chapter 16

Anatomy of the Heart

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Key Terms

aortic valve (p. 314)
atrioventricular valves (p. 313)
atrium (p. 311)
bicuspid valve (p. 314)
cardiology (p. 308)
chordae tendineae (p. 314)
coronary arteries (p. 316)
endocardium (p. 309)
epicardium (p. 308)
mitral valve (p. 314)
myocardium (p. 309)
pericardium (p. 310)
precordium (p. 308)
Purkinje fibers (p. 319)
semilunar valves (p. 313)
tricuspid valve (p. 314)
ventricles (p. 311)

Objectives

1. Describe the location of the heart.
2. Name the three layers and the covering of the heart.
3. Explain the function of the heart as two separate pumps.
4. Identify the four chambers and great vessels of the heart.
5. Explain the functions of the four heart valves.
6. Describe the physiological basis of the heart sounds.
7. Describe blood flow through the heart.
8. List the vessels that supply blood to the heart.
9. Identify the major components of the heart's conduction system.

Throughout history, many functions have been attributed to the heart. Some philosophers have called it "the seat of the soul." The ancient Egyptians, for example, weighed the heart after a person's death because they believed that the weight of the heart equaled the weight of the soul. The heart has also been described as the seat of wisdom and understanding; accordingly, it thinks and makes plans. More often than not, however, history has portrayed the heart as the seat of the emotions. An overly compassionate person is described as soft hearted, a generous person has a heart of gold, and a grief-stricken person is broken hearted. Every Valentine's Day card displays hearts, hearts, and more hearts to celebrate love. None focus on the heart as an efficient pump. Enter the modern-day heart specialist and the science of **cardiology**, the study of the heart.

FUNCTION, LOCATION, AND SIZE OF THE HEART

The heart is a hollow muscular organ. Its primary function is to pump and force blood through the blood vessels of the body, providing every cell in the body with vital nutrients and oxygen. The heart pumps an average of 72 times each minute for your entire lifetime. If you live until you are 75 years old, your heart will beat in excess of 3 billion times. Puts the Energizer Bunny to shame!

The adult heart is about the size of a closed fist and weighs less than 1 pound. The heart sits in the chest within the mediastinum, between the two lungs (Figure 16-1). Two thirds of the heart is located to the left of the midline of the sternum, and one third is located to the right. The upper flat portion of the heart, called the *base*, is located at the level of the second rib. The lower, more pointed end of the heart is the apex; it is located at the level of the fifth intercostal space. The **precordium** refers to the area of the anterior chest wall overlying the heart and great vessels. You need to know the precise location of the heart because you will be asked to evaluate different heart sounds, accurately position electrodes for an electrocardiogram, and provide lifesaving cardiopulmonary resuscitation (CPR).

LAYERS AND COVERING OF THE HEART

The heart is made up of three layers of tissue: endocardium, myocardium, and epicardium (Figure 16-2).

ENDOCARDIUM

The **endocardium** (en-doh-KAR-dee-um) is the heart's innermost layer. The endocardium also lines the valves

Go Figure

1. **According to Figure 15-2**
   a. The stem cell is also called the *reticulocyte*.
   b. Platelets give rise to megakaryocytes.
   c. Lymphocytes and monocytes are granulocytes.
   d. Stem cells can differentiate into RBCs, WBCs, and platelets.

2. **According to Figure 15-5**
   a. Erythropoiesis is stimulated by low levels of CO_2 in the blood.
   b. The secretion of erythropoietin increases as blood levels of O_2 decrease.
   c. Bilirubin stimulates the kidneys to secrete erythropoietin.
   d. Erythropoietin is secreted by the bone marrow in response to decreased blood levels of O_2.

3. **According to Figure 15-6, which of the following is not true?**
   a. Heme contains iron.
   b. Bilirubin is one of the degradation products of heme.
   c. Iron generated by the degradation of heme can be stored or recycled.
   d. Only the globin part of hemoglobin can produce bilirubin.

4. **According to Figures 15-11 and 15-12**
   a. PTA activates plasmin to plasminogen.
   b. Coumadin exerts an antithrombin effect.
   c. Both Coumadin and heparin exert an anticoagulant effect by decreasing the hepatic utilization of vitamin K in the synthesis of prothrombin.
   d. Heparin exerts an antithrombin effect, thereby delaying blood clotting.

5. **According to Figure 15-13**
   a. Anti-Rh antibodies are produced by the fetus.
   b. The mother is initially Rh+ and becomes Rh− as anti-Rh antibodies accumulate.
   c. The fetus is initially Rh+ and becomes Rh− as the disorder progresses.
   d. The mother is Rh− and the fetus is Rh+.

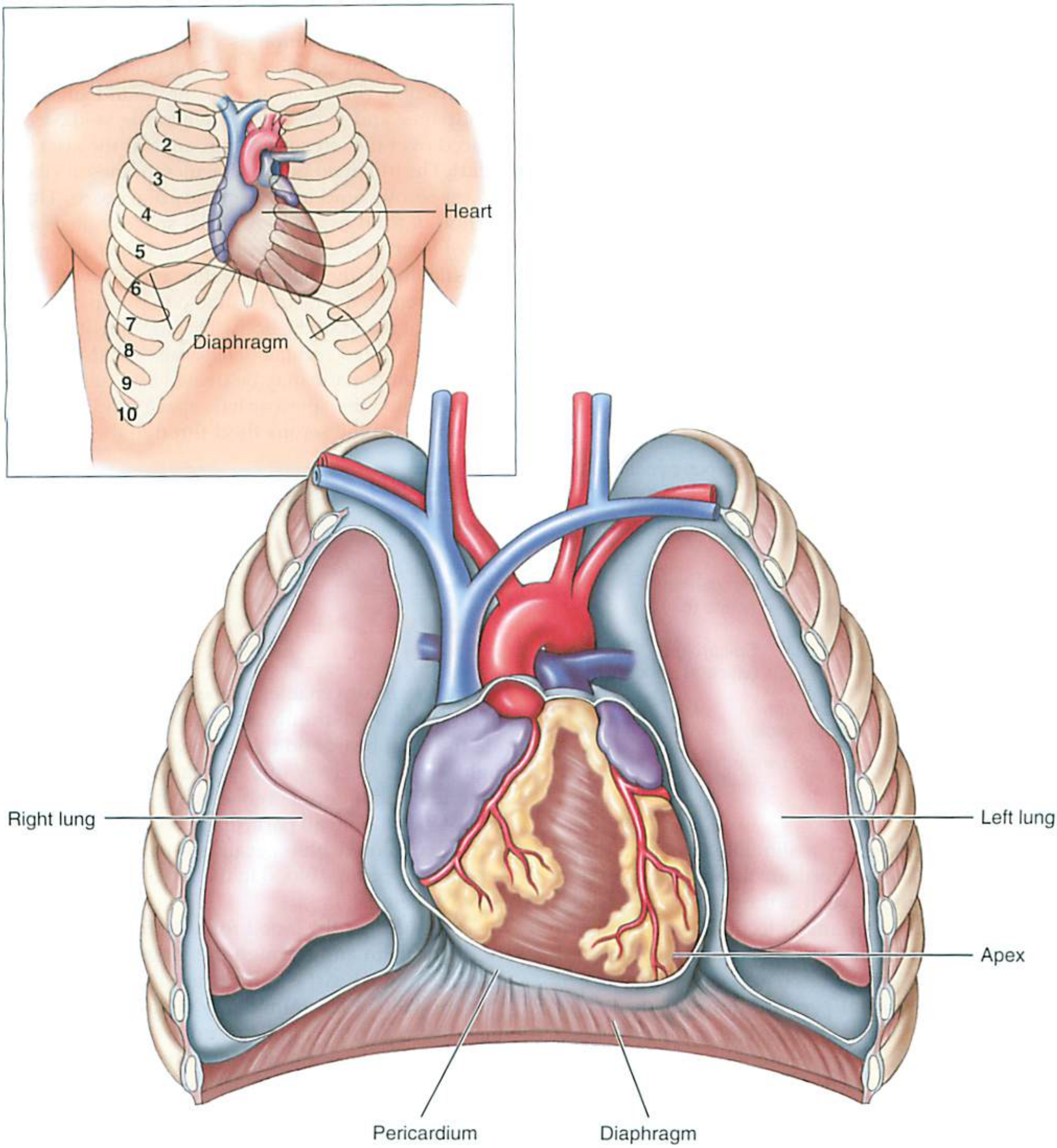
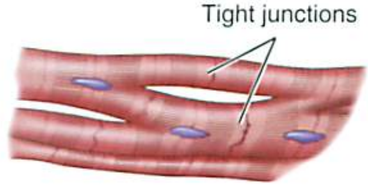


FIGURE 16-1 Location of the heart.

and is continuous with the blood vessels that enter and leave the heart. The smooth and shiny surface allows blood to flow over it easily.

MYOCARDIUM

The **myocardium** (my-oh-KAR-dee-um) is the middle layer of the heart. It is the thickest of the three layers. The myocardium is composed of cardiac muscle that contracts and pumps blood through the blood vessels. (Review muscle contraction in Chapter 9, especially the "sliding" of actin and myosin.)



Cardiac muscle

EPICARDIUM

The **epicardium** (ep-i-KAR-dee-um) is the thin outermost layer of the heart. The epicardium also helps form the pericardium.

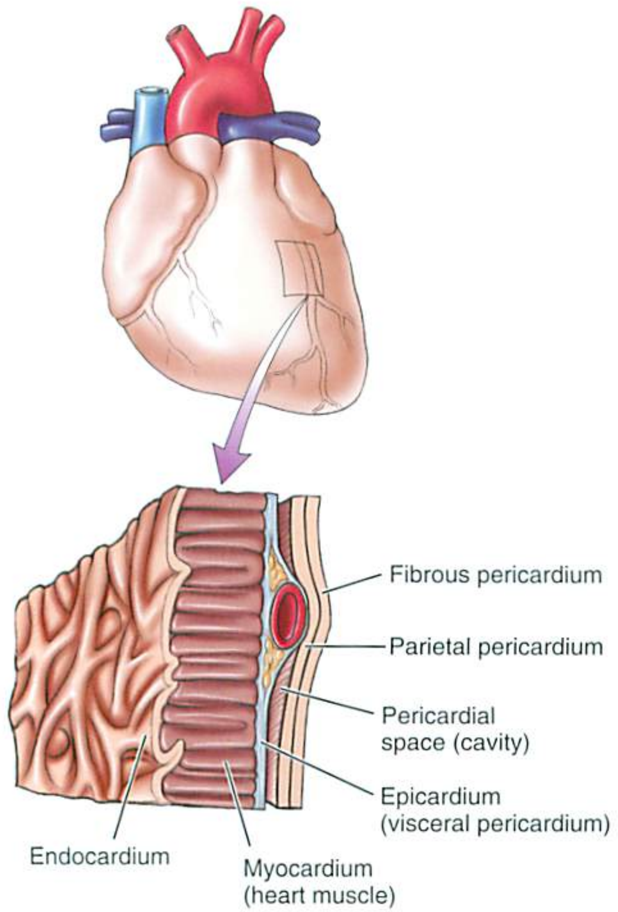
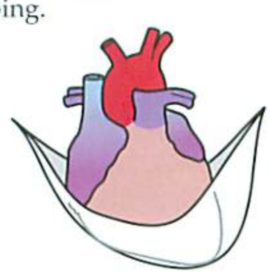


FIGURE 16-2 Layers of the heart and pericardium.

PERICARDIUM

The heart is supported by a slinglike structure called the **pericardium**. The pericardium attaches the heart to surrounding structures, such as the diaphragm and the large blood vessels that attach to the heart. The pericardium has three layers. The innermost layer (closest to the heart) is the epicardium, also called the *visceral pericardium*. The visceral pericardium folds back and becomes the *parietal pericardium*. The parietal pericardium attaches to the outer fibrous pericardium that anchors the heart to its surrounding structures. Between the visceral pericardium and parietal pericardium is a space called the *pericardial space*, or *pericardial cavity*. The pericardial membranes are serous membranes that secrete a small amount of slippery serous fluid (10 to 30 mL) into the pericardial space. The pericardial fluid lubricates the surfaces of the membranes and allows them to slide past one another with little friction or rubbing.



At times, the pericardial membranes become inflamed; this condition is called *pericarditis* and is characterized by pain and a sound called a *friction rub*. The friction rub is similar to the sound of scratchy sandpaper and is best heard when the stethoscope is placed over the left sternal border, near the apex of the heart. The inflamed pericardial membranes also secrete excess serous fluid into the pericardial space. This collection of fluid in the pericardial space (called *pericardial effusion*) may compress the heart externally, making it difficult for the heart to relax and fill with blood. Consequently, the heart is unable to pump a sufficient amount of blood to the body. This life-threatening condition is called *cardiac tamponade* (TAM-pon-ade). Cardiac tamponade may be treated by inserting a long needle into the pericardial space and aspirating (sucking out) the serous fluid through the needle.

? Re-Think

1. Locate the heart with specific references to the sternum and ribs.
2. List the three layers of the heart. Identify the pumping layer.

A DOUBLE PUMP AND TWO CIRCULATIONS

The myocardium enables the heart to pump blood. The heart is a double pump that beats as one. The pumps are the right heart and the left heart (Figure 16-3). The right heart receives unoxygenated blood from the superior and inferior venae cavae, large veins that collect blood from all parts of the body. The right heart, which is colored blue because it contains unoxygenated blood, pumps blood to the lungs, where the blood is oxygenated.

The path that the blood follows from the right side of the heart to and through the lungs and back to the left side of the heart is called the *pulmonary circulation*. The function of the pulmonary circulation is to pump blood through the lungs in order to pick up oxygen and get rid of carbon dioxide. Oxygen diffuses from the lungs into the blood for delivery to the tissues, whereas carbon dioxide diffuses from the blood into the lungs for excretion.

The left heart receives the oxygenated blood from the lungs and pumps it to all the organs of the body. The left heart is colored red because it contains oxygenated blood. The path that the blood follows from the left heart to all the organs of the body and back to the right heart is called the *systemic circulation*. The systemic circulation is the larger of the two circulations.

? Re-Think

1. Why are the two circulations color-coded red and blue?
2. What is the difference between the pulmonary and systemic circulations?

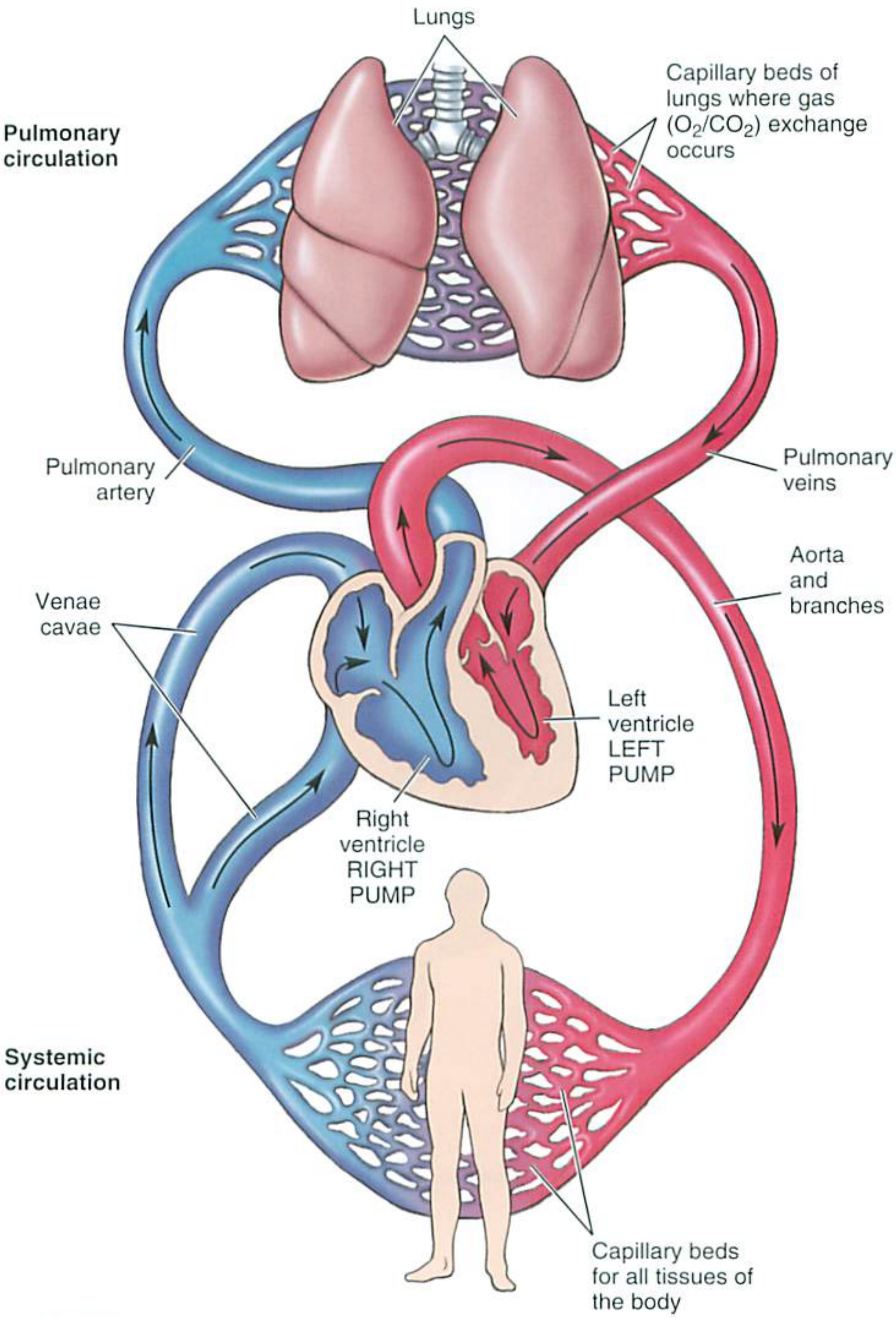


FIGURE 16-3 Double pump and two circulations: pulmonary and systemic circulations.

THE HEART'S CHAMBERS AND GREAT VESSELS

The heart has four chambers: two atria and two ventricles (Figure 16-4). The atria (sing., **atrium**) are the upper chambers and receive the blood into the heart; the **ventricles** (VEN-tri-kuls) are the lower chambers and pump blood out of the heart. The right and left hearts are separated from one another by two septa (sing., septum). The interatrial septum separates the two atria; the interventricular septum separates the two ventricles. Note the color coding. All structures that carry unoxygenated blood (right heart) are colored blue. All structures (left heart) that carry oxygenated blood are colored red.

RIGHT ATRIUM

The right atrium is a thin-walled cavity that receives unoxygenated blood from the superior and inferior venae cavae. The superior vena cava collects blood from the head and upper body region, whereas the inferior vena cava receives blood from the lower part of the body.

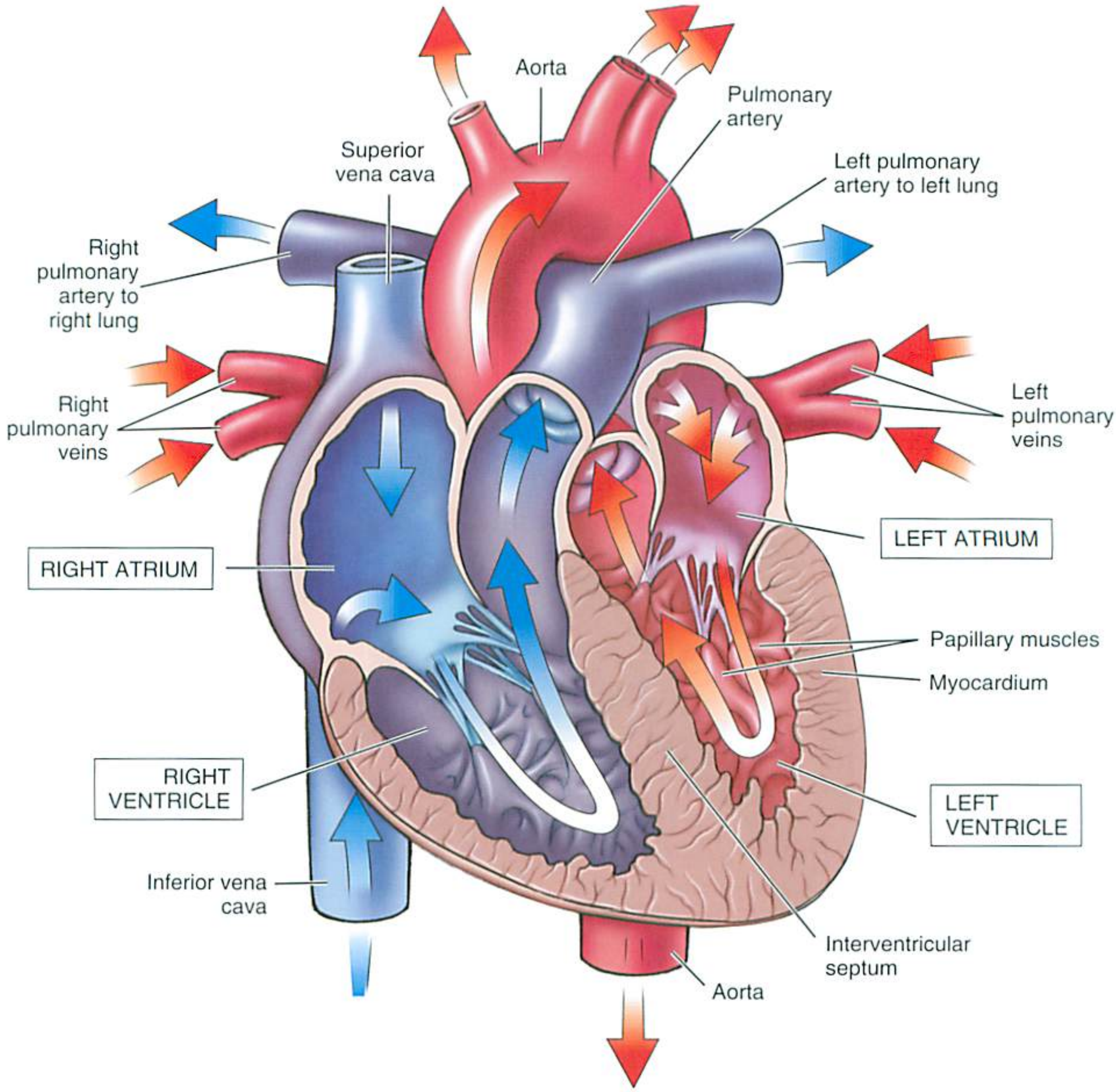


FIGURE 16-4 Chambers of the heart and the great vessels. The *arrows* indicate the blood flow through the heart.

RIGHT VENTRICLE

The right ventricle receives unoxygenated blood from the right atrium. The primary function of the right ventricle is to pump blood through the pulmonary arteries to the lungs.

LEFT ATRIUM

The left atrium is a thin-walled cavity that receives oxygenated blood from the lungs through four pulmonary veins.

LEFT VENTRICLE

The left ventricle receives oxygenated blood from the left atrium. The primary function of the left ventricle is to pump blood into the systemic circulation. Blood leaves the left ventricle through the aorta, the largest artery of the body. Note the thickness of the myocardial layer of the ventricles as compared with the thinner atrial muscle. The thick muscle is needed to create enough force to pump blood out of the heart. Note also that the left ventricular myocardium is thicker than the right ventricular myocardium. This difference is the result of the greater amount of force required to pump blood into the systemic circulation (aorta).

As noted, the thickness of the myocardium reflects the amount of work performed by the myocardium. If a ventricle is forced to overwork, it will eventually enlarge—a condition called *ventricular hypertrophy*. For example, a chronically hypertensive (high blood pressure) person generally develops left ventricular

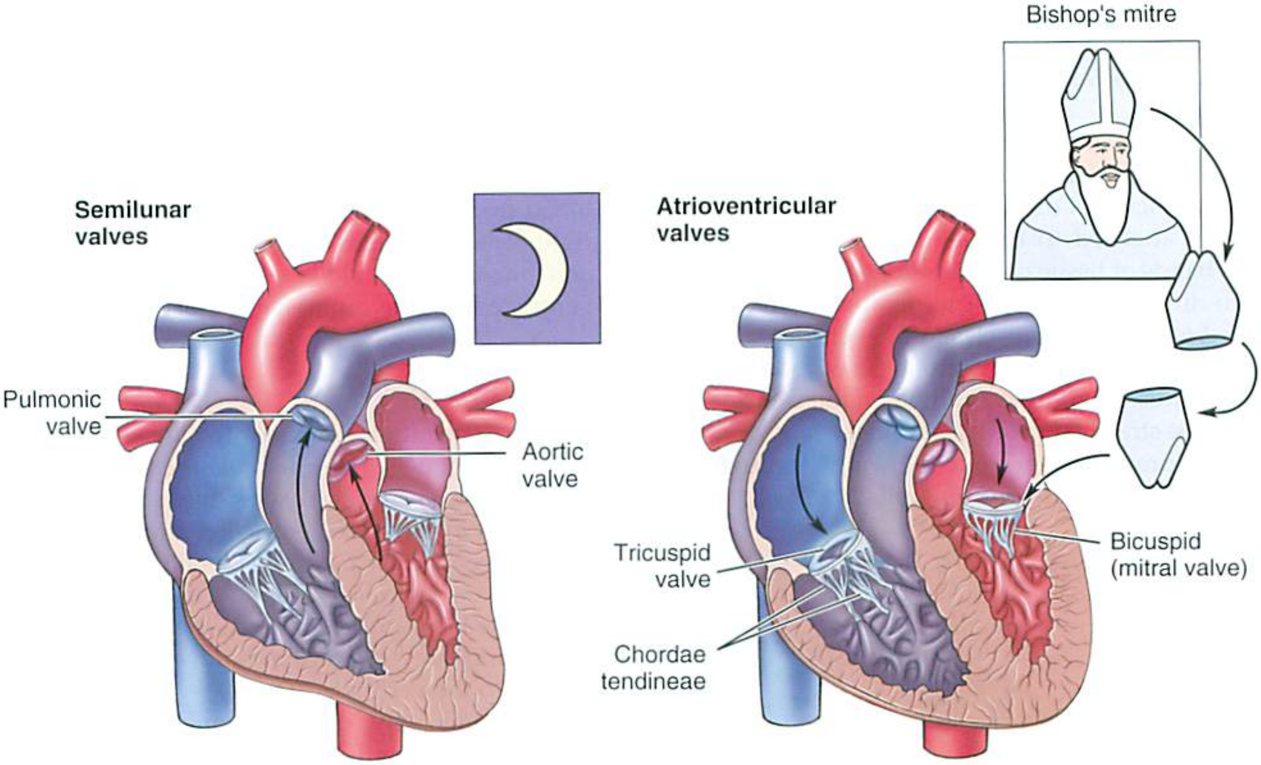


FIGURE 16-5 Valves of the heart: semilunar valves and atrioventricular valves.

hypertrophy. Why? The high blood pressure in the aorta makes it more difficult for the left ventricle to pump blood into the aorta. The left ventricle works harder and therefore enlarges, or hypertrophies. If the blood pressure is not lowered, the left ventricle will eventually weaken and fail as a pump. For the same reason, a person with pulmonary artery hypertension develops right ventricular hypertrophy and right heart failure.

GREAT VESSELS OF THE HEART

The large blood vessels attached to the heart are called the *great vessels*. They include the superior and inferior venae cavae, pulmonary artery, four pulmonary veins, and the aorta.

2+2 Sum It Up!

The heart, a hollow muscular organ that pumps blood, is located within the mediastinum of the thoracic cavity. The heart has three layers: endocardium, myocardium, and epicardium. It is supported and anchored by a slinglike pericardium. The heart is a double pump; the right heart pumps blood to the pulmonary circulation, and the left heart pumps blood to the systemic circulation. The heart has four chambers: two atria and two ventricles. The upper atria are receiving chambers, and the lower ventricles are pumping chambers. The great blood vessels carry blood to and from the heart.

HEART VALVES

The heart has four valves (Figure 16-5). The purpose of the heart valves is to keep the blood flowing in a forward direction. The valves lie at the entrance and exit of the ventricles. Two of the valves are called **atrioventricular valves** (AV valves), which are located between the atria and the ventricles. Blood flows from the atria through the AV valves into the ventricles. AV valves, which look like basketball nets, are entrance valves because they allow blood to enter the ventricles.

The other two valves are classified as **semilunar valves**, so-named because the cusps of the valves resemble a half-moon (*semi-* means "half," *lunar* means "moon"). The semilunar valves control the outflow of blood from the right and left ventricles and are therefore exit valves.

ATRIOVENTRICULAR VALVES

The AV valves are located between the atria and the ventricles on each side of the heart. The AV valves have cusps, or flaps (see Figure 16-5). When the ventricles are relaxed, the cusps hang loosely within the ventricles; in this position, the valves are open and permit the flow of blood from the atria into the ventricles.

What closes the AV valves? Pressure! When the ventricles contract, the heart muscle compresses or squeezes the blood in the ventricles. The blood then gets behind and pushes the cusps upward toward the atria, into a closed position. The closed AV valves prevent the backward flow of blood from the ventricles to the atria.

Why are the cusps not pushed completely through the openings, into the atria, as the pressures within the ventricles increase during muscle contraction? The cusps are attached to the ventricular wall by tough fibrous bands of tissue called **chordae tendineae** (KOR-day ten-din-EE-ay). The chordae tendineae, in turn, are attached to papillary muscles in the ventricular walls. As blood pushes the cusps into a closed position, the papillary muscles contract, pulling on the chordae tendineae. The stretched chordae tendineae hold on to the cusps and prevent them from "blowing" through into the atria, like an inside-out umbrella.

The right AV valve is located between the right atrium and the right ventricle. The right AV valve is called the **tricuspid valve** because it has three cusps. When the tricuspid valve is open, blood flows from the right atrium into the right ventricle. When the right ventricle contracts, however, the tricuspid valve closes and prevents blood from flowing back into the right atrium. The valve ensures a forward flow of blood.

The left AV valve is located between the left atrium and the left ventricle. The left AV valve is called the **bicuspid valve** because it has two cusps. It is also known as the **mitral valve** because it resembles a bishop's mitre—a hat with two flaps. When the mitral valve is open, blood flows from the left atrium into the left ventricle. When the left ventricle contracts, the mitral valve closes and prevents the flow of blood from the left ventricle back into the left atrium.

SEMILUNAR VALVES

The two semilunar valves (exit valves) are the pulmonic and aortic semilunar valves (see Figure 16-5).

PULMONIC VALVE

The pulmonic semilunar valve is also called the *right semilunar valve*. It is located between the right ventricle and the pulmonary artery. When the right ventricle relaxes, the valve is in a closed position. When the right ventricle contracts, thus increasing intraventricular pressure, blood from the ventricle forces the pulmonic valve open. Blood then flows into the pulmonary artery, the large vessel that carries the blood from the right ventricle to the lungs. When the right ventricle relaxes, the pulmonic valve snaps closed and prevents any blood from returning to the right ventricle from the pulmonary artery.

AORTIC VALVE

The aortic semilunar valve or the left semilunar valve is located between the left ventricle and the aorta. When the left ventricle relaxes, the valve is in a closed position. When the left ventricle contracts, thus increasing intraventricular pressure, blood from the ventricles forces the **aortic valve** open and flows into the aorta. When the left ventricle relaxes, the aortic valve snaps closed and prevents any backflow of blood from the aorta into the ventricle.

How and why do the semilunar valves close? Pressure! The semilunar valves close when the pressure in the pulmonary artery and the aorta becomes greater than the pressure in the relaxed ventricles. The blood in these large blood vessels gets behind the cusps of the valves, snapping them closed. The closed semilunar valves prevent the backward flow of blood from the pulmonary artery and aorta into the ventricles. To repeat: Valves open and close in response to the changing pressures within the heart chambers.

Valves are sometimes defective; they can become narrow or incompetent. Narrowing of the valve is called *stenosis*. A stenotic valve makes it difficult for a heart chamber to force blood through the stenosed valve, thereby increasing the work of the pumping chamber. Thus, aortic valve stenosis increases the work of the left ventricle, causing left ventricular hypertrophy and failure. What happens when a heart valve becomes leaky? A leaky, or incompetent, valve allows blood to leak back into the chamber from which it has just been pumped. For example, an incompetent aortic valve allows blood that has been pumped into the aorta to leak back into the left ventricle. The left ventricle must then pump the same blood again. Over time, stenotic and leaky valves damage the heart.

? Re-Think

1. List and locate the atrioventricular valves.
2. List and locate the semilunar valves.
3. Explain the reason for the following: When the ventricles contract, the AV valves close and the semilunar valves open.

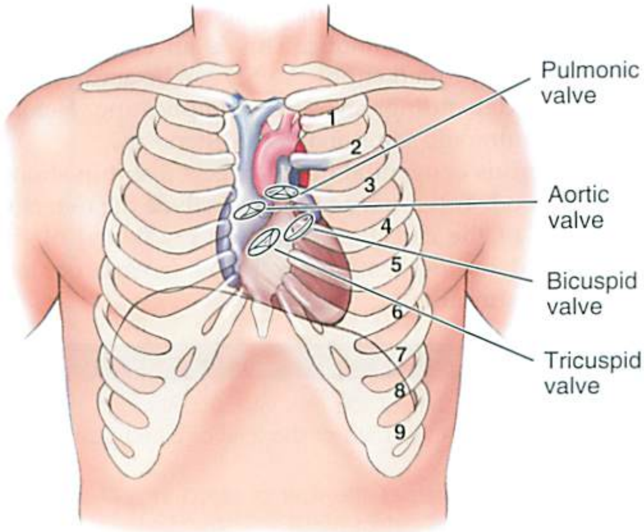


FIGURE 16-6 Areas on the precordium where valve sounds are best heard by stethoscope.

HEART SOUNDS

The heart sounds ("lubb-dupp, lubb-dupp") are made by the vibrations caused by the closure of the valves. When valves become faulty, the heart sounds change. Abnormal heart sounds are called *murmurs*.

The heart sounds can be heard through a stethoscope placed over the chest wall (Figure 16-6). The first heart sound (the "lubb") is called S_1. S_1 is caused by the closure of the AV valves at the beginning of ventricular contraction; it is best heard over the apex. The second heart sound (the "dupp") is called S_2. S_2 is caused by the closure of the semilunar valves at the beginning of ventricular relaxation. S_2 can be heard best at the base of the heart. Listening to S_1 and S_2 is like the sound made by drumming two fingers on a table. Sometimes extra sounds (called S_3 and S_4) can be heard; they are due to vibrations caused by the rapid flow of blood into the ventricles. When both S_3 and S_4 occur, a "gallop rhythm" is heard, which sounds like a galloping horse.

2+2 Sum It Up!

The purpose of the heart valves is to keep blood flowing forward. There are four heart valves. The two atrioventricular valves are the tricuspid (right heart) and the bicuspid or mitral valves (left heart). The two semilunar valves are the pulmonic (right heart) and aortic (left heart) semilunar valves. The heart sounds ("lubb dupp") are caused by the closure of the valves.

PATHWAY OF BLOOD FLOW THROUGH THE HEART

The arrows in Figure 16-4 indicate the pathway of blood as it flows through the heart. Unoxygenated blood enters the right atrium from the superior and inferior venae cavae. The blood flows through the tricuspid valve into the right ventricle. From the right ventricle, the blood flows through the pulmonic valve into the pulmonary artery. The pulmonary artery branches into the right and left pulmonary arteries. The right and left pulmonary arteries carry unoxygenated blood to the right and left lungs for gas exchange. The blood releases carbon dioxide as waste and picks up a fresh supply of oxygen. Note the blue color coding of the right heart structures.

The oxygenated blood flows through four pulmonary veins from the lungs into the left atrium. From the left atrium, the blood flows through the bicuspid, or mitral, valve into the left ventricle. Left ventricular contraction forces blood through the aortic valve into the aorta for distribution to the systemic circulation. The pathway of blood flow through the heart and pulmonary circulation is summarized in Figure 16-7.

BLOOD FLOW AND SHUNTS

Normally, blood flows through four separate chambers, from the right side of the heart to the lungs and back to the left side of the heart. Congenital heart defects often detour, or shunt, blood so that the normal pathway is disrupted. Let's see how this happens. Keep in mind the following points as we analyze the effects of shunts:

- The right and left hearts are separated by the interatrial and interventricular septa.
- Blood flows in response to a pressure gradient (from high pressure to low pressure).
- Pressure is higher in the left heart than in the right heart.
- Blood in the left heart is oxygenated and is bright red, whereas blood in the right heart is unoxygenated and is bluish-red.

SHUNTS

A shunt is a passageway that diverts blood from its normal pathway. There are two types of shunts: a left-to-right shunt and a right-to-left shunt.

Left-to-Right Shunt

A left-to-right shunt diverts blood from the left heart to the right heart; it can be illustrated by a child with a hole in the interventricular septum. The ventricular septal defect (VSD) causes the left ventricle to do two things. It pumps blood into the aorta; it also pumps blood into the right ventricle through the hole in the septum. Because blood is shunted from the left heart to the right heart, it is called a *left-to-right shunt*. The child is acyanotic (not cyanotic) because the left ventricle is pumping oxygenated blood to the systemic circulation. A VSD is thus described as a left-to-right shunt that is acyanotic.

Right-to-Left Shunt

A right-to-left shunt diverts blood from the right to the left heart; it is illustrated by a child who has a VSD and

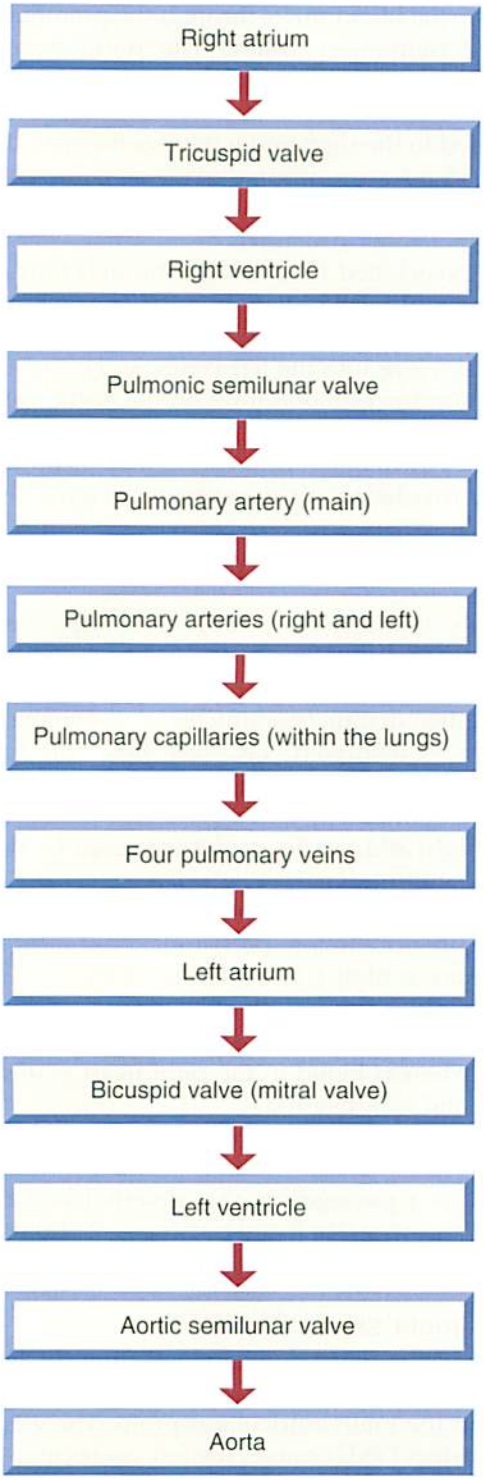


FIGURE 16-7 Blood flow through the heart and pulmonary circulation.

a stenotic (narrowed) pulmonic semilunar valve. Pulmonary valve stenosis increases the pressure within the right ventricle. The elevated right ventricular pressure pumps blood into the left ventricle through the ventricular septal defect. Because blood is shunted from the right heart to the left heart, it is called a *right-to-left shunt*. Note that the left ventricle now contains unoxygenated blood. The left ventricle pumps unoxygenated blood into the systemic circulation and the child appears cyanotic. This is an example of a cyanotic right-to-left shunt. A VSD can be acyanotic or cyanotic, depending on other complicating factors, such as pulmonic semilunar valve stenosis.

Numerous congenital heart defects result in shunting of blood. You must be able to analyze the defect(s) in terms of the direction (pressure gradients) of the shunt and its implication for blood oxygen content (oxygen saturation).

? Re-Think

1. Describe the path of the flow of blood through the right heart. Describe the path of the flow of blood through the left heart.
2. Describe the path of the flow of blood in a child with a ventricular septal defect (VSD).

BLOOD SUPPLY TO THE MYOCARDIUM

Although blood constantly flows through the chambers of the heart, this blood does not nourish the myocardium. The blood supply that nourishes and oxygenates the myocardium is provided by the coronary arteries (Figure 16-8). The arteries supplying the myocardium are called **coronary arteries** because they resemble a crown encircling the heart. The coronary arteries arise from the base of the aorta, just distal to the aortic semilunar valve.

The two main coronary arteries are the left and right coronary arteries. The right coronary artery nourishes the right side of the heart, especially the right ventricle. It also supplies blood to the parts of the electrical conduction system, including the sinoatrial (SA) node and the atrioventricular (AV) node. These nodes are important in establishing the normal heart rate and rhythm and will be described more fully later in the chapter. The left coronary artery branches into the left anterior descending (LAD) artery and the circumflex artery. These arteries carry blood to the left side of the heart, especially the left ventricular wall and interventricular septum. Small branches of the right and left coronary arteries fuse, forming interconnections that help maintain an adequate blood supply to the myocardium, despite pressure fluctuations within the heart. The coronary veins collect the blood that nourishes the myocardium. The coronary veins carry the blood to the coronary sinus, which empties the blood into the right atrium.

Coronary blood flow has three important characteristics:

- Coronary blood flow can increase. The heart must have a constant supply of oxygenated blood. Under resting conditions, the heart muscle removes almost all the oxygen from the blood flowing through the coronary arteries. Thus, if the heart needs more oxygen, coronary arteries dilate and blood flow increases. With exertion, coronary blood flow

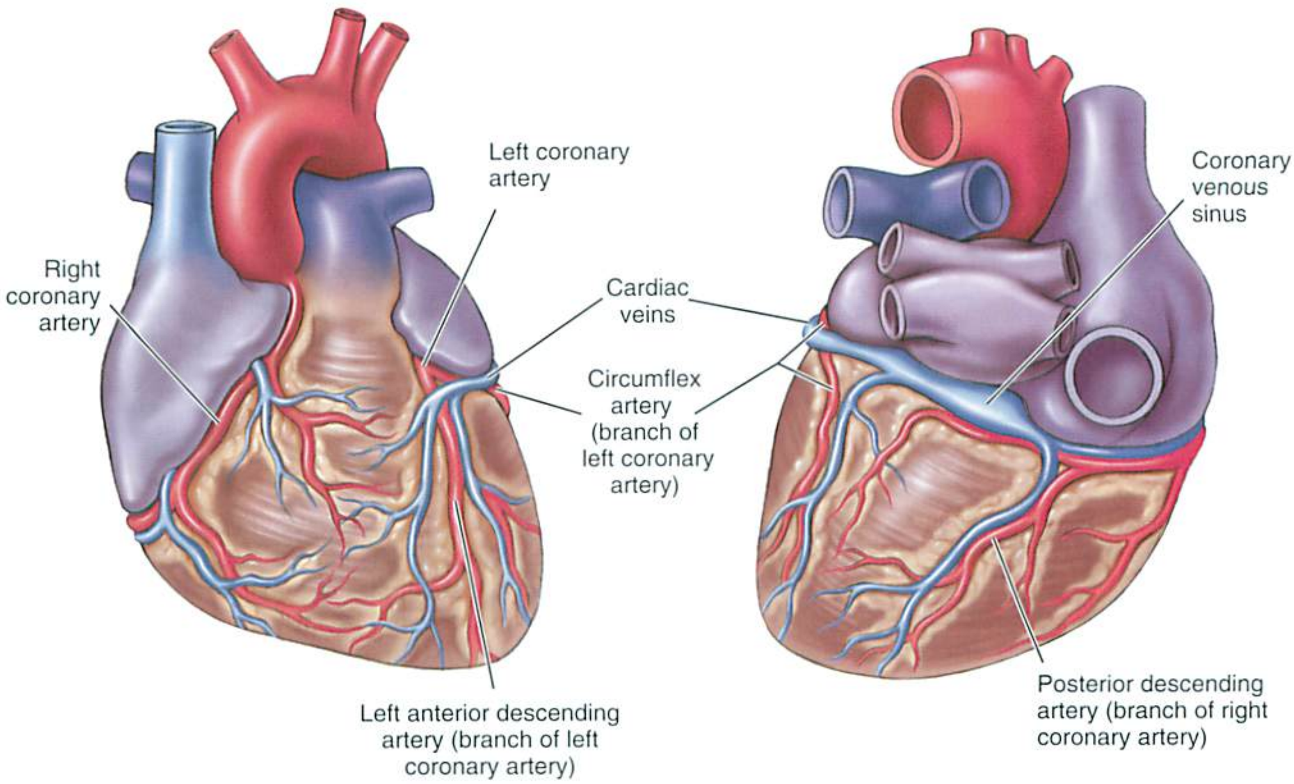
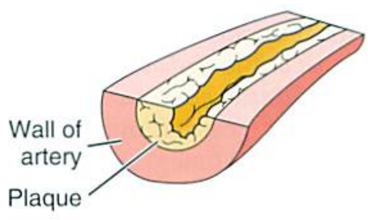


FIGURE 16-8 Blood supply to the myocardium: coronary blood vessels.

can increase up to nine times in the normal heart. However, coronary arteries that have severe fatty plaque buildup are usually maximally dilated at rest. With exertion, coronary blood flow cannot increase and the myocardium experiences oxygen deprivation. Thus, patients with coronary artery disease will often experience pain (angina) with exertion.



- Coronary blood flow is greatest during myocardial relaxation. Why? Because contraction of the myocardium externally compresses or squeezes the coronary arteries, thereby cutting off blood flow. When the heart muscle relaxes, the coronary arteries open, thereby restoring blood flow. When the relaxation phase is shortened, as in a "racing heart," coronary blood flow decreases and the myocardial cells may experience signs of oxygen deprivation, causing chest pain (angina).
- Coronary arteries can form anastomoses, or multiple connections between the arteries. An anastomosis allows blood to flow around an artery that is blocked. Additional collateral blood vessels develop in response to chronic diminished coronary blood flow, as often occurs with aging and chronic coronary artery disease. For this reason, older persons often experience less myocardial damage from a heart attack than younger persons.

? Re-Think

1. Why is coronary blood flow highest when the myocardium is relaxed?
2. Explain why a rapid heart rate can cause chest pain.

ISCHEMIA AND INFARCTION

If coronary blood flow diminishes, the myocardium experiences oxygen deprivation (ischemia) and soon informs its owner of the situation. For example, a coronary artery may become partially occluded by fatty plaque or blood vessel spasm, thereby diminishing coronary blood flow. The person experiences chest pain that often radiates to the left shoulder and down the left arm into the fingers (referred pain). "Pain at the pump"? Think angina. Angina is often relieved by rest and the administration of drugs such as nitroglycerin and beta-adrenergic blockers that decrease the work of the heart.

Do You Know...

About Balloons and CABGs as Treatment for Coronary Artery Disease?

Angina is usually caused by the accumulation of fatty plaque within the coronary arteries. Coronary artery occlusion is often treated with balloon therapy. A deflated balloon is inserted into the coronary artery. It is then inflated against the fatty plaque, flattening the plaque against the arterial wall and restoring coronary blood flow. A stent is then inserted to maintain the opening of the coronary vessel. A stent is a hollow, wire mesh cylinder that looks like a tiny Slinky. Improved cardiac blood flow improves myocardial oxygenation, reduces chest pain, and prevents myocardial damage. A patient may not be a suitable candidate for balloon angioplasty and stent; instead, he or she may require a CABG (pronounced like the vegetable, cabbage). CABG refers to a *c*oronary *a*rtery *b*ypass *g*raft, whereby the surgeon bypasses the obstructions in the coronary vessels with donor blood vessels.

Sometimes, the coronary artery occlusion worsens when a platelet-containing fatty plaque ruptures and completely blocks coronary blood flow. The oxygen-deprived myocardial cells die, causing a myocardial infarction (MI), or heart attack. A man having a heart attack often experiences nausea and vomiting, diaphoresis (profuse sweating), and severe crushing chest pain. With a fist clenched over his heart, he may complain that the pain feels as though an elephant is sitting on his chest. Occlusion of the left anterior descending artery (LAD) is particularly devastating because it oxygenates so much of left ventricle. For this reason occlusion of the LAD is called the "widow maker."

Older people and women who experience an MI may present a very different clinical picture. For example, many do not experience crushing chest pain and diaphoresis. They often complain of fatigue and digestive symptoms, such as heartburn and upset stomach. Depending on the severity and location of the infarction, the person may recover uneventfully or experience a lethal electrical disturbance (dysrhythmia), cardiogenic shock, or heart failure. Time to treatment is crucial! Cardiologists have a saying: "Time is muscle." The faster the intervention, the less myocardial damage is sustained.

CARDIAC ENZYMES AND LEAKY CELLS

The dead myocardial cells leak enzymes into the blood, causing plasma elevations of cardiac enzymes such as creatine phosphokinase (CPK), aspartate aminotransferase (AST), and lactic dehydrogenase (LDH). A regulator myocardial protein, called *troponin,* also leaks out of the necrotic myocardium into the blood. Thus, plasma elevations of CPK, AST, LDH, and troponin are indicative of MI. The leaked enzymes thus provide a valuable diagnostic tool for heart attacks.

2+2 Sum It Up!

Blood flows from the right atrium to the right ventricle, where it is pumped to the lungs for oxygenation (pulmonary circulation). Oxygenated blood returns to the left atrium and then to the left ventricle where it is pumped into the aorta and systemic circulation. Shunts, usually congenital, divert the path of blood flow through the heart. The myocardium (pump) is nourished by the left and right coronary arteries. Coronary blood flow must be maintained if the heart is to function normally. Coronary blood flow is greatest during ventricular relaxation. Occlusion of the coronary arteries is a major cause of disability and death.

CARDIAC CONDUCTION SYSTEM

How does the heart know when to contract (pump) and when to relax? The heart's conduction system initiates an electrical signal and then moves that signal along a special pathway through the heart. The cardiac conduction system not only provides the stimulus (cardiac impulse) for muscle contraction, but also coordinates the pumping activity of the atria and ventricles. First, both atria must contract, forcing blood into the relaxed ventricles. Then, the ventricles contract, forcing blood out of the heart. The cardiac conduction system gets it going and keeps it organized!

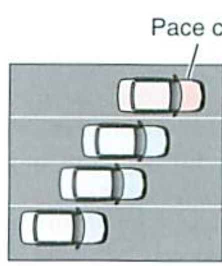
PARTS OF THE CARDIAC CONDUCTION SYSTEM

The conduction system is located within the walls and septum of the heart. The conduction system consists of the following structures: the sinoatrial node, the atrial conducting fibers, the atrioventricular node, and the His-Purkinje system (Figure 16-9).

SINOATRIAL NODE

The sinoatrial (SA) node is located in the upper posterior wall of the right atrium. An electrical signal originates within the SA node. The electrical signal is called the *action potential* or the *cardiac impulse*. In this chapter, we use the term *cardiac impulse*.

The SA node fires a cardiac impulse 60 to 100 times per minute (average, 72 times/min). Because the firing of the SA node sets the rate at which the heart beats, or contracts and relaxes, the SA node is called the *pacemaker* of the heart. The heart rate is set by this pacemaker, just as the speed of a race is set by the pace car.



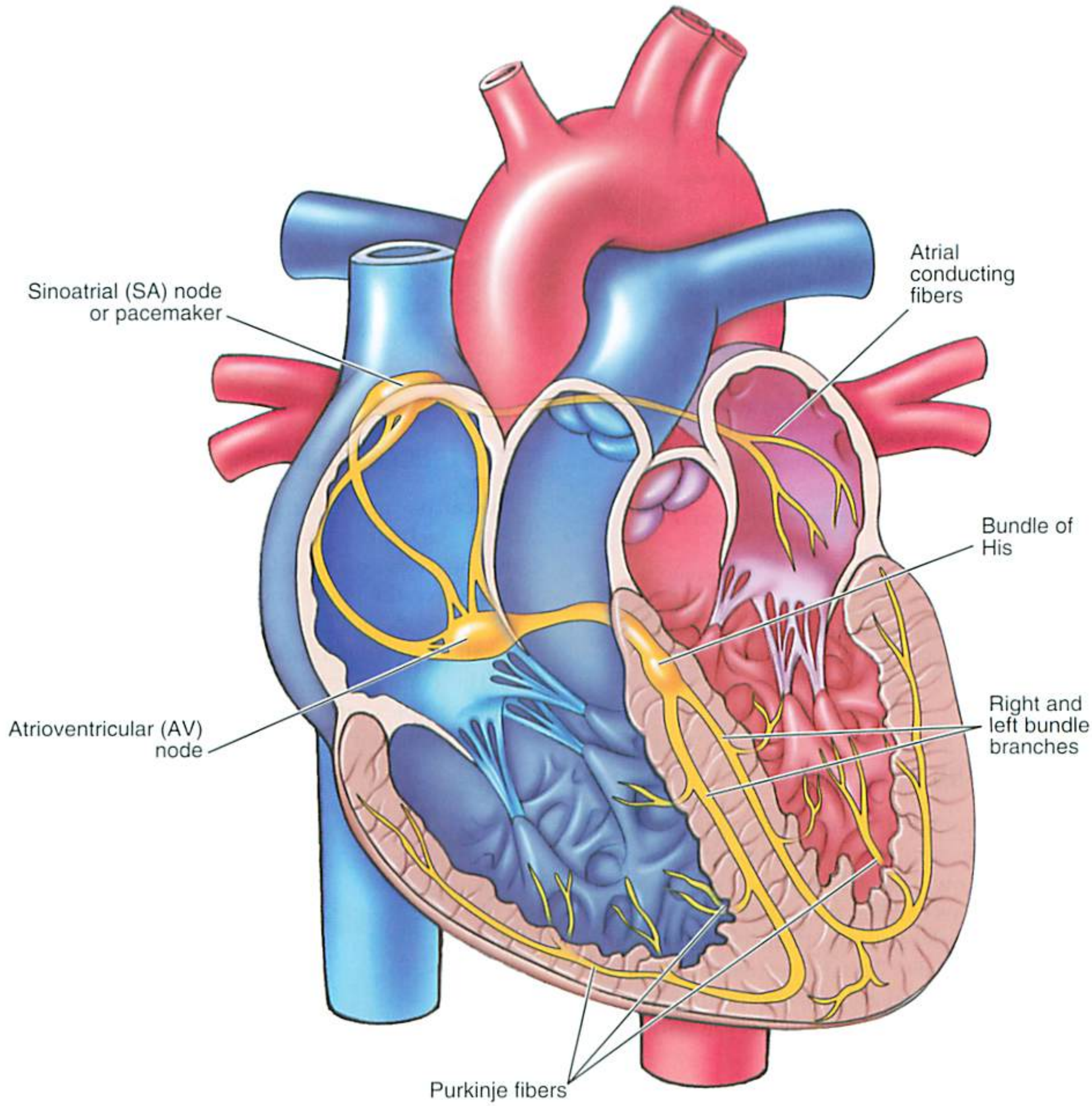


FIGURE 16-9 Conduction system of the heart.

ATRIAL CONDUCTING FIBERS

The cardiac impulse spreads from the SA node through both atria along the atrial conducting fibers. The signal also spreads to the AV node.

ATRIOVENTRICULAR NODE

The atrioventricular (AV) node is located in the floor of the right atrium, near the interatrial septum. The purpose of the AV node is twofold: (1) it acts as a path for the cardiac impulse to travel from the atrial conducting fibers into the ventricular bundle of His, and (2) the AV node slows the cardiac impulse as it moves through the AV node into the bundle of His.

The slowing of the cardiac impulse by the AV node is important because it delays ventricular activation and allows the relaxed ventricle time to fill with blood during atrial contraction.

NOTE: Do not confuse the AV node with the AV valve.

HIS-PURKINJE SYSTEM

The cardiac impulse next enters the bundle of His, specialized conduction tissue located in the interventricular septum. The bundle of His divides into two branches: the right and left bundle branches. These branches send out numerous long fibers called **Purkinje fibers**. Purkinje (pur-KIN-jee) fibers are distributed throughout the ventricular myocardium. Purkinje fibers conduct the cardiac impulse very rapidly throughout the ventricles, thereby ensuring a coordinated contraction of both ventricles. The pathway followed by the cardiac impulse is summarized in Figure 16-10. Be sure you can trace the path of the cardiac impulse from its origin, the SA node, to its destination, the Purkinje fibers.

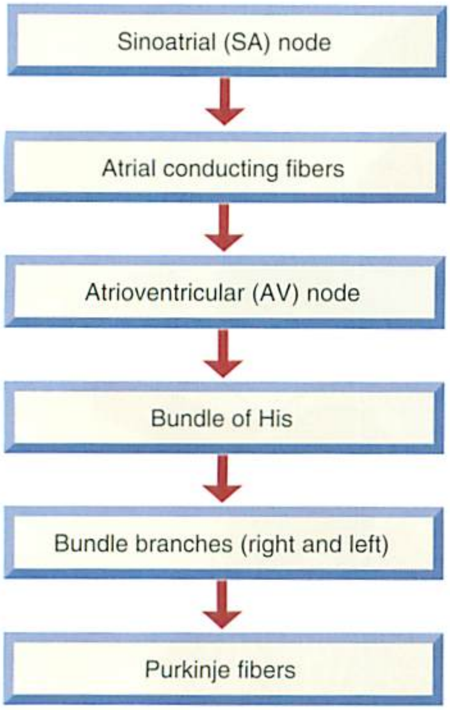


FIGURE 16-10 Pathway followed by a cardiac impulse.

AUTOMATICITY AND RHYTHMICITY

Your heart has automaticity and rhythmicity. Automaticity refers to the ability of cardiac pacemaker cells to generate their own electrical signal with no help from extrinsic nerves coming from the central nervous system. The signal arises automatically (see the "Ramp It Up!" box on Pacemaker Cells). Because cardiac tissue fires a cardiac impulse regularly, the heart is said to have rhythmicity. Feel the rhythmicity of your heart rate at the radial (wrist) pulse.

NORMAL, SLOW, AND SLOWER

Not all pacemaker cells fire at the same rate. The SA node is *the* pacemaker of the heart; it sets the heart rate between 60 and 100 beats/min. There are many other pacemaker cells within the heart, but they fire at a slower rate. For example, when the SA node fails to function as a pacemaker, the AV takes over and fires at a slower rate of 40 to 60 beats/min. Sometimes the ventricles assume the pacemaker role and fire at a much slower rate of 30 to 40 beats/min. Impaired pacemaker activity often requires the insertion of an artificial pacemaker.

At times, the rhythm of the heart is disturbed; the heart is then said to be dysrhythmic (difficulty with rhythm). Some dysrhythmias are relatively harmless; others are life threatening and demand immediate attention. For example, ventricular fibrillation is a life-threatening dysrhythmia because it causes the ventricular myocardium to fibrillate. A fibrillating muscle merely quivers and is unable to contract and pump blood. Dysrhythmias that are caused by excess electrical activity are called *tachydysrhythmias*, whereas dysrhythmias characterized by diminished electrical activity are called *bradydysrhythmias*.

? Re-Think

1. Trace the electrical signal (cardiac impulse) from its origin to the ventricles.
2. Why is it important that the AV node slows the conduction of the cardiac impulse from the atria to the ventricles?
3. What happens if the AV nodal rate exceeds the rate of the SA node?

ELECTROCARDIOGRAM

The cardiac impulse that stimulates muscle contraction is an electrical signal. The entire electrical activity of the heart is measured by placing electrodes on the surface of the chest and attaching the electrodes to a recording device. The record of these electrical signals is called an *electrocardiogram* (ECG) (Figure 16-11).

The components of the ECG include a P wave, a QRS complex, and a T wave. The P wave reflects the electrical activity associated with atrial depolarization.

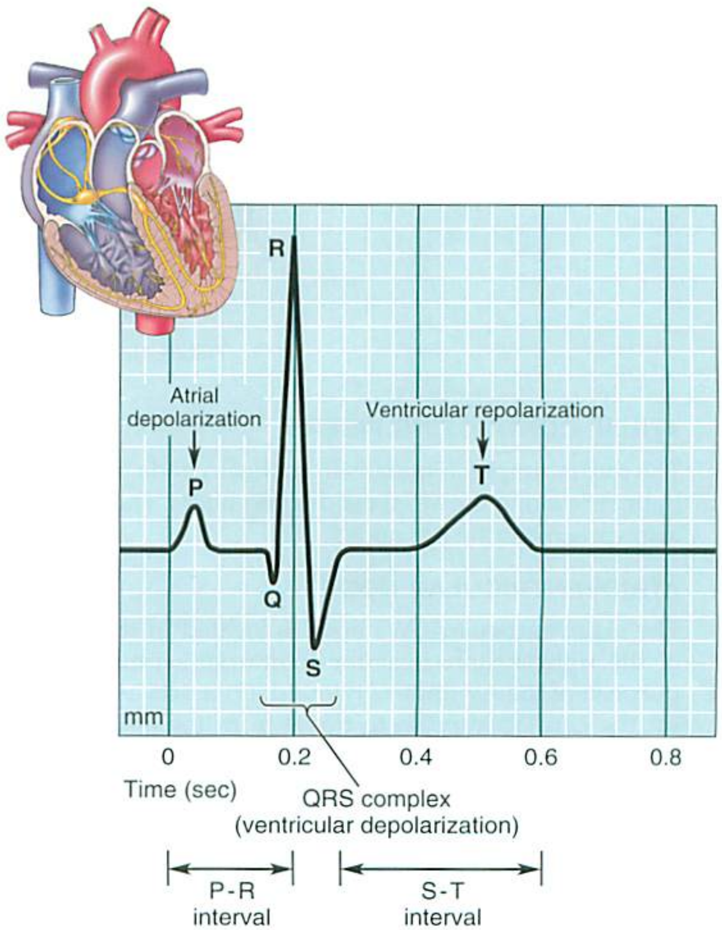


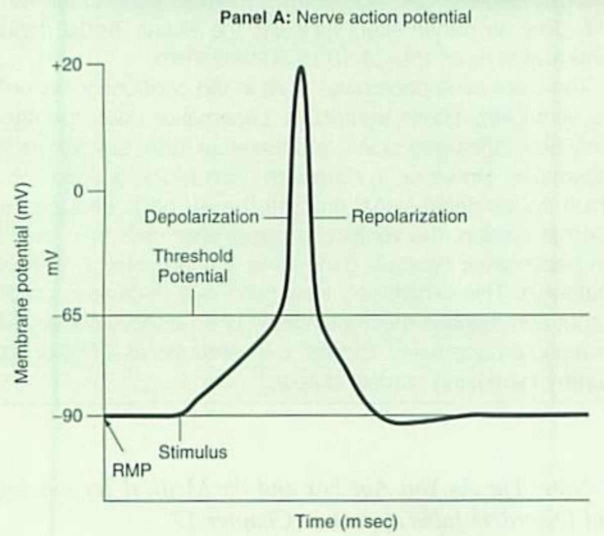
FIGURE 16-11 Electrocardiogram (ECG).

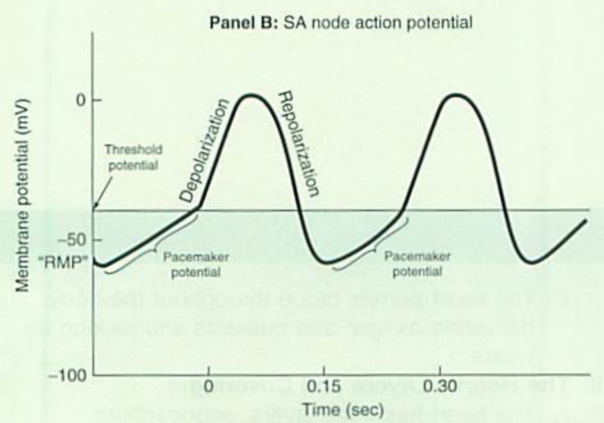
Depolarization precedes and triggers contraction of the heart muscle. (See Chapter 10 for a review of polarization, depolarization, and repolarization.) The QRS complex reflects the electrical activity associated with ventricular depolarization. The T wave reflects the electrical activity associated with ventricular repolarization.

In addition to identifying areas of depolarization and repolarization, the P, QRS, and T deflections (waves) of the ECG provide other useful information. For example, the P-R interval represents the time it takes for the cardiac impulse to travel from the atria (P wave) to the ventricles (QRS complex). Other measurements include the width of the QRS complex and the length of the S-T interval. Normal sinus rhythm (NSR) means that the ECG appears normal and that the impulse originates in the SA node. If the electrical signal originates outside of the SA node, it is referred to as *ectopic*.

Note that the ECG is recorded on special graph paper that allows electrical events to be timed. The clinician can determine whether the electrical signals are moving too fast, too slow, or generating an irregular pattern.

Ramp It Up!





Pacemaker Cells

What is a pacemaker cell? This is best understood by first comparing pacemaker cells with the nerve action potential illustrated in Panel A.

Panel A shows a nerve action potential. The nerve action has a resting membrane potential of −90 mV, reflecting the internal negativity of the cell. When the nerve cell is stimulated, the cell membrane depolarizes to a point called the *threshold potential* (−65 mV). When the threshold potential is reached, the cell fires an action potential; it depolarizes to +20 mV and then very quickly returns to its resting state (repolarization). The cell does not fire another action potential until stimulated again.

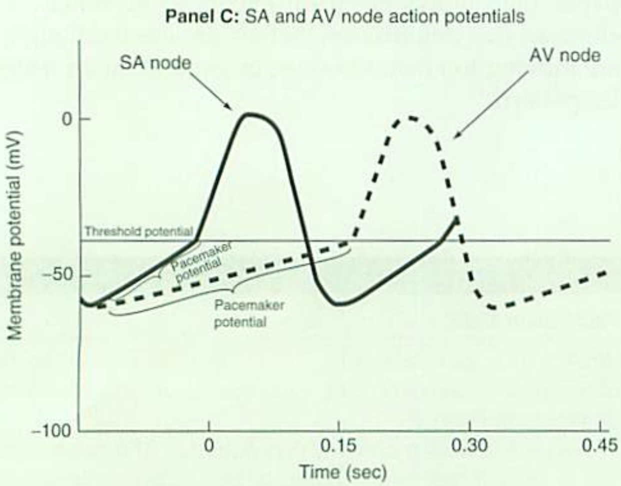
Panel B shows the action potential of the SA node (pacemaker) cell. The SA node does not have a stable resting membrane potential (RMP); the cell momentarily rests at −60 mV. The membrane immediately and spontaneously depolarizes to its threshold potential (−40 mV) and fires an action potential. The important term is *spontaneous depolarization*. The slope of the spontaneous depolarization is called the *pacemaker potential*. Repolarization resets the action potential to −60 mV. The spontaneous depolarization immediately begins again, thereby firing a second action potential. Note that a pacemaker cell is not stimulated to fire an action potential (like the nerve cell)—it fires "on its own."

Can the rate of spontaneous depolarization change?

Yes. The faster the rate of spontaneous depolarization, the faster the heart rate. The slower the rate of spontaneous depolarization, the slower the heart rate. Several factors affect the rate of spontaneous depolarization. First, autonomic nerve stimulation affects the rate of spontaneous depolarization. Sympathetic nerve stimulation increases the rate of spontaneous depolarization, thereby increasing heart rate. Excessive sympathetic stimulation can cause tachycardia and tachydysrhythmias. Parasympathetic or vagal simulation slows the rate of spontaneous depolarization, thereby slowing heart rate. Intense vagal discharge, in fact, can cause bradycardia and heart block, and even cardiac standstill. Hormones and drugs also affect the rates of depolarization.

Continued

Ramp It Up!—cont'd



Panel C shows a comparison of the action potential of the SA and AV nodes. Note that both the SA and AV nodes can both spontaneously depolarize to threshold potential. Thus, both cells have pacemaker capabilities. The SA node, however, is *the* pacemaker. Why? The SA node spontaneously depolarizes at a faster rate than the AV node. Once the SA node depolarizes, it sends an electrical signal throughout the conduction system of the heart, including the AV node. Consequently, all cells, including the AV node, must repolarize and thus reset to the RMP. Why isn't the AV node the pacemaker? The SA depolarizes at a faster rate.

Can the AV node ever become the pacemaker?

Yes. If the rate of SA node activity slows too much or if the rate of the AV node increases too much, the AV node can assume the role of pacemaker activity. This is called *nodal rhythm*. For example, a diseased SA node, such as in sick sinus syndrome or scarring of the conduction pathway, can seriously depress SA node activity, thereby allowing the AV to take over as pacemaker. Typically, the slower nodal rhythm generates a heart rate of 40 to 50 beats/min.

There are even pacemaker cells in the conduction tissue of the ventricles. These ventricular pacemaker cells spontaneously depolarize very slowly and therefore rarely function as the pacemaker. However, in complete heart block, a condition in which no electrical signal crosses the AV node into the His-Purkinje system, the ventricular pacemaker cells take over as the pacemaker, typically generating a heart rate of 30 to 40 beats/min. This excessively slow heart rate decreases cardiac output and requires the implantation of an artificial pacemaker. An artificial pacemaker "drives" the ventricles at a higher rate, thereby increasing cardiac output.

2+2 Sum It Up!

Heart muscle contracts in response to an electrical signal called the *cardiac impulse*, which spreads throughout the heart, coordinating cardiac muscle contraction. The cardiac impulse normally arises within the SA node and spreads throughout both atria over specialized conduction tissue. The cardiac impulse then enters the AV node, where it is momentarily delayed before entering the His-Purkinje system in the ventricles. Cardiac conduction tissue displays automaticity and rhythmicity. The electrical events are recorded as the electrocardiogram (ECG).

Note: The As You Age box and the Medical Terminology and Disorders table appear in Chapter 17.

Get Ready for Exams!

Summary Outline

The heart is a four-chambered pump that delivers blood to the pulmonic and systemic circulations.

I. Function, Location, and Size of the Heart

A. The heart (size of a fist) is located in the mediastinum, toward the left side of the sternum.
B. Located between the second rib and fifth intercostal space
C. The heart pumps blood throughout the body, delivering oxygen and nutrients and picking up waste.

II. The Heart's Layers and Covering

A. The heart has three layers: endocardium, myocardium, and epicardium.
B. The heart is supported by a slinglike pericardium.
C. Two layers of the pericardium form the pericardial space (contains serous fluid).

III. A Double Pump and Two Circulations
- A. The right heart pumps blood to the lungs for oxygenation (called the *pulmonary circulation*).
- B. The left heart pumps blood throughout the rest of the body (called the *systemic circulation*).

IV. The Heart's Chambers and Great Vessels
- A. The heart has four chambers: two atria and two ventricles.
- B. The atria receive the blood and the ventricles pump the blood to the pulmonary and systemic circulations.

V. Heart Valves
- A. The purpose of heart valves is to keep blood flowing in a forward direction.
- B. Two atrioventricular (AV) valves are the tricuspid valve (right heart) and the bicuspid (mitral) valve (left heart).
- C. The two semilunar valves are the pulmonic valve (right heart) and the aortic valve (left heart).

VI. Heart Sounds
- A. The heart sounds ("lubb-dupp") are made by the vibrations caused by closure of the valves.
- B. The "lubb" (S_1) is caused by the closure of the AV valves at the beginning of ventricular contraction. The "dupp" (S_2) is caused by the closure of the semilunar valves at the beginning of ventricular relaxation.

VII. Pathway: Blood Flow through the Heart
- A. The right heart receives blood from the venae cavae and pumps it to the lungs for oxygenation. The left heart receives oxygenated blood from the lungs and pumps it to the systemic circulation.
- B. Blood flow through the heart is summarized in the flow chart (see Figure 16-7).
- C. Shunts alter the path of blood flow through the heart.

VIII. Blood Supply to the Myocardium
- A. The left and right coronary arteries supply the myocardium with oxygen and nutrients.
- B. The coronary veins drain the unoxygenated blood and empty it into the coronary sinus, which empties into the right atrium.

IX. Cardiac Conduction System
- A. The SA node generates an electrical signal (cardiac impulse) that moves throughout the heart in a coordinated way. The electrical signal causes the myocardium to contract.
- B. The pathway followed by the cardiac impulse is summarized in Figure 16-10.
- C. Cardiac muscle displays automaticity and rhythmicity.
- D. The SA node is the pacemaker of the heart. Pacemaker cells throughout the heart fire at different rates: normal, slow, and slower.
- E. The electrical activity of cardiac muscle is recorded as an electrocardiogram.

Review Your Knowledge

Matching: Structures of the Heart

Directions: Match the following words with their descriptions below. Some words may be used more than once.

a. left ventricle
b. coronary arteries
c. right atrium
d. left atrium
e. right ventricle
f. myocardium
g. pericardium
h. precordium

1. ___ Slinglike structure that supports the heart
2. ___ Delivers oxygenated blood to the myocardium
3. ___ Layer of the heart that contains actin and myosin; arranged in sarcomeres
4. ___ Chamber that receives unoxygenated blood from the venae cavae
5. ___ Chamber that receives oxygenated blood from the four pulmonary veins
6. ___ Chamber that pumps blood into the aorta
7. ___ Chamber that has the thickest myocardium
8. ___ Chamber that pumps blood into the pulmonary artery
9. ___ The left ventricle receives oxygenated blood from this chamber.
10. ___ Refers to the area of the chest that overlies the heart

Matching: Valves

Directions: Match the following words with their descriptions below. Some words may be used more than once.

a. aortic
b. tricuspid
c. bicuspid
d. pulmonic

1. ___ The semilunar valve through which blood exits the right ventricle
2. ___ The exit valve for the right ventricle
3. ___ The atrioventricular valve that "sees" unoxygenated blood
4. ___ The valve that is also called the mitral valve
5. ___ The semilunar valve through which blood exits the left ventricle
6. ___ The AV valve that "sees" oxygenated blood
7. ___ The AV valve located between the left atrium and left ventricle
8. ___ If "leaky," this valve allows blood to flow backward from the pulmonary artery.
9. ___ This valve is located in the right heart and does not have chordae tendineae.
10. ___ This valve is located in the left heart and has chordae tendineae.

Multiple Choice

1. Which of the following is not true of the heart?
   - **a.** The heart is located within the mediastinum.
   - **b.** The apex is located to the left of the sternal midline at the level of the fifth intercostal space.
   - **c.** The base of the heart is located at the level of the second rib.
   - **d.** The precordium is composed of cardiac muscle.

2. Which of the following is descriptive of the myocardium?
   a. Composed of contractile proteins (actin and myosin)
   b. Thicker in the ventricles than the atria
   c. Thicker in the left ventricle than the right ventricle
   d. All of the above.
3. Which of the following is the function of a valve?
   a. Regulates the direction of the flow of blood through the heart
   b. Regulates the amount of oxygen bound to hemoglobin
   c. Regulates heart rate
   d. Directs the progression of the cardiac impulse
4. Which of the following is true regarding the structures of the electrical conduction system?
   a. The AV node is the pacemaker.
   b. In normal sinus rhythm, the electrical signal arises within the SA node.
   c. The His-Purkinje system spreads the electrical signal from the right atrium to the left atrium.
   d. The purpose of the AV node is to increase the speed at which the cardiac impulse moves from the atria to the ventricles.
5. Which of the following is least true of the aortic valve?
   a. "Sees" oxygenated blood
   b. Causes left ventricular hypertrophy if the valve is stenotic
   c. Allows blood to flow from the ventricle into the pulmonary artery
   d. Classified as a semilunar valve
6. Pacemaker cells fire at a faster rate in the
   a. left coronary artery.
   b. SA node.
   c. ventricular myocardium.
   d. AV node.
7. The coronary arteries
   a. exit the aorta at a point immediately distal to the aortic semilunar valve.
   b. fill the right atrium with blood with each myocardial contraction.
   c. are color-coded blue.
   d. deliver most O_2 and nutrients while the myocardium is contracted.
8. Which of the following blood flow statements is true?
   a. Blood is pumped by the right atrium through the mitral valve.
   b. Blood is pumped by the right ventricle into the pulmonary artery.
   c. Blood is pumped by the left ventricle through the mitral valve.
   d. An incompetent or leaky tricuspid valve allows blood to flow from the pulmonary artery to the right ventricle.
9. The structure(s) that is/are color-coded red:
   a. Right ventricle
   b. Both AV valves
   c. Both semilunar valves
   d. Pulmonary veins
10. The chordae tendineae are necessary for the proper functioning of the
    a. SA node.
    b. pericardium.
    c. pulmonic semilunar valve.
    d. mitral valve.

Go Figure

1. **According to Figure 16-1**
   a. The apex (tip) of the heart is at the level of the 10th intercostal space.
   b. The apex of the heart is located left of the midsternal line.
   c. The ascending aorta is located to the right of the midsternal line.
   d. The base of the heart is located at the level of the fifth intercostal space.

2. **According to Figure 16-3**
   a. The left heart pumps blood to the lungs for oxygenation.
   b. The right heart pumps blood into the systemic circulation.
   c. The systemic circulation delivers blood to the brain, liver, feet, and digestive tract.
   d. The right heart is color-coded blue because it carries oxygenated blood.

3. **According to Figure 16-4**
   a. Pulmonary veins are color-coded red, meaning that they carry oxygenated blood.
   b. All arteries carry oxygenated blood.
   c. The venae cavae carry blood to the left side of the heart.
   d. The left side of the heart carries unoxygenated blood.

4. **According to Figures 16-5 and 16-6**
   a. All AV valves are located in the right heart.
   b. All semilunar valves are located in the left heart.
   c. Both AV valves contain cusps and are attached to papillary muscles of the ventricular wall by chordae tendineae.
   d. All valvular sounds are best heard at the second intercostal space.

5. **According to Figure 16-9**
   a. The sinoatrial node is located within the interatrial septum and is the pacemaker of the heart.
   b. The AV node is located on the cusps of the AV valves.
   c. Fast-conducting Purkinje fibers are located within the ventricular myocardium.
   d. NSR (normal sinus rhythm) implies that the electrical signal arises within the AV node and acts as pacemaker.