11 The Cardiovascular System

FUNCTION PREVIEW

- The heart pumps blood.
- Blood vessels provide the conduits within which blood circulates to all body tissues.

When most people hear the term *cardiovascular system,* they immediately think of the heart. We have all felt our own heart "pound" from time to time, and we tend to get a bit nervous when this happens. The crucial importance of the heart has been recognized for ages. However, the **cardiovascular system** is much more than just the heart, and from a scientific and medical standpoint, it is important to understand *why* this system is so vital to life.

The almost continuous traffic into and out of a busy factory at rush hour occurs at a snail's pace compared to the endless activity going on within our bodies. Night and day, minute after minute, our trillions of cells take up nutrients and excrete wastes. Although the pace of these exchanges slows during sleep, they must go on continuously, because when they stop we die. Cells can make such exchanges only with the tissue fluid in their immediate vicinity. Thus, some means of changing and "refreshing" these fluids is necessary to renew the nutrients and prevent pollution caused by the buildup of wastes. Like the bustling factory, the body must have a transportation system to carry its various "cargos" back and forth. Instead of roads, railway tracks, and airways, the body's delivery routes are its hollow blood vessels.

Most simply stated, the major function of the cardiovascular system is transportation. Using blood as the transport vehicle, the system carries oxygen, nutrients, cell wastes, hormones, and many other substances vital for body homeostasis to and from the cells. The force to move the blood around the body is provided by the beating heart and by blood pressure.

The cardiovascular system can be compared to a muscular pump equipped with one-way valves and a system of large and small plumbing tubes within which the blood travels. We discussed blood (the substance transported) in Chapter 10. Here we will consider the heart (the pump) and the blood vessels (the network of tubes).

The Heart

Anatomy of the Heart

✓ Describe the location of the heart in the body, and identify its major anatomical areas on an appropriate model or diagram.

Size, Location, and Orientation

The modest size and weight of the heart give few hints of its incredible strength. Approximately the size of a person's fist, the hollow, cone-shaped heart weighs less than a pound. Snugly enclosed within the inferior **mediastinum** (me″de-ah-sti′num), the medial cavity of the thorax, the heart is flanked on each side by the lungs (**Figure 11.1**). Its more pointed **apex** is directed toward the left hip and rests on the diaphragm, approximately at the level of the fifth intercostal space. (This is exactly where one would place a stethoscope to count the heart rate for an apical pulse.) Its broad posterosuperior aspect, or **base,** from which the great vessels of the body emerge, points toward the right shoulder and lies beneath the second rib.

Coverings and Walls of the Heart

The heart is enclosed by a double-walled sac called the **pericardium** (per′i-kar″de-um). The loosely fitting superficial part of this sac is referred to as the **fibrous pericardium.** This fibrous layer helps protect the heart and anchors it to surrounding structures, such as the diaphragm and sternum. Deep to the fibrous pericardium is the slippery, two-layer **serous pericardium.** Its **parietal layer** lines the interior of the fibrous pericardium. At the superior aspect of the heart, this parietal layer attaches to the large arteries leaving the heart and then makes a U-turn and continues inferiorly over the heart surface as the **visceral layer,** or **epicardium,** which is actually part of the heart wall (**Figure 11.2**). A slippery lubricating fluid (serous fluid) is produced by the serous pericardial membranes. This fluid allows the heart to beat easily in a relatively frictionless environment as the serous pericardial layers slide smoothly across each other.

HOMEOSTATIC IMBALANCE

Inflammation of the pericardium, **pericarditis** (per″ĭ-kar-di′tis), often results in a decrease in the serous fluid. This causes the pericardial layers to bind and stick to each other, forming painful *adhesions* that interfere with heart movements. ◗

The heart walls are composed of three layers: the outer *epicardium* (the visceral pericardium described above), the *myocardium,* and the innermost *endocardium* (Figure 11.2). The **myocardium** (mi″o-kar′de-um) consists of thick bundles of cardiac muscle twisted and whorled into ringlike arrangements (see Figure 6.2b, p. 184). It is the layer that actually contracts. Its cells exhibit both tight junctions, which strongly bind the mobile cardiac cells together, and gap junctions, which allow ions to flow from cell to cell carrying a wave of excitement across the heart. The myocardium is reinforced internally by a dense, fibrous connective tissue network called the "skeleton of the heart." The **endocardium** (en″do-kar′de-um) is a thin, glistening sheet of endothelium that lines the heart chambers. It is continuous with the linings of the blood vessels leaving and entering the heart. **Figure 11.3** shows two views of the heart—an external anterior view and a frontal section. As the anatomical areas of the heart are described in the next section, keep referring to Figure 11.3 to locate each of the heart structures or regions.

Chambers and Associated Great Vessels

✓ Trace the pathway of blood through the heart.

✓ Compare the pulmonary and systemic circuits.

The heart has four hollow chambers, or cavities—two **atria** (a′tre-ah; singular *atrium*) and two

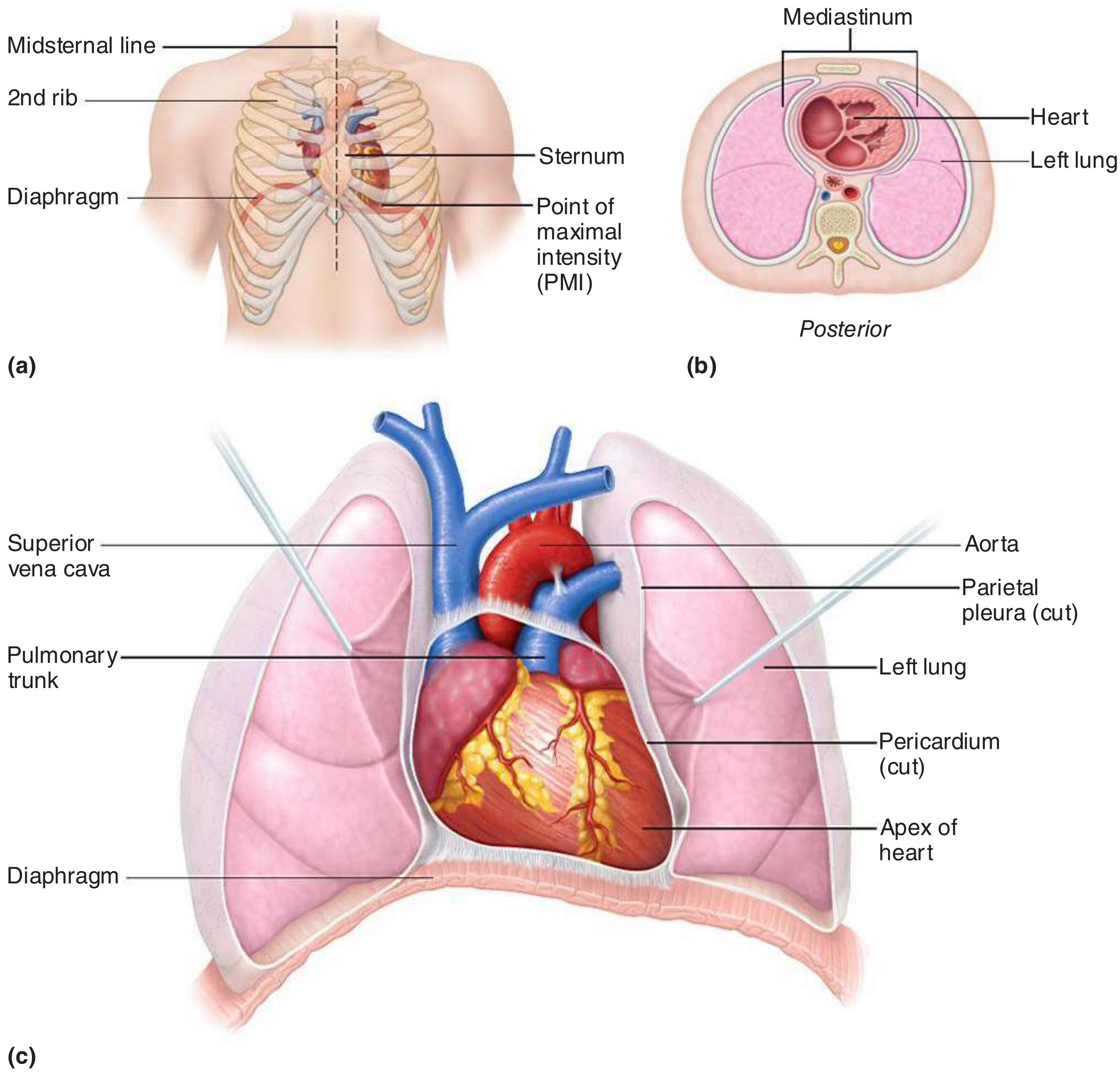


Figure 11.1 Location of the heart within the thorax. (a) Relationship of the heart to the sternum and ribs. **(b)** Cross-sectional view showing relative position of the heart in the thorax. **(c)** Relationship of the heart and great vessels to the lungs.

ventricles (ven′trĭ-kulz). Each of these chambers is lined with endocardium, which helps blood flow smoothly through the heart. The superior atria are primarily *receiving chambers.* As a rule, they are not important in the pumping activity of the heart. Blood flows into the atria under low pressure from the veins of the body and then continues on to fill the ventricles. The inferior, thick-walled ventricles are the *discharging chambers,* or actual pumps of the heart. When they contract, blood is propelled out of the heart and into the circulation. As illustrated in Figure 11.3a, the right ventricle forms most of the heart's anterior surface; the left ventricle forms its apex. The septum that divides the heart longitudinally is referred to as either the **interventricular septum** or the **interatrial septum,** depending on which chamber it separates.

Although it is a single organ, the heart functions as a double pump. The right side works as

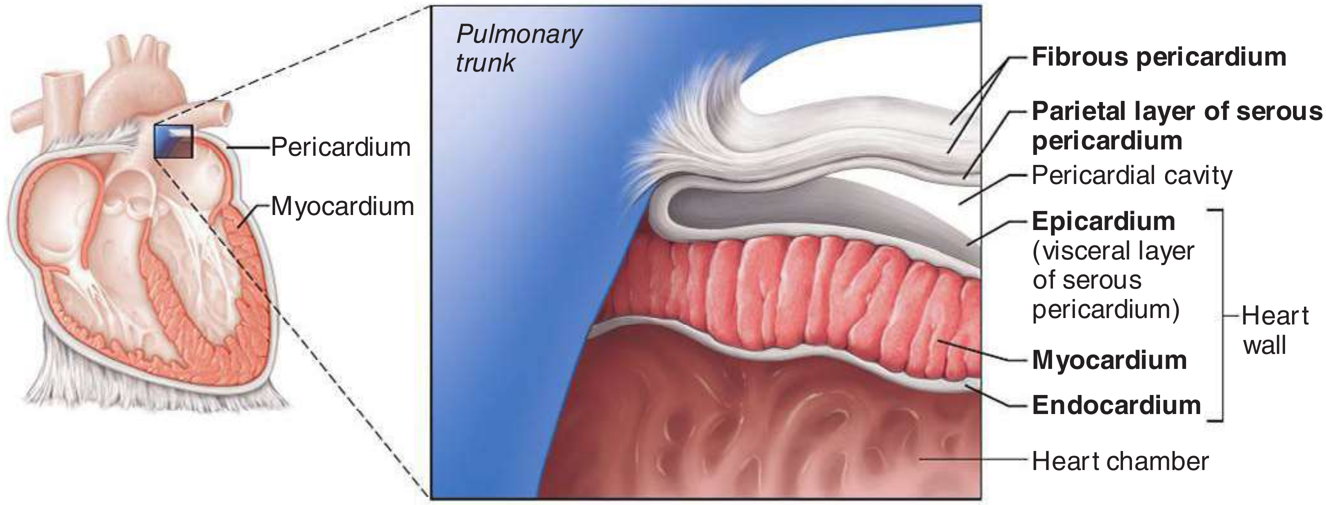


Figure 11.2 **Heart wall and coverings.**

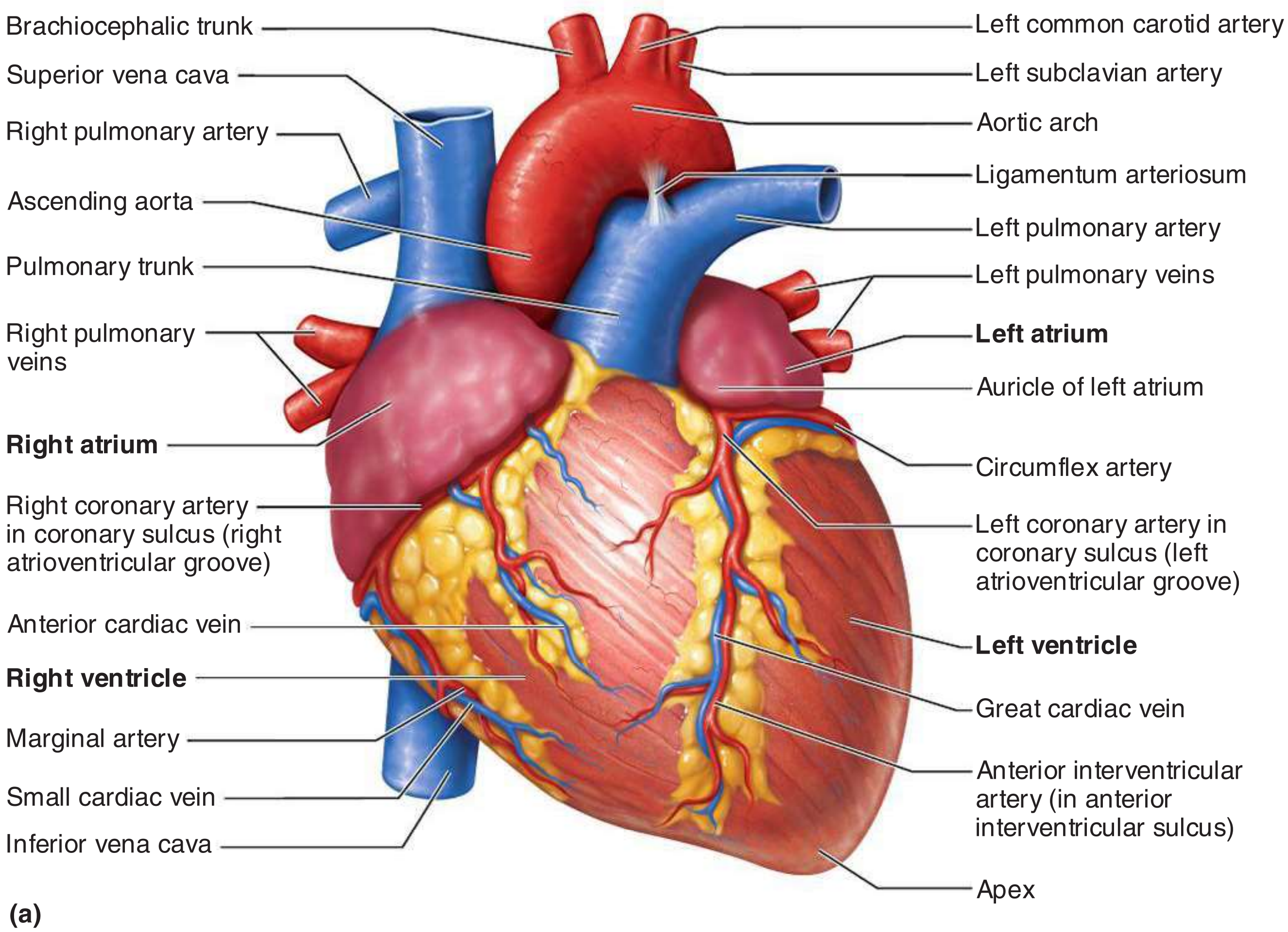
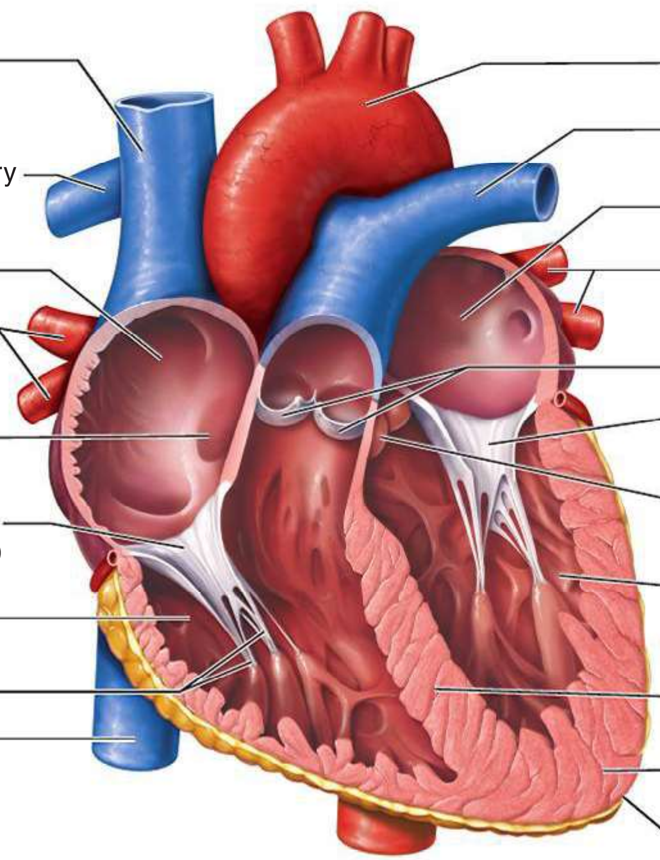


Figure 11.3 **Gross anatomy of the heart.** *(Continues on page 360)*



(b) Frontal section showing interior chambers and valves.

Figure 11.3 *(continued)* **Gross anatomy of the heart.**

the pulmonary circuit pump. It receives relatively oxygen-poor blood from the veins of the body through the large **superior** and **inferior venae cavae** (ka′ve) and pumps it out through the **pulmonary trunk.** The pulmonary trunk splits into the right and left **pulmonary arteries,** which carry blood to the lungs, where oxygen is picked up and carbon dioxide is unloaded. Oxygen-rich blood drains from the lungs and is returned to the left side of the heart through the four **pulmonary veins.** The circulation just described, from the right side of the heart to the lungs and back to the left side of the heart, is called the **pulmonary circulation** (**Figure 11.4**). Its only function is to carry blood to the lungs for gas exchange and then return it to the heart.

Blood returned to the left side of the heart is pumped out of the heart into the **aorta** (a-or′tah), from which the systemic arteries branch to supply essentially all body tissues. Oxygen-poor blood circulates from the tissues back to the right atrium via the systemic veins, which finally empty their cargo into either the superior or inferior vena cava. This second circuit, from the left side of the heart through the body tissues and back to the right side of the heart, is called the **systemic circulation** (see Figure 11.4). It supplies oxygen- and nutrient-rich blood to all body organs. Because the left ventricle is the systemic pump that pumps blood over a much longer pathway through the body, its walls are substantially thicker than those of the right ventricle (**Figure 11.5**), and it is a much more powerful pump.

DID YOU GET IT?

1. What is the location of the heart in the thorax?
2. Which heart chamber has the thickest walls? What is the functional significance of this structural difference?
3. How does the function of the systemic circulation differ from that of the pulmonary circulation?

For answers, see Appendix D.

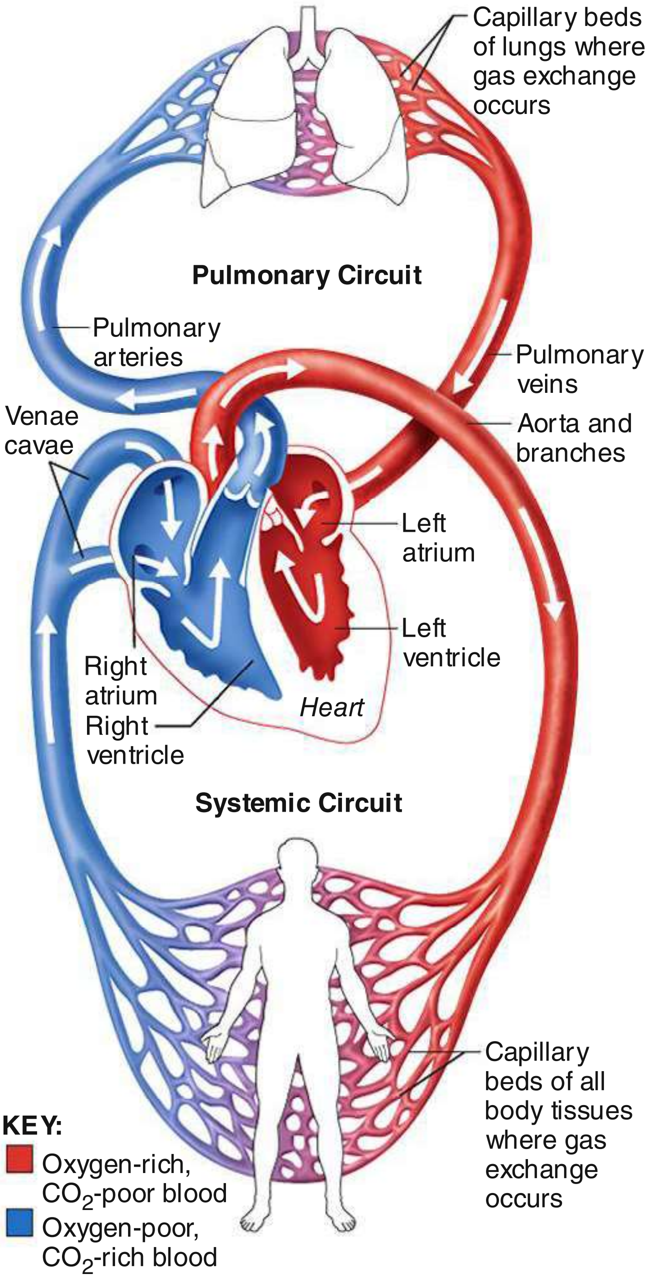


Figure 11.4 The systemic and pulmonary circulations. The left side of the heart is the systemic pump; the right side is the pulmonary circuit pump. (Although there are two pulmonary arteries, one each to the right and left lung, for simplicity only one is shown.)

Heart Valves

✓ Explain the operation of the heart valves.

The heart is equipped with four valves, which allow blood to flow in only one direction through the heart chambers—from the atria through the ventricles and out the great arteries leaving the heart (see Figure 11.3b). The **atrioventricular** (a″tre-o-ven-trik′ u-lar), or **AV, valves** are located between the atrial and ventricular chambers on each side. These valves prevent backflow into the atria when the ventricles contract. The left AV valve—the **bicuspid,** or **mitral** (mi′ tral), **valve**—consists of two flaps, or cusps, of endocardium. The right AV valve, the **tricuspid valve,** has three flaps. Tiny white cords, the **chordae tendineae** (kor′ de ten-din′ e)—literally, "tendinous cords" (but I like to think of them as the "heart strings" of song)—anchor the flaps to the walls of the ventricles. When the heart is relaxed and blood is passively filling its chambers, the AV valve flaps hang limply into the ventricles (**Figure 11.6a**).

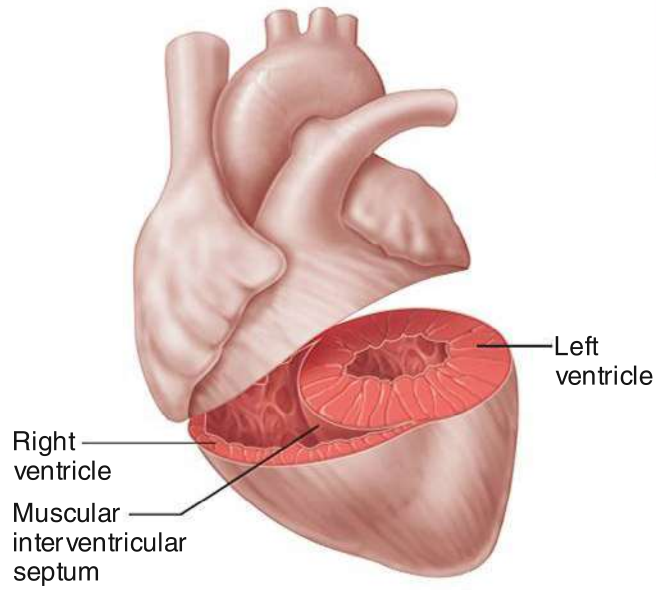


Figure 11.5 Anatomical differences in right and left ventricles. The left ventricle has a thicker wall, and its cavity is basically circular. The right ventricle cavity is crescent-shaped and wraps around the left ventricle.

As the ventricles contract, they press on the blood in their chambers, and the intraventricular pressure (pressure inside the ventricles) begins to rise. This forces the AV valve flaps upward, closing the valves. At this point the chordae tendineae are working to anchor the flaps in a closed position. If the flaps were unanchored, they would blow upward into the atria like an umbrella being turned inside out by a gusty wind. In this manner, the AV valves prevent backflow into the atria when the ventricles are contracting.

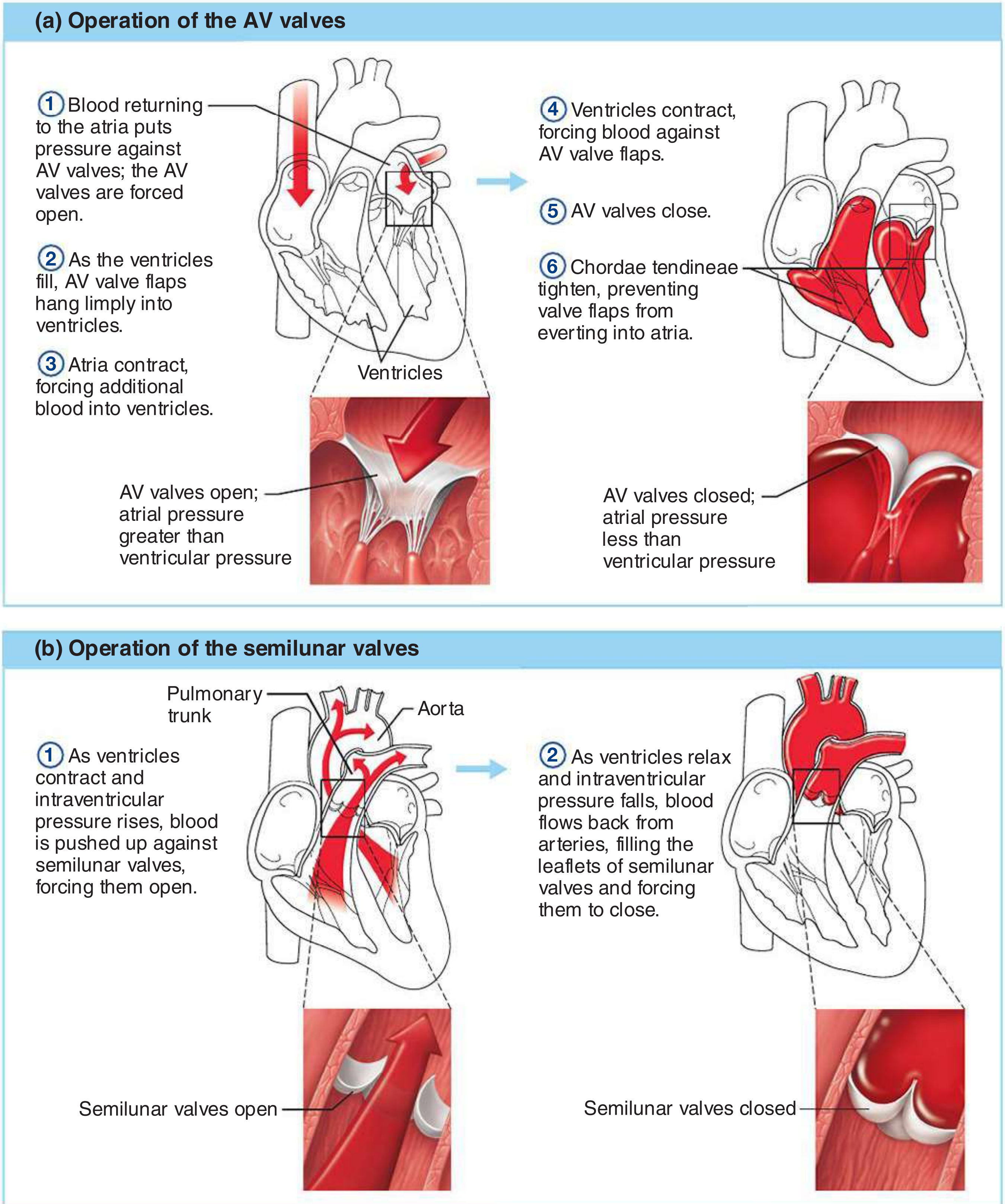


Figure 11.6 Operation of the heart valves. (a) Atrioventricular (AV) valves. **(b)** Semilunar valves.

The second set of valves, the **semilunar** (sem″e-lu′nar) **valves,** guards the bases of the two large arteries leaving the ventricular chambers. Thus, they are known as the **pulmonary** and **aortic semilunar valves** (see Figure 11.3b). Each semilunar valve has three leaflets that fit tightly together when the valves are closed. When the ventricles are contracting and forcing blood out of the heart, the leaflets are forced open and flattened against the walls of the arteries by the tremendous force of rushing blood (Figure 11.6b). Then, when the ventricles relax, the blood begins to flow backward toward the heart, and the leaflets fill with blood, closing the valves. This prevents arterial blood from reentering the heart.

Each set of valves operates at a different time. The AV valves are open during heart relaxation and closed when the ventricles are contracting. The semilunar valves are closed during heart relaxation and are forced open when the ventricles contract. As they open and close in response to pressure changes in the heart, the valves force blood to continually move forward in its journey through the heart.

HOMEOSTATIC IMBALANCE

Heart valves are basically simple devices, and the heart—like any mechanical pump—can function with "leaky" valves as long as the damage is not too great. However, severely deformed valves can seriously hamper cardiac function. For example, an *incompetent valve* forces the heart to pump and repump the same blood because the valve does not close properly and blood backflows. In *valvular stenosis,* the valve flaps become stiff, often because of repeated bacterial infection of the endocardium **(endocarditis).** This forces the heart to contract more vigorously than normal. In each case, the heart's workload increases, and ultimately the heart weakens and may fail. Under such conditions, the faulty valve is replaced with a synthetic valve, a cryopreserved human valve, or a chemically treated valve taken from a pig heart. ◗

Cardiac Circulation

✓ Name the functional blood supply of the heart.

Although the heart chambers are bathed with blood almost continuously, the blood contained in the heart does *not* nourish the myocardium. The *functional blood supply* that oxygenates and nourishes the heart is provided by the right and left coronary arteries. The **coronary arteries** branch from the base of the aorta and encircle the heart in the **coronary sulcus (atrioventricular groove)** at the junction of the atria and ventricles (see Figure 11.3a). The coronary arteries and their major branches (the **anterior interventricular** and **circumflex arteries** on the left, and the **posterior interventricular** and **marginal arteries** on the right) are compressed when the ventricles are contracting and fill when the heart is relaxed. The myocardium is drained by several **cardiac veins,** which empty into an enlarged vessel on the posterior of the heart called the **coronary sinus.** The coronary sinus, in turn, empties into the right atrium.

HOMEOSTATIC IMBALANCE

When the heart beats at a very rapid rate, the myocardium may receive an inadequate blood supply because the relaxation periods (when the blood is able to flow to the heart tissue) are shortened. Situations in which the myocardium is deprived of oxygen often result in crushing chest pain called **angina pectoris** (an-ji′nah pek′tor-is). This pain is a warning that should *never* be ignored, because if angina is prolonged the oxygen-deprived heart cells may die, forming an **infarct.** The resulting **myocardial infarction** (in-fark′shun) is commonly called a "heart attack" or "coronary." ◗

DID YOU GET IT?

4. Why are the heart valves important?

5. Why might a thrombus in a coronary artery cause sudden death?

For answers, see Appendix D.

Physiology of the Heart

As the heart beats, or contracts, the blood makes continuous round-trips—into and out of the heart, through the rest of the body, and then back to the heart—only to be sent out again. The amount of work that a heart does is almost too incredible to believe. In one day it pushes the body's supply of 6 quarts or so of blood (6 liters [L]) through the blood vessels over 1000 times, meaning that it actually pumps about 6000 quarts of blood in a single day!

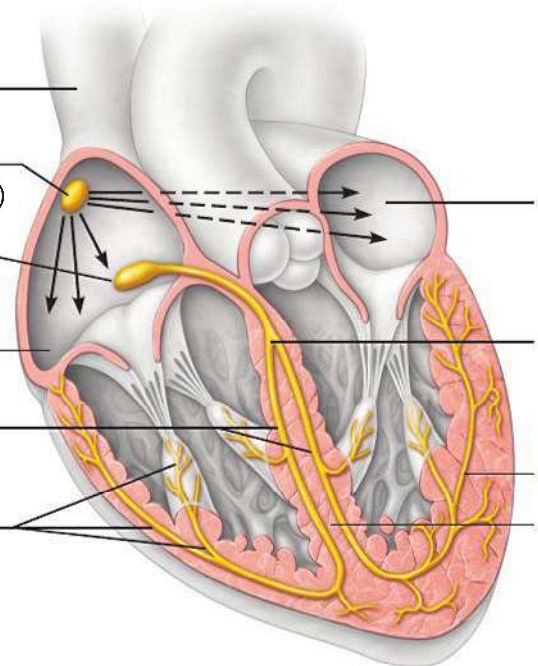


Figure 11.7 **The intrinsic conduction system of the heart.** The depolarization wave initiated by the sinoatrial (SA) node passes successively through the atrial myocardium to the atrioventricular (AV) node, the AV bundle, the right and left bundle branches, and the Purkinje fibers in the ventricular walls.

Intrinsic Conduction System of the Heart: Setting the Basic Rhythm

- ✓ Name the elements of the intrinsic conduction system of the heart, and describe the pathway of impulses through this system.
- ✓ Explain what information can be gained from an electrocardiogram.

What makes the heart beat? Unlike skeletal muscle cells, which must be stimulated by nerve impulses before they will contract, cardiac muscle cells can and do contract spontaneously and independently, even if all nervous connections are severed. Moreover, these spontaneous contractions occur in a regular and continuous way. Although cardiac muscle *can* beat independently, the muscle cells in different areas of the heart have different rhythms. The atrial cells beat about 60 times per minute, but the ventricular cells contract more slowly (20–40/min). Therefore, without some type of unifying control system, the heart would be an uncoordinated and inefficient pump.

Two systems act to regulate heart activity. One of these involves the nerves of the autonomic nervous system, which act like brakes and accelerators to decrease or increase the heart rate depending on which division is activated. We consider this topic later (see p. 368). The second system is the **intrinsic conduction system,** or **nodal system,** that is built into the heart tissue (**Figure 11.7**) and sets its basic rhythm. The intrinsic conduction system is composed of a special tissue found nowhere else in the body; it is much like a cross between muscle and nervous tissue. This system causes heart muscle depolarization in only one direction—from the atria to the ventricles. In addition, it enforces a contraction rate of approximately 75 beats per minute on the heart; thus, the heart beats as a coordinated unit.

One of the most important parts of the intrinsic conduction system is a crescent-shaped node of tissue called the **sinoatrial** (si″no-a′tre-al) **(SA) node,** located in the right atrium. Other components include the **atrioventricular (AV) node** at the junction of the atria and ventricles, the **atrioventricular (AV) bundle (bundle of His)** and the right and left **bundle branches** located in the interventricular septum, and finally the **Purkinje** (pur-kin′je) **fibers,** which spread within the muscle of the ventricle walls.

The SA node is a tiny cell mass with a mammoth job. Because it has the highest rate of depolarization in the whole system, it starts each heartbeat and sets the pace for the whole heart. Consequently, the SA node is often called the **pacemaker.** From the SA node, the impulse spreads through the atria to the AV node, and then the atria contract. At the AV node, the impulse is delayed briefly to give the atria time to finish contracting. It then passes rapidly through the AV bundle, the bundle branches, and the Purkinje fibers, resulting in a "wringing" contraction of the ventricles that begins at the heart apex and moves toward the atria. This contraction effectively ejects blood superiorly into the large arteries leaving the heart. "A Closer Look" on p. 367 describes *electrocardiography,* the clinical procedure for mapping the electrical activity of the heart.

HOMEOSTATIC IMBALANCE

Because the atria and ventricles are separated from one another by "insulating" connective tissue, which is part of the fibrous skeleton of the heart, depolarization waves can reach the ventricles only by traveling through the AV node. Thus, any damage to the AV node can partially or totally release the ventricles from the control of the SA node. When this occurs, the ventricles (thus the heart) begin to beat at their own rate, which is much slower, some or all of the time. This condition is called **heart block.**

There are other conditions that can interfere with the regular conduction of impulses across the heart—for example, damage to the SA node results in a slower heart rate. When this is a problem, artificial pacemakers are usually installed surgically.

Ischemia (is-ke′me-ah), or lack of an adequate blood supply to the heart muscle, may lead to **fibrillation**—a rapid, uncoordinated shuddering of the heart muscle (it looks like a bag of worms). Fibrillation makes the heart totally useless as a pump and is a major cause of death from heart attacks in adults. Some restaurants train their employees in the use of on-site *defibrillators,* which has proven to be lifesaving in many cases.

Tachycardia (tak″e-kar′de-ah) is a rapid heart rate (over 100 beats per minute). **Bradycardia** (brad″e-kar′de-ah) is a heart rate that is substantially slower than normal (less than 60 beats per minute). Neither condition is pathological, but prolonged tachycardia may progress to fibrillation.

Cardiac Cycle and Heart Sounds

✓ Define *systole, diastole, stroke volume, cardiac cycle, heart sounds,* and *murmur.*

In a healthy heart, the atria contract simultaneously. Then, as they start to relax, contraction of the ventricles begins. **Systole** (sis′to-le) and **diastole** (di-as′to-le) mean heart *contraction* and *relaxation,* respectively. Because most of the pumping work is done by the ventricles, these terms always refer to the contraction and relaxation of the *ventricles* unless otherwise stated.

The term **cardiac cycle** refers to the events of one complete heartbeat, during which both atria and ventricles contract and then relax. The average heart beats approximately 75 times per minute, so the length of the cardiac cycle is normally about 0.8 second. We will consider the cardiac cycle in terms of events occurring during three periods—*mid-to-late diastole, ventricular systole,* and *early diastole* (**Figure 11.8**).

1. **Mid-to-late diastole.** Our discussion begins with the heart in complete relaxation. At this point, the pressure in the heart is low, and blood is flowing passively into and through the atria into the ventricles from the pulmonary and systemic circulations. The semilunar valves are closed, and the AV valves are open. Then the atria contract and force the blood remaining in their chambers into the ventricles.
2. **Ventricular systole.** Shortly after, ventricular contraction (systole) begins, and the pressure within the ventricles increases rapidly, closing the AV valves. When the intraventricular pressure (pressure in the ventricles) is higher than the pressure in the large arteries leaving the heart, the semilunar valves are forced open, and blood rushes through them out of the ventricles. During ventricular systole, the atria are relaxed, and their chambers are again filling with blood.
3. **Early diastole.** At the end of systole, the ventricles relax, the semilunar valves snap shut (preventing backflow), and for a moment the ventricles are completely closed chambers. During early diastole, the intraventricular pressure drops. When it drops below the pressure in the atria (which has been increasing as blood

Q: *Are the ventricular cardiac cells contracting isometrically or isotonically during the first part of phase 2?*

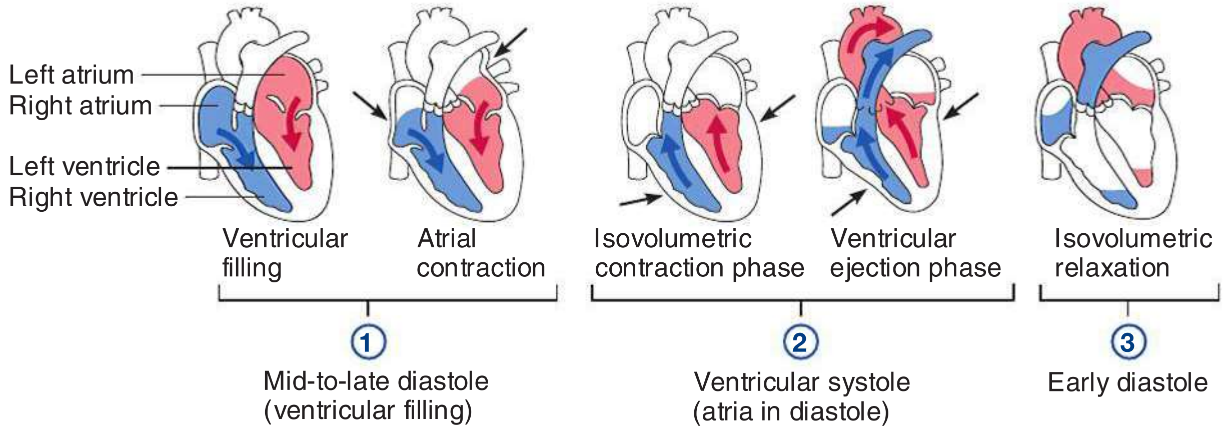


Figure 11.8 Summary of events occurring during the cardiac cycle. Small black arrows indicate the regions of the heart that are contracting; thick red and blue arrows indicate direction of blood flow. During the *isovolumetric* (literally "same volume measurement") phases in periods 2 and 3, the ventricles are closed chambers and the volume of blood they contain is unchanging.

has been filling their chambers), the AV valves are forced open, and the ventricles again begin to refill rapidly with blood, completing the cycle.

When using a stethoscope, you can hear two distinct sounds during each cardiac cycle. These **heart sounds** are often described by the two syllables "lub" and "dup," and the sequence is lub-dup, pause, lub-dup, pause, and so on. The first heart sound (lub) is caused by the closing of the AV valves. The second heart sound (dup) occurs when the semilunar valves close at the end of systole. The first heart sound is longer and louder than the second heart sound, which tends to be short and sharp.

HOMEOSTATIC IMBALANCE

Abnormal or unusual heart sounds are called **heart murmurs.** Blood flows silently as long as the flow is smooth and uninterrupted. If it strikes obstructions, its flow becomes turbulent and generates sounds, such as heart murmurs, that can be heard with a stethoscope. Heart murmurs are fairly common in young children (and some elderly people) with perfectly healthy hearts, probably because their heart walls are relatively thin and vibrate with rushing blood. However, murmurs in patients who do not fall into either of these groups most often indicate valve problems. For example, if a valve does not close tightly (is *incompetent*), a swishing sound will be heard *after* that valve has (supposedly) closed, as the blood flows back through the partially open valve. Distinct sounds also can be heard when blood flows turbulently through *stenosed* (narrowed) valves.

DID YOU GET IT?

6. What is the function of the intrinsic conduction system of the heart?
7. To which heart chambers do the terms *systole* and *diastole* usually apply?
8. What causes the lub-dup sounds heard with a stethoscope?

For answers, see Appendix D.

A: *The cells contract isometrically until they have enough force to overcome the back pressure of the blood against the semilunar valves, at which point their contraction becomes isotonic.*