causing edema in the periphery.

Cyanosis (sī-ă-nō′sis) is a symptom of inadequate heart function in babies suffering from congenital heart disease. The term *blue baby* is sometimes used to refer to infants with cyanosis. Low blood oxygen levels in the peripheral blood vessels cause the skin to look blue.

Heart Failure

Heart failure is the result of progressive weakening of the heart muscle and the failure of the heart to pump blood effectively. Hypertension (high blood pressure) increases the afterload on the heart, can produce significant enlargement of the heart, and can finally result in heart failure. Advanced age, malnutrition, chronic infections, toxins, severe anemias, or hyperthyroidism can cause degeneration of the heart muscle, resulting in heart failure. Hereditary factors can also be responsible for increased susceptibility to heart failure.

Heart Medications

Digitalis (dij-i-tal′is, dij-i-ta′lis) slows and strengthens contractions of the heart muscle. This drug is frequently given to people who suffer from heart failure, although it also can be used to treat atrial tachycardia.

Nitroglycerin (nī-trō-glis′er-in) causes dilation of all of the veins and arteries, including coronary arteries, without an increase in heart rate or stroke volume. When all blood vessels dilate, a greater volume of blood pools in the dilated blood vessels, causing a decrease in the venous return to the heart. The flow of blood through coronary arteries also increases. The reduced preload causes cardiac output to decrease, resulting in a decreased amount of work performed by the heart. Nitroglycerin is frequently given to people who suffer from coronary artery disease, which restricts coronary blood flow. The decreased work performed by the heart reduces the amount of oxygen required by the cardiac muscle. Consequently, the heart doesn't suffer from a lack of oxygen, and angina pectoris doesn't develop.

Beta-adrenergic-blocking agents reduce the rate and strength of cardiac muscle contractions, thus reducing the heart's demand for oxygen. These blocking agents bind to receptors for norepinephrine and epinephrine and prevent these substances from having their normal effects. They are often used to treat people who suffer from rapid heart rates, certain types of arrhythmias, and hypertension.

Calcium channel blockers reduce the rate at which Ca^{2+} diffuse into cardiac muscle cells and smooth muscle cells. Because the action potentials that produce cardiac muscle contractions depend in part on the flow of Ca^{2+} into cardiac muscle cells, calcium channel blockers can be used to control the force of heart contractions and reduce arrhythmia, tachycardia, and hypertension. Because entry of Ca^{2+} into smooth muscle cells causes contraction, calcium channel blockers cause dilation of coronary blood vessels and can be used to treat angina pectoris.

Antihypertensive (an′tē-hī-per-ten′siv) **agents** comprise several drugs used specifically to treat hypertension. These drugs reduce blood pressure and, therefore, reduce the work required by the heart to pump blood. In addition, the reduction of blood pressure reduces the risk of heart attacks and strokes. Drugs used to treat hypertension include those that reduce the activity of the sympathetic nervous system, that dilate arteries and veins, that increase urine production (diuretics), and that block the conversion of angiotensinogen to angiotensin I.

Anticoagulants (an′tē-kō-ag′ū-lantz) prevent clot formation in persons with damage to heart valves or blood vessels or in persons who have had a myocardial infarction. Aspirin functions as a weak anticoagulant.

Instruments and Selected Procedures

An **artificial pacemaker** is an instrument placed beneath the skin, equipped with an electrode that extends to the heart. The instrument provides an electric stimulus to the heart at a set frequency. Artificial pacemakers are used in patients in whom the natural pacemaker of the heart doesn't produce a heart rate high enough to sustain normal physical activity. Modern electronics has made it possible to design artificial pacemakers that can increase the heart rate as increases in physical activity occur. Pacemakers can also detect cardiac arrest, extreme arrythmias, or fibrillation. In response, strong stimulation of the heart by the pacemaker may restore heart function.

A **heart lung machine** serves as a temporary substitute for a patient's heart and lungs. It oxygenates the blood, removes carbon dioxide, and pumps blood throughout the body. It has made possible many surgeries on the heart and lungs.

Heart valve replacement or repair is a surgical procedure performed on those who have diseased valves that are so deformed and scarred from conditions like endocarditis that the valves are severely incompetent or stenosed. Substitute valves made of synthetic materials like plastic or Dacron are effective; valves transplanted from pigs are also used.

A **heart transplant** is a surgical procedure made possible when the immune characteristics of a donor and the recipient are closely matched (see chapter 22). The heart of a recently deceased donor is transplanted to the recipient, and the diseased heart of the recipient is removed. People who have received heart transplants must continue to take drugs that suppress their immune responses for the rest of their lives. If they don't, their immune system will reject the transplanted heart.

An **artificial heart** is a mechanical pump that replaces the heart. It is still experimental and cannot be viewed as a permanent substitute for the heart. It has been used to keep a patient alive until a donor heart can be found.

Cardiac assistance involves temporarily implanting a mechanical device that assists the heart in pumping blood. In some cases, the decreased workload on the heart provided by the device appears to promote recovery of failing hearts, and the device has been successfully removed. In **cardiomyoplasty,** a piece of a back muscle (latissimus dorsi) is wrapped around the heart and stimulated to contract in synchrony with the heart.

Prevention of Heart Disease

Proper nutrition is important in reducing the risk of heart disease (see chapter 25). A recommended diet is low in fats, especially saturated fats and cholesterol, and low in refined sugar. Diets should be high in fiber, whole grains, fruits, and vegetables. Total food intake should be limited to avoid obesity, and sodium chloride intake should be reduced.

Tobacco and excessive use of alcohol should be avoided. Smoking increases the risk of heart disease at least 10-fold, and excessive use of alcohol also substantially increases the risk of heart disease.

Chronic stress, frequent emotional upsets, and a lack of physical exercise can increase the risk of cardiovascular disease. Remedies include relaxation techniques and aerobic exercise programs involving gradual increases in duration and difficulty in activities, such as walking, swimming, jogging, or aerobic dancing.

Hypertension (hī′per-ten′shŭn) is abnormally high systemic blood pressure. It affects about one-fifth of the U.S. population. Regular blood pressure measurements are important because hypertension does not produce obvious symptoms. If hypertension cannot be controlled by diet and exercise, it's important to treat the condition with prescribed drugs. The cause of hypertension in the majority of cases is unknown.

Some data suggest that taking an aspirin daily reduces the chance of a heart attack. Aspirin inhibits the synthesis of prostaglandins in platelets, thereby helping to prevent clot formation.

Systems Pathology

Myocardial Infarction

Mr. P was an overweight, out-of-shape executive who regularly smoked and consumed food with a high fat content. He viewed his job as frustrating because he was frequently confronted with stressful deadlines. He had not had a physical examination for several years, so he was not aware that his blood pressure was high. One evening, Mr. P was walking to his car after work when he began to feel chest pain that radiated down his left arm. Shortly after the onset of pain, he felt out of breath, developed marked pallor, became dizzy, and had to lie down on the sidewalk. The pain in his chest and arm was poorly localized, but intense, and he became anxious and then disoriented. Mr. P lost consciousness, although he did not stop breathing. After a short delay, one of his coworkers noticed him and called for help. When paramedics arrived they determined that Mr. P's blood pressure was low and he exhibited arrhythmia and tachycardia. The paramedics transmitted the electrocardiogram they took to a physician by way of their electronic communications system, and they discussed Mr. P's symptoms with the physician who was at the hospital. The paramedics were directed to administer oxygen and medication to control arrhythmias and transport him to the hospital. At the hospital, tissue plasminogen activator (t-PA) was administered, which improved blood flow to the damaged area of the heart by activating plasminogen, which dissolves blood clots. Enzymes, like creatine phosphokinase, increased in Mr. P's blood over the next few days, which confirmed that damage to cardiac muscle resulted from an infarction.

In the hospital, Mr. P began to experience shortness of breath because of pulmonary edema, and after a few days in the hospital, he developed pneumonia. He was treated for pneumonia and gradually improved over the next few weeks. An angiogram performed several days after Mr. P's infarction indicated that he had suffered damage to a significant part of the lateral wall of his left ventricle and that neither angioplasty nor bypass surgery were necessary, although Mr. P has some serious restrictions to blood flow in his coronary arteries.

Background Information

Mr. P experienced a myocardial infarction. A thrombosis in one of the branches of the left coronary artery reduces the blood supply to the lateral wall of the left ventricle, resulting in ischemia of the left ventricle wall. That t-PA is effective in treating a heart attack is consistent with the conclusion that the infarction was caused by a thrombosis. An ischemic area of the heart wall is not able to contract normally and, therefore, the pumping effectiveness of the heart is dramatically reduced. The reduced pumping capacity of the heart is responsible for the low blood pressure, which causes the blood flow to the brain to decrease resulting in confusion, disorientation, and unconsciousness.

Low blood pressure, increasing blood carbon dioxide levels, pain, and anxiousness increase sympathetic stimulation of the heart and adrenal glands. Increased sympathetic stimulation of the adrenal medulla results in release of epinephrine. Increased parasympathetic stimulation of the heart results from pain sensations. In such cases, the heart is periodically arrhythmic due to the combined effects of parasympathetic stimulation, epinephrine and norepinephrine from the adrenal gland, and sympathetic stimulation. In addition, ectopic beats are produced by the ischemic areas of the left ventricle.

Pulmonary edema results from the increased pressure in the pulmonary veins because of the inability of the left ventricle to pump blood. The edema allows bacteria to infect the lungs and cause pneumonia.

Mr. P's heart began to beat rhythmically in response to medication because the infarction did not damage the conducting system of the heart, which is an indication that the no permanent arrhythmias developed. Permanent arrhythmias are indications of damage done to cardiac muscle specialized to conduct action potentials in the heart.

Analysis of the electrocardiogram, blood pressure measurements, and the angiogram (figure A) indicate that the infarction, in this case, was located on the left side of Mr. P's heart. Mr. P exhibited several characteristics that are correlated with an increased probability of myocardial infarction: lack of physical exercise, being overweight, smoking, and stress.

Mr. P's physician made it very clear to him that he was lucky to have survived a myocardial infarction, and the physician recommended a weight-loss program, a low-sodium and low-fat diet, and that Mr. P should stop smoking. He explained that Mr. P would have to take medication for high blood pressure if his blood pressure did not decrease in response to the recommended changes. After a period of recovery, Mr. P's physician recommended an aerobic exercise program to him. He advised Mr. P to seek ways to reduce the stress associated with his job. His physician also recommended that Mr. P regularly take a small amount of aspirin. The aspirin was prescribed to reduce the probability of thrombosis. Because aspirin inhibits prostaglandin synthesis, it reduces the tendency for blood to clot. Mr. P followed the doctor's recommendations, and after several months, he began to feel better than he had in years, and his blood pressure was normal.

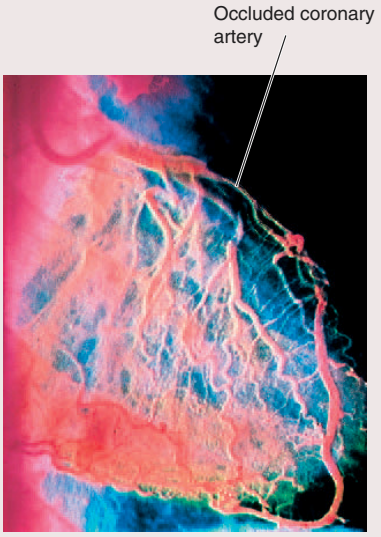


Figure A Angiogram

An angiogram (an′jē-ō-gram) is a picture of a blood vessel. It is usually obtained by placing a catheter into a blood vessel and injecting a dye that can be detected with x-rays. Note the occluded (blocked) coronary blood vessel in this angiogram, which has been computer-enhanced to show colors.

P R E D I C T 10

Severe ischemia in the wall of a ventricle can result in the death of cardiac muscle cells. Inflammation around the necrotic tissue results, and macrophages invade the necrotic tissue and phagocytize dead cells. At the same time, blood vessels and connective tissue grow into the necrotic area and begin to deposit connective tissue to replace the necrotic tissue. Assume that Mr. P had a myocardial infarction and was recovering. After about a week, however, his blood pressure suddenly decreased to very low levels, and he died within a very short time. At autopsy, a large amount of blood was found in the pericardial sac, and the wall of the left ventricle was ruptured. Explain.

System Interactions Effect of Myocardial Infarction on Other Systems

System	Interaction
Integumentary	Pallor of the skin resulted from intense constriction of peripheral blood vessels, including those in the skin.
Muscular	Reduced skeletal muscle activity required for activities such as walking results from lack of blood flow to the brain and because blood is shunted from blood vessels that supply skeletal muscles to those that supply the heart and brain.
Nervous	Decreased bood flow to the brain, decreased blood pressure, and pain due to ischemia of heart muscle result in increased sympathetic and decreased parasympathetic stimulation of the heart. Loss of consciousness occurs when the blood flow to the brain decreases enough to result in too little oxygen to maintain normal brain function, especially in the reticular activating system.
Endocrine	When blood pressure decreases to low values, antidiuretic hormone (ADH) is released from the posterior pituitary gland and renin, released from the kidney, activates the renin-angiotensinogen-aldosterone mechanism. ADH, secreted in large amounts, and angiotensin II cause vasoconstriction of peripheral blood vessels. ADH and aldosterone act on the kidneys to retain water and electrolytes. An increased blood volume increases venous return, which results in an increased stroke volume of the heart and an increase in blood pressure unless damage to the heart is very severe.
Lymphatic or Immune	White blood cells, including macrophages, move to the area of cardiac muscle damaged and phagocytize any dead cardiac muscle cells.
Respiratory	Decreased blood pressure results in a decreased blood flow to the lungs. The decrease in gas exchange results in increased blood CO_2 levels, acidosis, and decreased blood O_2 levels. Initially, respiration becomes deep and labored because of the elevated CO_2 levels, decreased blood pH, and depressed O_2 levels. If the blood O_2 levels decrease too much, the person loses consciousness. Pulmonary edema can result when the pumping effectiveness of the left ventricle is substantially reduced.
Digestive	Decreased blood flow to the digestive system to very low levels often results in increased nausea and vomiting.
Urinary	Blood flow to the kidney decreases dramatically in response to sympathetic stimulation. If the kidney becomes ischemic, damage to the kidney tubules can occur, resulting in acute renal failure. Acute renal failure reduces urine production. Increased blood urea nitrogen, increased blood levels of K^+, and edema are indications that the kidneys cannot eliminate waste products and excess water. If damage is not too great, the period of reduced urine production may last up to 3 weeks and then the rate of urine production slowly returns to normal as the kidney tubules heal.

S U M M A R Y

Functions of the Heart (p. 668)

The heart produces the force that causes blood circulation.

Size, Shape, and Location of the Heart (p. 668)

The heart is approximately the size of a closed fist and is shaped like a blunt cone. It is in the mediastinum.

Anatomy of the Heart (p. 670)

The heart consists of two atria and two ventricles.

Pericardium

1. The pericardium is a sac that surrounds the heart and consists of the fibrous pericardium and the serous pericardium.
2. The fibrous pericardium helps hold the heart in place.
3. The serous pericardium reduces friction as the heart beats. It consists of the following parts:
   - The parietal pericardium lines the fibrous pericardium.
   - The visceral pericardium lines the exterior surface of the heart.
   - The pericardial cavity lies between the parietal and visceral pericardium and is filled with pericardial fluid.

Heart Wall

1. The heart wall has three layers:
   - The outer epicardium (visceral pericardium) provides protection against the friction of rubbing organs.
   - The middle myocardium is responsible for contraction.
   - The inner endocardium reduces the friction resulting from blood's passing through the heart.
2. The inner surfaces of the atria are mainly smooth. The auricles have raised areas called musculi pectinati.
3. The ventricles have ridges called trabeculae carneae.

External Anatomy and Coronary Circulation

1. Each atrium has a flap called the auricle.
2. The coronary sulcus separates the atria from the ventricles. The interventricular grooves separate the right and left ventricles.
3. The inferior and superior venae cavae and the coronary sinus enter the right atrium. The four pulmonary veins enter the left atrium.
4. The pulmonary trunk exits the right ventricle, and the aorta exits the left ventricle.
5. Coronary arteries branch off the aorta to supply the heart. Blood returns from the heart tissues to the right atrium through the coronary sinus and cardiac veins.

Heart Chambers and Valves

1. The interatrial septum separates the atria from each other, and the interventricular septum separates the ventricles.
2. The tricuspid valve separates the right atrium and ventricle. The bicuspid valve separates the left atrium and ventricle. The chordae tendineae attach the papillary muscles to the atrioventricular valves.
3. The semilunar valves separate the aorta and pulmonary trunk from the ventricles.

Route of Blood Flow Through the Heart (p. 677)

1. Blood from the body flows through the right atrium into the right ventricle and then to the lungs.
2. Blood returns from the lungs to the left atrium, enters the left ventricle, and is pumped back to the body.

Histology (p. 679)

Heart Skeleton

The fibrous heart skeleton supports the openings of the heart, electrically insulates the atria from the ventricles, and provides a point of attachment for heart muscle.

Cardiac Muscle

1. Cardiac muscle cells are branched and have a centrally located nucleus. Actin and myosin are organized to form sarcomeres. The sarcoplasmic reticulum and T tubules are not as organized as in skeletal muscle.
2. Cardiac muscle cells are joined by intercalated disks, which allow action potentials to move from one cell to the next. Thus, cardiac muscle cells function as a unit.
3. Cardiac muscle cells have a slow onset of contraction and a prolonged contraction time caused by the length of time required for calcium to move to and from the myofibrils.
4. Cardiac muscle is well supplied with blood vessels that support aerobic respiration.
5. Cardiac muscle aerobically uses glucose, fatty acids, and lactic acid to produce ATP for energy. Cardiac muscle does not develop a significant oxygen debt.

Conducting System

1. The SA node and the AV node are in the right atrium.
2. The AV node is connected to the bundle branches in the interventricular septum by the AV bundle.
3. The bundle branches give rise to Purkinje fibers, which supply the ventricles.
4. The SA node initiates action potentials, which spread across the atria and cause them to contract.
5. Action potentials are slowed in the AV node, allowing the atria to contract and blood to move into the ventricles. Then, the action potentials travel through the AV bundles and bundle branches to the Purkinje fibers, causing the ventricles to contract, starting at the apex.

Electrical Properties (p. 681)

Action Potentials

1. After depolarization and partial repolarization, a plateau is reached, during which the membrane potential only slowly repolarizes.
2. The movement of Na^+ through the voltage-gated Na^+ channels causes depolarization.
3. During depolarization, voltage-gated K^+ channels close and voltage-gated Ca^{2+} channels begin to open.
4. Early repolarization results from closure of the voltage-gated Na^+ channels and the opening of some voltage-gated K^+ channels.
5. The plateau exists because voltage-gated Ca^{2+} channels remain open.
6. The rapid phase of repolarization results from closure of the voltage-gated Ca^+ channels and the opening of many voltage-gated K^+ channels.

Autorhythmicity of Cardiac Muscle

1. Cardiac pacemaker muscle cells are autorhythmic because of the spontaneous development of a prepotential.
2. The prepotential results from the movement of Na^+ and Ca^{2+} into the pacemaker cells.
3. Ectopic foci are areas of the heart that regulate heart rate under abnormal conditions.

Refractory Period of Cardiac Muscle

Cardiac muscle has a prolonged depolarization and thus a prolonged refractory period, which allows time for the cardiac muscle to relax before the next action potential causes a contraction.

Electrocardiogram

1. The ECG records only the electrical activities of the heart.
   - Depolarization of the atria produces the P wave.
   - Depolarization of the ventricles produces the QRS complex. Repolarization of the atria occurs during the QRS complex.
   - Repolarization of the ventricles produces the T wave.
2. Based on the magnitude of the ECG waves and the time between waves, ECGs can be used to diagnose heart abnormalities.

Cardiac Cycle (p. 685)

1. The cardiac cycle is repetitive contraction and relaxation of the heart chambers.
2. Blood moves through the circulatory system from areas of higher pressure to areas of lower pressure. Contraction of the heart produces the pressure.
3. The cardiac cycle is divided into five periods.
   - Although the heart is contracting, during the period of isovolumic contraction ventricular volume doesn't change because all the heart valves are closed.
   - During the period of ejection, the semilunar valves open, and blood is ejected from the heart.
   - Although the heart is relaxing, during the period of isovolumic relaxation, ventricular volume doesn't change because all the heart valves are closed.
   - Passive ventricular filling results when blood flows from the higher pressure in the veins and atria to the lower pressure in the relaxed ventricles.
   - Active ventricular filling results when the atria contract and pump blood into the ventricles.

Events Occurring During Ventricular Systole

1. Contraction of the ventricles closes the AV valves, opens the semilunar valves, and ejects blood from the heart.
2. The volume of blood in a ventricle just before it contracts is the end-diastolic volume. The volume of blood after contraction is the end-systolic volume.

Events Occurring During Ventricular Diastole

1. Relaxation of the ventricles results in closing of the semilunar valves, opening of the AV valves, and the movement of blood into the ventricles.
2. Most ventricular filling occurs when blood flows from the higher pressure in the veins and atria to the lower pressure in the relaxed ventricles.
3. Contraction of the atria completes ventricular filling.

Heart Sounds

1. Closure of the atrioventricular valves produces the first heart sound.
2. Closure of the semilunar valves produces the second heart sound.

Aortic Pressure Curve

1. Contraction of the ventricles forces blood into the aorta, thus producing the peak systolic pressure.
2. Blood pressure in the aorta falls to the diastolic level as blood flows out of the aorta.
3. Elastic recoil of the aorta maintains pressure in the aorta and produces the dicrotic notch.

Mean Arterial Blood Pressure (p. 692)

1. Mean arterial pressure is the average blood pressure in the aorta. Adequate blood pressure is necessary to ensure delivery of blood to the tissues.
2. Mean arterial pressure is proportional to cardiac output (amount of blood pumped by the heart per minute) times peripheral resistance (total resistance to blood flow through blood vessels).
3. Cardiac output is equal to stroke volume times heart rate.
4. Stroke volume, the amount of blood pumped by the heart per beat, is equal to end-diastolic volume minus end-systolic volume.
   - Venous return is the amount of blood returning to the heart. Increased venous return increases stroke volume by increasing end-diastolic volume.
   - Increased force of contraction increases stroke volume by decreasing end-systolic volume.
5. Cardiac reserve is the difference between resting and exercising cardiac output.

Regulation of the Heart (p. 693)

Intrinsic Regulation

1. Venous return is the amount of blood that returns to the heart during each cardiac cycle.
2. Starling's law of the heart describes the relationship between preload and the stroke volume of the heart. An increased preload causes the cardiac muscle fibers to contract with a greater force and produce a greater stroke volume.

Extrinsic Regulation

1. The cardioregulatory center in the medulla oblongata regulates the parasympathetic and sympathetic nervous control of the heart.
2. Parasympathetic control
   - Parasympathetic stimulation is supplied by the vagus nerve.
   - Parasympathetic stimulation decreases heart rate.
   - Postganglionic neurons secrete acetylcholine, which increases membrane permeability to K^+, producing hyperpolarization of the membrane.
3. Sympathetic control
   - Sympathetic stimulation is supplied by the cardiac nerves.
   - Sympathetic stimulation increases heart rate and the force of contraction (stroke volume).
   - Postganglionic neurons secrete norepinephrine, which increases membrane permeability to Na^+ and Ca^{2+} and produces depolarization of the membrane.
4. Epinephrine and norepinephrine are released into the blood from the adrenal medulla as a result of sympathetic stimulation.
   - The effects of epinephrine and norepinephrine on the heart are long lasting compared to those of neural stimulation.
   - Epinephrine and norepinephrine increase the rate and force of heart contraction.

Heart and Homeostasis (p. 696)

Effect of Blood Pressure

1. Baroreceptors monitor blood pressure.
2. In response to a decrease in blood pressure, the baroreceptor reflexes increase sympathetic stimulation and decrease parasympathetic stimulation of the heart, resulting in an increase in heart rate and force of contraction.

Effect of pH, Carbon Dioxide, and Oxygen

1. Chemoreceptors monitor blood carbon dioxide, pH, and oxygen levels.
2. In response to increased carbon dioxide and decreased pH, medullary chemoreceptor reflexes increase sympathetic stimulation and decrease parasympathetic stimulation of the heart.
3. Carotid body chemoreceptor receptors stimulated by low oxygen levels result in a decreased heart rate and vasoconstriction.
4. All regulatory mechanisms functioning together in response to low blood pH, high blood carbon dioxide, and low blood oxygen levels usually produce an increase in heart rate and vasoconstriction. Decreased oxygen levels stimulate an increase in heart rate indirectly by stimulating respiration, and the stretch of the lungs activates a reflex that increases sympathetic stimulation of the heart.

Effect of Extracellular Ion Concentration

1. An increase or decrease in extracellular K^+ decreases heart rate.
2. Increased extracellular Ca^{2+} increase the force of contraction of the heart and decrease the heart rate. Decreased Ca^{2+} levels produce the opposite effect.

Effect of Body Temperature

Heart rate increases when body temperature increases, and it decreases when body temperature decreases.

Effects of Aging on the Heart (p. 699)

1. Aging results in gradual changes in the function of the heart which are minor under resting conditions but are more significant during exercise.
2. Hypertrophy of the left ventricle is a common age-related condition.
3. The maximum heart rate decreases and by age 85 the cardiac output may be decreased by 30–60%.
4. There is an increased tendency for valves to function abnormally and for arrhythmias to occur.
5. An increased oxygen consumption, required to pump the same amount of blood, makes age-related coronary artery disease more severe.
6. Exercise improves the functional capacity of the heart at all ages.

REVIEW AND COMPREHENSION

1. The fibrous pericardium
   a. is in contact with the heart.
   b. is a serous membrane.
   c. is also known as the epicardium.
   d. forms the outer layer of the pericardial sac.
   e. all of the above.
2. Which of these structures returns blood to the right atrium?
   a. coronary sinus
   b. inferior vena cava
   c. superior vena cava
   d. both b and c
   e. all of the above
3. The valve located between the right atrium and the right ventricle is the
   a. aortic semilunar valve.
   b. pulmonary semilunar valve.
   c. tricuspid valve.
   d. bicuspid (mitral) valve.
4. The papillary muscles
   a. are attached to chordae tendineae.
   b. are found in the atria.
   c. contract to close the foramen ovale.
   d. are attached to the semilunar valves.
   e. surround the openings of the coronary arteries.
5. Given these blood vessels:
   1. aorta
   2. inferior vena cava
   3. pulmonary trunk
   4. pulmonary vein

   Choose the arrangement that lists the vessels in the order a red blood cell would encounter them in going from the systemic veins back to the systemic arteries.
   a. 1,3,4,2
   b. 2,3,4,1
   c. 2,4,3,1
   d. 3,2,1,4
   e. 3,4,2,1
6. Which of these does *not* correctly describe the skeleton of the heart?
   a. electrically insulates the atria from the ventricles
   b. provides a rigid source of attachment for the cardiac muscle
   c. functions to reinforce or support the valve openings
   d. is composed mainly of cartilage
7. The bulk of the heart wall is
   a. epicardium.
   b. pericardium.
   c. myocardium.
   d. endocardium.
   e. exocardium.
8. Muscular ridges on the interior surface of the auricles are called
   a. trabeculae carneae.
   b. crista terminalis.
   c. musculi pectinati.
   d. endocardium.
   e. papillary muscles.
9. Cardiac muscle has
   a. sarcomeres.
   b. a sarcoplasmic reticulum.
   c. transverse tubules.
   d. many mitochondria.
   e. all of the above.
10. Action potentials pass from one cardiac muscle cell to another
    a. through gap junctions.
    b. by a special cardiac nervous system.
    c. because of the large voltage of the action potentials.
    d. because of the plateau phase of the action potentials.
    e. by neurotransmitters.
11. During the transmission of action potentials through the conducting system of the heart, there is a temporary delay at the
    a. bundle branches.
    b. Purkinje fibers.
    c. AV node.
    d. SA node.
    e. AV bundle.
12. Given these structures of the conduction system of the heart:
    1. atrioventricular bundle
    2. AV node
    3. bundle branches
    4. Purkinje fibers
    5. SA node

Choose the arrangement that lists the structures in the order an action potential passes through them.
a. 2,5,1,3,4
b. 2,5,3,1,4
c. 2,5,4,1,3
d. 5,2,1,3,4
e. 5,2,4,3,1

13. Purkinje fibers
a. are specialized cardiac muscle cells.
b. conduct impulses much more slowly than ordinary cardiac muscle.
c. conduct action potentials through the atria.
d. connect between the SA node and the AV node.
e. ensure that ventricular contraction starts at the base of the heart.

14. T waves on an ECG represent
a. depolarization of the ventricles.
b. repolarization of the ventricles.
c. depolarization of the atria.
d. repolarization of the atria.

15. Which of these conditions observed in an electrocardiogram suggests that the AV node is not conducting action potentials?
a. complete lack of the P wave
b. complete lack of the QRS complex
c. more QRS complexes than P waves
d. a prolonged PR interval
e. P waves and QRS complexes are not synchronized

16. The greatest amount of ventricular filling occurs during
a. the first one-third of diastole.
b. the middle one-third of diastole.
c. the last one-third of diastole.
d. ventricular systole.

17. While the semilunar valves are open during a normal cardiac cycle, the pressure in the left ventricle is
a. greater than the pressure in the aorta.
b. less than the pressure in the aorta.
c. the same as the pressure in the left atrium.
d. less than the pressure in the left atrium.

18. The pressure within the left ventricle fluctuates between
a. 120 and 80 mm Hg.
b. 120 and 0 mm Hg.
c. 80 and 0 mm Hg.
d. 20 and 0 mm Hg.

19. Blood flows neither into nor out of the ventricles during
a. the period of isovolumic contraction.
b. the period of isovolumic relaxation.
c. diastole.
d. systole.
e. both a and b.

20. Stroke volume is the
a. amount of blood pumped by the heart per minute.
b. difference between end-diastolic and end-systolic volume.
c. difference between the amount of blood pumped at rest and that pumped at maximum output.
d. amount of blood pumped from the atria into the ventricles.

21. Cardiac output is defined as
a. blood pressure times peripheral resistance.
b. peripheral resistance times heart rate.
c. heart rate times stroke volume.
d. stroke volume times blood pressure.
e. blood pressure minus peripheral resistance.

22. Pressure in the aorta is at its lowest
a. at the time of the first heart sound.
b. at the time of the second heart sound.
c. just before the AV valves open.
d. just before the semilunar valves open.

23. Just after the dicrotic notch on the aortic pressure curve,
a. the pressure in the aorta is greater than the pressure in the left ventricle.
b. the pressure in the left ventricle is greater than the pressure in the aorta.
c. the pressure in the left atrium is greater than the pressure in the left ventricle.
d. the pressure in the left atrium is greater than the pressure in the aorta.
e. blood pressure in the aorta is 0 mm Hg.

24. The "lubb" sound (first heart sound) of the heart is caused by the
a. closing of the AV valves.
b. closing of the semilunar valves.
c. blood rushing out of the ventricles.
d. filling of the ventricles.
e. ventricular contraction.

25. Increased venous return results in
a. increased stroke volume.
b. increased cardiac output.
c. decreased heart rate.
d. both a and b.

26. Parasympathetic nerve fibers are found in the _____ nerves and release _____ at the heart.
a. cardiac, acetylcholine
b. cardiac, norepinephrine
c. vagus, acetylcholine
d. vagus, norepinephrine

27. Increased parasympathetic stimulation of the heart
a. increases the force of ventricular contraction.
b. increases the rate of depolarization in the SA node.
c. decreases the heart rate.
d. increases cardiac output.

28. Because of the baroreceptor reflex, when normal arterial blood pressure decreases
a. heart rate decreases.
b. stroke volume decreases.
c. the frequency of afferent action potentials from baroreceptors decreases.
d. the cardioregulatory center stimulates parasympathetic neurons.
e. all of the above.

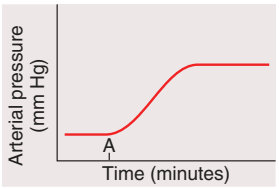
29. A decrease in blood pH and an increase in blood carbon dioxide levels result in
a. increased heart rate.
b. increased stroke volume.
c. increased sympathetic stimulation of the heart.
d. increased cardiac output.
e. all of the above.

30. An increase in extracellular potassium levels could cause
a. an increase in stroke volume.
b. an increase in the force of contraction.
c. a decrease in heart rate.
d. both a and b.

Answers in Appendix F

CRITICAL THINKING

1. Explain why the walls of the ventricles are thicker than the walls of the atria.
2. In most tissues, peak blood flow occurs during systole and decreases during diastole. In heart tissue, however, the opposite is true, and peak blood flow occurs during diastole. Explain why this difference occurs.
3. A patient has tachycardia. Would you recommend a drug that prolongs or shortens the plateau of cardiac muscle cell action potentials?
4. Endurance-trained athletes often have a decreased heart rate compared to that of a nonathlete when both are resting. Explain why an endurance-trained athlete's heart rate decreases rather than increases.
5. A doctor lets you listen to a patient's heart with a stethoscope at the same time that you feel the patient's pulse. Once in a while you hear two heartbeats very close together, but you feel only one pulse beat. Later, the doctor tells you that the patient has an ectopic focus in the right atrium. Explain why you hear two heartbeats very close together. The doctor also tells you that the patient exhibits a pulse deficit (i.e., the number of pulse beats felt is fewer than the number of heartbeats heard). Explain why a pulse deficit occurs.
6. Heart rate and cardiac output were measured in a group of nonathletic students. After 2 months of aerobic exercise training, their measurements were repeated. It was found that heart rate had decreased, but cardiac output remained the same for many activities. Explain these findings.
7. Explain why it's sufficient to replace the ventricles, but not the atria, in artificial heart transplantation.
8. During an experiment in a physiology laboratory, a student named Cee Saw was placed on a table that could be tilted. The instructor asked the students to predict what would happen to Cee Saw's heart rate if the table were tilted so that her head was lower than her feet. Some students predicted an increase in heart rate, and others claimed it would decrease. Can you explain why both predictions might be true?
9. After Cee Saw is tilted so that her head is lower than her feet for a few minutes, the regulatory mechanisms that control blood pressure adjust so that the heart pumps sufficient blood to supply the needs of her tissues. If she is then tilted so that her head is higher than her feet, gravity causes blood to flow toward her feet, and the blood pressure in the carotid sinus and aortic arch decreases. The decrease in blood pressure is detected by the baroreceptors in these vessels and activates baroreceptor reflexes. The result is increased sympathetic and decreased parasympathetic stimulation of the heart and an increase in the heart rate. The increased heart rate functions to increase the blood pressure to its normal value.
10. A friend tells you that her son had an ECG and it revealed that he has a slight heart murmur. Should you be convinced that he has a heart murmur? Explain.
11. An experiment on a dog was performed in which the mean arterial blood pressure was monitored before and after the common carotid arteries were partially clamped (at time A). The results are graphed below:



Explain the change in mean arterial blood pressure (hint: baroreceptors are located in the internal carotid arteries, which are superior to the site of clamping of the common carotid arteries).

12. During hemorrhagic shock (caused by loss of blood) the blood pressure may fall dramatically, although the heart rate is elevated. Explain why the blood pressure falls despite the increase in heart rate.

Answers in Appendix G

ANSWERS TO PREDICT QUESTIONS

1. The heart tissues supplied by the artery lose their oxygen and nutrient supply and die. This part of the heart (and possibly the entire heart) stops functioning. If this condition develops rapidly, it's called a heart attack, or myocardial infarction.
2. The heart must continue to function under all conditions and requires energy in the form of ATP. During heavy exercise, lactic acid is produced in skeletal muscle as a by-product of anaerobic metabolism. The ability to use lactic acid provides the heart with an additional energy source.
3. Contraction of the ventricles, beginning at the apex and moving toward the base of the heart, forces blood out of the ventricles and toward their outflow vessels—the aorta and pulmonary trunk. The aorta and pulmonary trunks are located at the base of the heart.
4. Ectopic foci cause various regions of the heart to contract at different times. As a result, pumping effectiveness is reduced. Cardiac muscle contraction is not coordinated, which interrupts the cyclic filling and emptying of the ventricles.
5. If cardiac muscle could undergo tetanic contraction, it would contract for a long time without relaxing. Its pumping action then would stop because that action requires alternating contraction and relaxation.
6. During isovolumic contraction, the volume of the ventricles does not change because no blood leaves the ventricle. Therefore, the pressure increases but the length of the cardiac muscle doesn't change significantly. Therefore, the contraction is isometric (see chapter 9).
7. The left ventricle has the thickest wall. The pressure produced by the left ventricle is much higher than the pressure produced by the right ventricle, when the ventricles contract. It's important for each ventricle to pump the same amount of blood because, with two connected circulation loops, the blood flowing into one must equal the blood flowing into the other so that one doesn't become overfilled with blood at the expense of the other. For example, if the right ventricle pumps less blood than the left ventricle, blood must accumulate in the systemic blood vessels. If the left ventricle pumps less blood than the right ventricle, blood accumulates in the pulmonary blood vessels.

8. Fibrillation makes cardiac muscle an ineffective pump. The pumping action of the heart depends on coordinated contraction of cardiac muscle. Fibrillation destroys the coordinated contractions and results in the loss of the ability for cardiac muscle to function as a pump. The ventricles are the primary pumping chambers of the heart. Ventricular fibrillation results in death because of the inability of the heart to pump blood. The atria function primarily as reservoirs. Their pumping action is most important during exercise. Therefore atrial fibrillation does not destroy the ability of the ventricles to pump blood.
9. Sympathetic stimulation increases heart rate. If venous return remains constant, stroke volume decreases as the number of beats per minute increases. Dilation of the coronary arteries is important because, as the heart does more work, the cardiac tissue requires more energy and, therefore, a greater blood supply to carry more oxygen.
10. Rupture of the left ventricle, as experienced by Mr. P, is more likely several days after a myocardial infarction. As the necrotic tissues are removed by macrophages, the wall of the ventricle becomes thinner and may bulge during systole. If the wall of the ventricle becomes very thin before new connective tissue is deposited, it may rupture. If the left ventricle ruptures, blood flows from the left ventricle into the pericardial sac. As blood fills the pericardial sac, it compresses the ventricle from the outside. This is called cardiac tamponade (tam-pŏ-nād′). Thus the ventricle is not able to fill with blood and its pumping ability is eliminated. Death occurs quickly in response to a ruptured wall of the left ventricle.