18

The Cardiovascular System: The Heart

Our ceaselessly beating heart has intrigued people for centuries. The ancient Greeks believed the heart was the seat of intelligence. Others thought it was the source of emotions. While these ideas have proved false, we do know that emotions affect heart rate. When your heart pounds or skips a beat, you become acutely aware of how much you depend on this dynamic organ for your very life.

Despite its vital importance, the heart does not work alone. Indeed, it is only part of the cardiovascular system, which includes the miles of blood vessels that run through your

body. Day and night, tissue cells take in nutrients and oxygen and excrete wastes. Cells can make such exchanges only with their immediate environment, so some means of changing and renewing that environment is necessary to ensure a continual supply of nutrients and prevent a buildup of wastes. The cardiovascular system provides the transport system "hardware" that keeps blood continuously circulating to fulfill this critical homeostatic need.

The Pulmonary and Systemic Circuits

Stripped of its romantic cloak, the **heart** is no more than the transport system pump, and the hollow blood vessels are the delivery routes. In fact, the heart is actually two pumps side by side **(Figure 18.1)**.

- The *right side* of the heart receives oxygen-poor blood from body tissues and then pumps this blood to the lungs to pick up oxygen and dispel carbon dioxide. The blood vessels that carry blood to and from the lungs form the **pulmonary circuit** (*pulmo* = lung).
- The *left side* of the heart receives the oxygenated blood returning from the lungs and pumps this blood throughout the body to supply oxygen and nutrients to body tissues. The blood vessels that carry blood to and from all body tissues form the **systemic circuit**.

The heart has two receiving chambers, the *right atrium* and *left atrium*, that receive blood returning from the systemic and pulmonary circuits. The heart also has two main pumping chambers, the *right ventricle* and *left ventricle*, that pump blood around the two circuits. Using blood as the transport medium, the heart continually propels oxygen, nutrients, wastes, and many other substances into the interconnecting blood vessels that service body cells.

Heart Anatomy

- ✓ Describe the size, shape, location, and orientation of the heart in the thorax.
- ✓ Name the coverings of the heart.
- ✓ Describe the structure and function of each of the three layers of the heart wall.

Size, Location, and Orientation

The modest size and weight of the heart belie its incredible strength and endurance. About the size of a fist, the hollow, cone-shaped heart has a mass of 250 to 350 grams—less than a pound **(Figure 18.2)**.

Snugly enclosed within the **mediastinum** (me″de-ah-sti′num), the medial cavity of the thorax, the heart extends obliquely for 12 to 14 cm (about 5 inches) from the second rib to the fifth intercostal space (Figure 18.2a). As it rests on the superior surface of the diaphragm, the heart lies anterior to the vertebral column and posterior to the sternum. Approximately two-thirds of its mass lies to the left of the midsternal line; the balance projects to the right. The lungs flank the heart laterally and partially obscure it (Figure 18.2b, c).

Its broad, flat **base**, or posterior surface, is about 9 cm (3.5 in) wide and directed toward the right shoulder. Its **apex** points inferiorly toward the left hip. If you press your fingers between the fifth and sixth ribs just below the left nipple, you can easily feel the **apical impulse** caused by your beating heart's apex where it touches the chest wall.

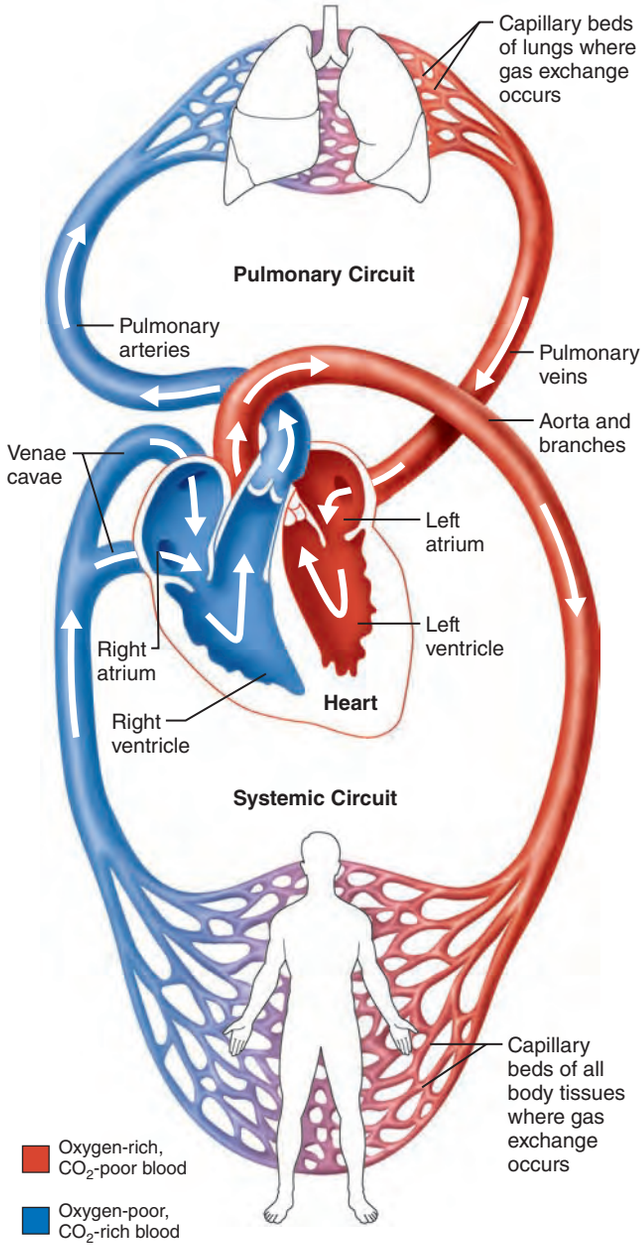


Figure 18.1 The systemic and pulmonary circuits. The right side of the heart pumps blood through the pulmonary circuit* (to the lungs and back to the left side of the heart). The left side of the heart pumps blood through the systemic circuit to all body tissues and back to the right side of the heart. The arrows indicate the direction of blood flow.

*For simplicity, the actual number of two pulmonary arteries and four pulmonary veins has been reduced to one each.

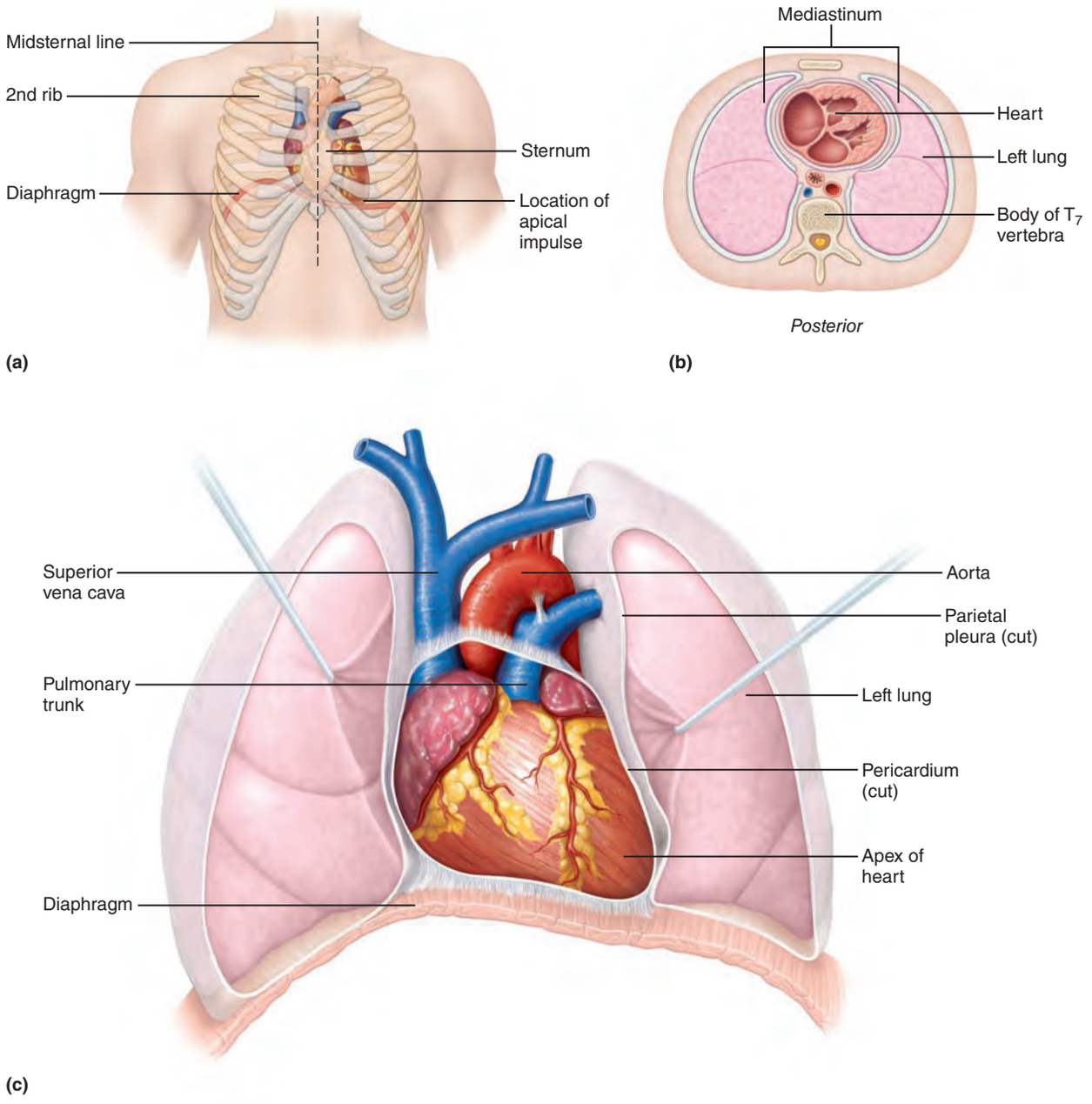


Figure 18.2 Location of the heart in the mediastinum. (a) Relationship of the heart to the sternum, ribs, and diaphragm in a person who is lying down (the heart is slightly inferior to this position in a standing person). **(b)** Inferior view of a cross section showing the heart's relative position in the thorax. **(c)** Relationship of the heart and great vessels to the lungs.

Coverings of the Heart

The heart is enclosed in a double-walled sac called the **pericardium** (per″ĭ-kar′de-um; *peri* = around, *cardi* = heart) **(Figure 18.3)**. The loosely fitting superficial part of this sac is the **fibrous pericardium**. This tough, dense connective tissue layer (1) protects the heart, (2) anchors it to surrounding structures, and (3) prevents overfilling of the heart with blood.

Deep to the fibrous pericardium is the **serous pericardium**, a thin, slippery, two-layer serous membrane that forms a closed sac around the heart (see Figure 1.10, p. 19). Its **parietal layer** lines the internal surface of the fibrous pericardium. At the superior margin of the heart, the parietal layer attaches to the large arteries exiting the heart, and then turns inferiorly and continues over the external heart surface as the **visceral layer**, also called the **epicardium** ("upon the heart"), which is an integral part of the heart wall.

Between the parietal and visceral layers is the slitlike **pericardial cavity**, which contains a film of serous fluid. The serous membranes, lubricated by the fluid, glide smoothly past one another, allowing the mobile heart to work in a relatively friction-free environment.

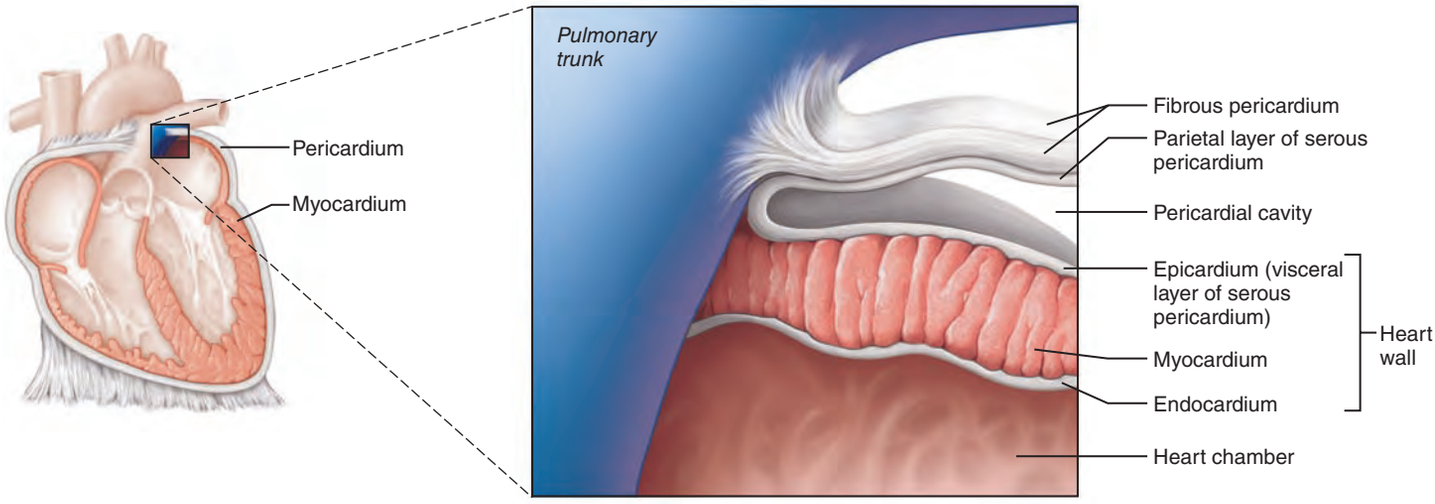


Figure 18.3 **The pericardial layers and layers of the heart wall.**

Homeostatic Imbalance 18.1

Pericarditis, inflammation of the pericardium, roughens the serous membrane surfaces. Consequently, as the beating heart rubs against its pericardial sac, it creates a creaking sound (*pericardial friction rub*) that can be heard with a stethoscope. Pericarditis is characterized by pain deep to the sternum. Over time, it may lead to adhesions in which the visceral and parietal pericardia stick together and impede heart activity.

In severe cases, large amounts of inflammatory fluid seep into the pericardial cavity. This excess fluid compresses the heart and limits its ability to pump blood, a condition called *cardiac tamponade* (tam″pŏ-nād′), literally, "heart plug." Physicians treat cardiac tamponade by inserting a syringe into the pericardial cavity and draining off the excess fluid. ✚

Layers of the Heart Wall

The heart wall, richly supplied with blood vessels, is composed of three layers: the epicardium, myocardium, and endocardium (Figure 18.3).

As we have noted, the superficial **epicardium** is the visceral layer of the serous pericardium. It is often infiltrated with fat, especially in older people.

The middle layer, the **myocardium** ("muscle heart"), is composed mainly of cardiac muscle and forms the bulk of the heart. This is the layer that contracts. In the myocardium, the branching cardiac muscle cells are tethered to one another by crisscrossing connective tissue fibers and arranged in spiral or circular *bundles* **(Figure 18.4)**. These interlacing bundles effectively link all parts of the heart together.

The connective tissue fibers form a dense network, the fibrous **cardiac skeleton**, that reinforces the myocardium internally and anchors the cardiac muscle fibers. This network of collagen and elastic fibers is thicker in some areas than others. For example, it constructs ropelike rings that provide additional support where the great vessels issue from the heart and around

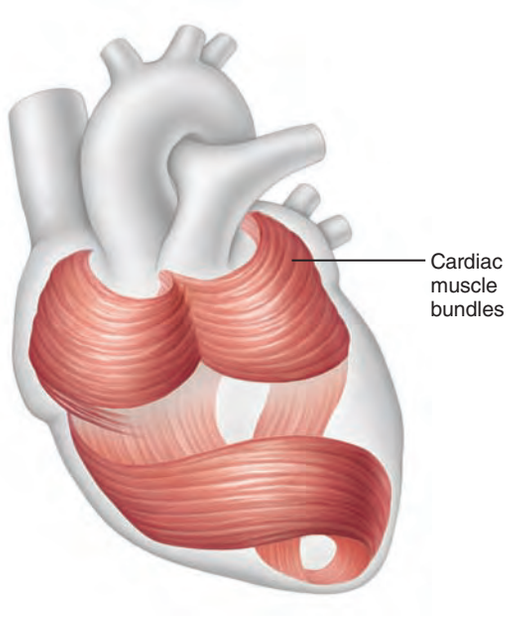


Figure 18.4 **The circular and spiral arrangement of cardiac muscle bundles in the myocardium of the heart.**

the heart valves (see Figure 18.6a, p. 666). Without this support, the vessels and valves might eventually become stretched because of the continuous stress of blood pulsing through them. Additionally, because connective tissue is not electrically excitable, the cardiac skeleton limits the spread of action potentials to specific pathways in the heart.

The third layer of the heart wall, the **endocardium** ("inside the heart"), is a glistening white sheet of endothelium (squamous epithelium) resting on a thin connective tissue layer. Located on the inner myocardial surface, it lines the heart chambers and covers the fibrous skeleton of the valves. The endocardium is continuous with the endothelial linings of the blood vessels leaving and entering the heart.

Check Your Understanding

1. The heart is in the mediastinum. Just what is the mediastinum?
2. From inside to outside, list the layers of the heart wall and the coverings of the heart.
3. What is the purpose of the serous fluid inside the pericardial cavity?

For answers, see Appendix H.

Chambers and Associated Great Vessels

✓ Describe the structure and functions of the four heart chambers. Name each chamber and provide the name and general route of its associated great vessel(s).

The heart has four chambers **(Figure 18.5e)**—two superior **atria** (a′tre-ah) and two inferior **ventricles** (ven′trĭ-klz). The internal partition that divides the heart longitudinally is called the **interatrial septum** where it separates the atria, and the **interventricular septum** where it separates the ventricles. The right ventricle forms most of the anterior surface of the heart. The left ventricle dominates the inferoposterior aspect of the heart and forms the heart apex.

Two grooves visible on the heart surface indicate the boundaries of its four chambers and carry the blood vessels supplying the myocardium. The **coronary sulcus** (Figure 18.5b, d), or *atrioventricular groove*, encircles the junction of the atria and ventricles like a crown (*corona* = crown). The **anterior interventricular sulcus**, cradling the anterior interventricular artery, marks the anterior position of the septum separating the right and left ventricles. It continues as the **posterior interventricular sulcus**, which provides a similar landmark on the heart's posteroinferior surface.

Atria: The Receiving Chambers

Except for small, wrinkled, protruding appendages called **auricles** (or′ĭ-klz; *auricle* = little ear), which increase the atrial volume somewhat, the right and left atria are remarkably free of distinguishing surface features. Internally, the right atrium has two basic parts (Figure 18.5c): a smooth-walled posterior part and an anterior portion in which bundles of muscle tissue form ridges in the walls. These muscle bundles are called **pectinate muscles** because they look like the teeth of a comb (*pectin* = comb). The posterior and anterior regions of the right atrium are separated by a C-shaped ridge called the *crista terminalis* ("terminal crest").

In contrast, the left atrium is mostly smooth and pectinate muscles are found only in the auricle. The interatrial septum bears a shallow depression, the **fossa ovalis** (o-vă′lis), that marks the spot where an opening, the *foramen ovale*, existed in the fetal heart (Figure 18.5c, e).

Functionally, the atria are receiving chambers for blood returning to the heart from the circulation (*atrium* = entryway). The atria are relatively small, thin-walled chambers because they need to contract only minimally to push blood "downstairs" into the ventricles. As a rule, they contribute little to the propulsive pumping activity of the heart.

Blood enters the *right atrium* via three veins (Figure 18.5c–e):

- The **superior vena cava** returns blood from body regions superior to the diaphragm.
- The **inferior vena cava** returns blood from body areas below the diaphragm.
- The **coronary sinus** collects blood draining from the myocardium.

Four **pulmonary veins** enter the *left atrium*, which makes up most of the heart's base. These veins, which transport blood from the lungs back to the heart, are best seen in a posterior view (Figure 18.5d).

Ventricles: The Discharging Chambers

Together the ventricles (*ventr* = underside) make up most of the volume of the heart. As already mentioned, the right ventricle forms most of the heart's anterior surface and the left ventricle dominates its posteroinferior surface. Irregular ridges of muscle called **trabeculae carneae** (trah-bek′u-le kar′ne-e; "crossbars of flesh") mark the internal walls of the ventricular chambers. Still other muscle bundles, the conelike **papillary muscles**, which play a role in valve function, project into the ventricular cavity (Figure 18.5e).

The ventricles are the discharging chambers, the actual pumps of the heart. Their walls are much more massive than the atrial walls, reflecting the difference in function between the atria and ventricles (Figure 18.5e and f). When the ventricles contract, they propel blood out of the heart into the circulation. The right ventricle pumps blood into the **pulmonary trunk**, which routes the blood to the lungs where gas exchange occurs. The left ventricle ejects blood into the **aorta** (a-or′tah), the largest artery in the body.

Heart Valves

✓ Name the heart valves and describe their location, function, and mechanism of operation.

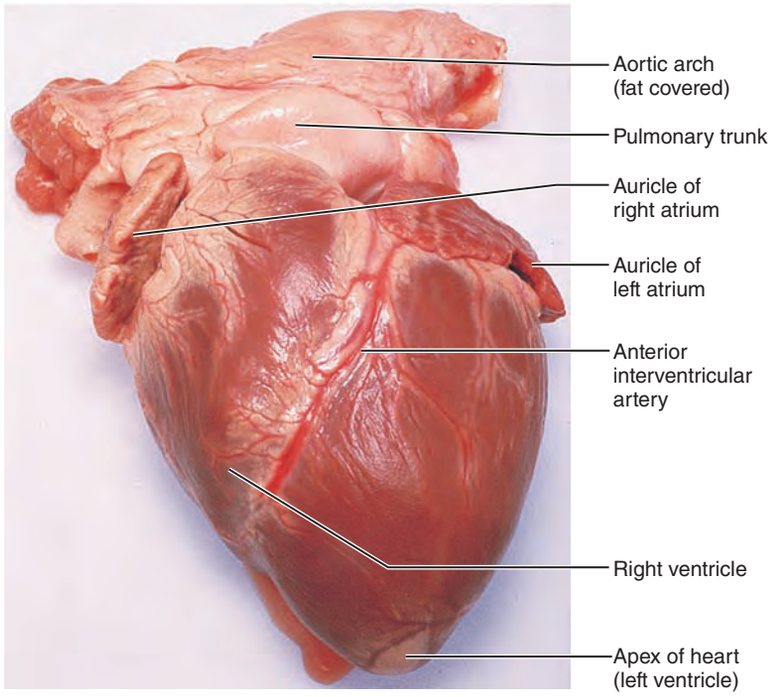
Blood flows through the heart in one direction: from atria to ventricles and out the great arteries leaving the superior aspect of the heart. Four valves enforce this one-way traffic (Figure 18.5e and **Figure 18.6**). They open and close in response to differences in blood pressure on their two sides.

Atrioventricular (AV) Valves

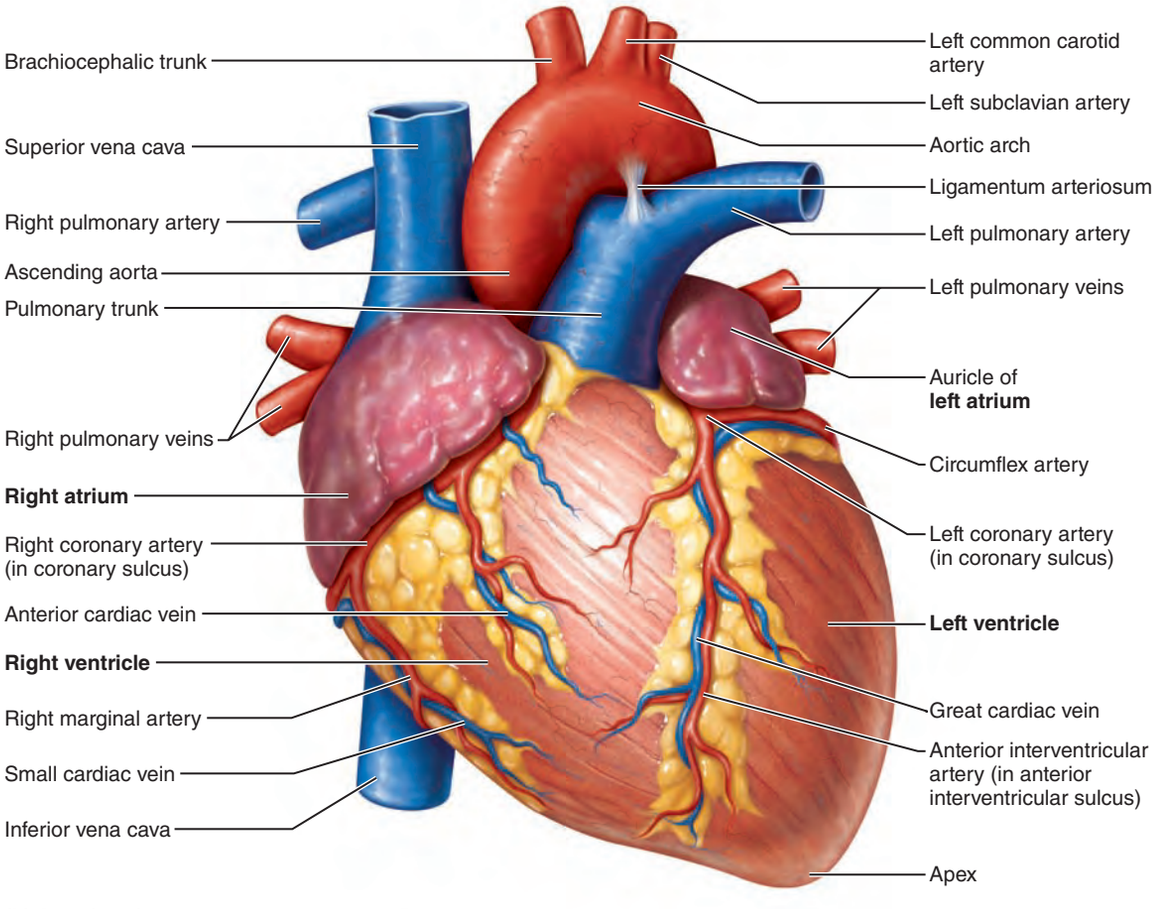
The two **atrioventricular (AV) valves**, one located at each atrial-ventricular junction, prevent backflow into the atria when the ventricles contract.

- The right AV valve, the **tricuspid valve** (tri-kus′pid), has three flexible cusps (flaps of endocardium reinforced by connective tissue cores).
- The left AV valve, with two cusps, is called the **mitral valve** (mi′tral) because it resembles the two-sided bishop's miter or hat. It is sometimes called the *bicuspid valve*.

(Text continues on p. 667.)

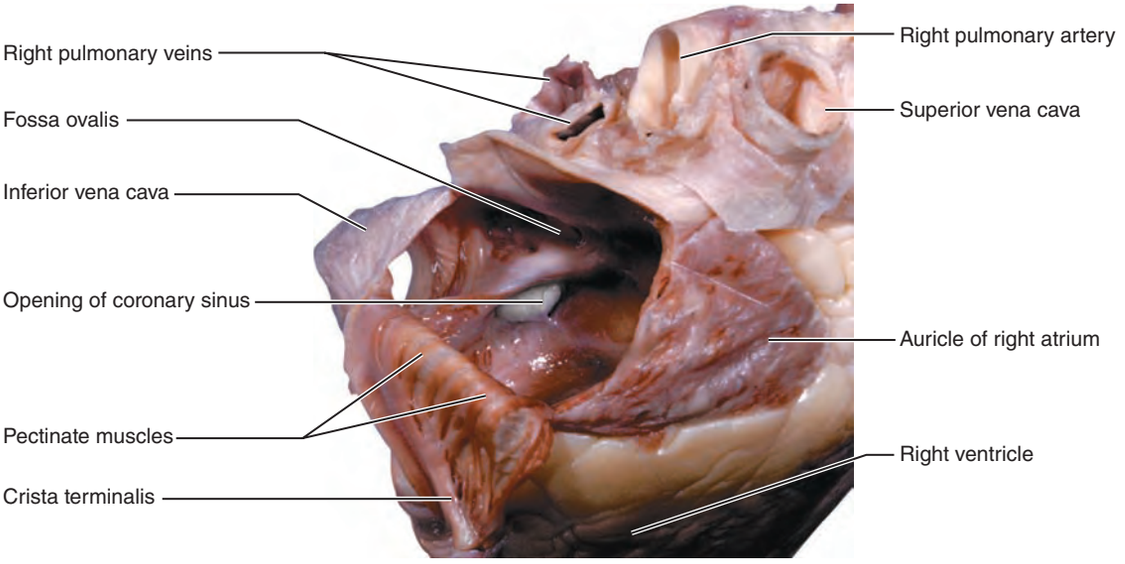


(a) Anterior aspect (pericardium removed)

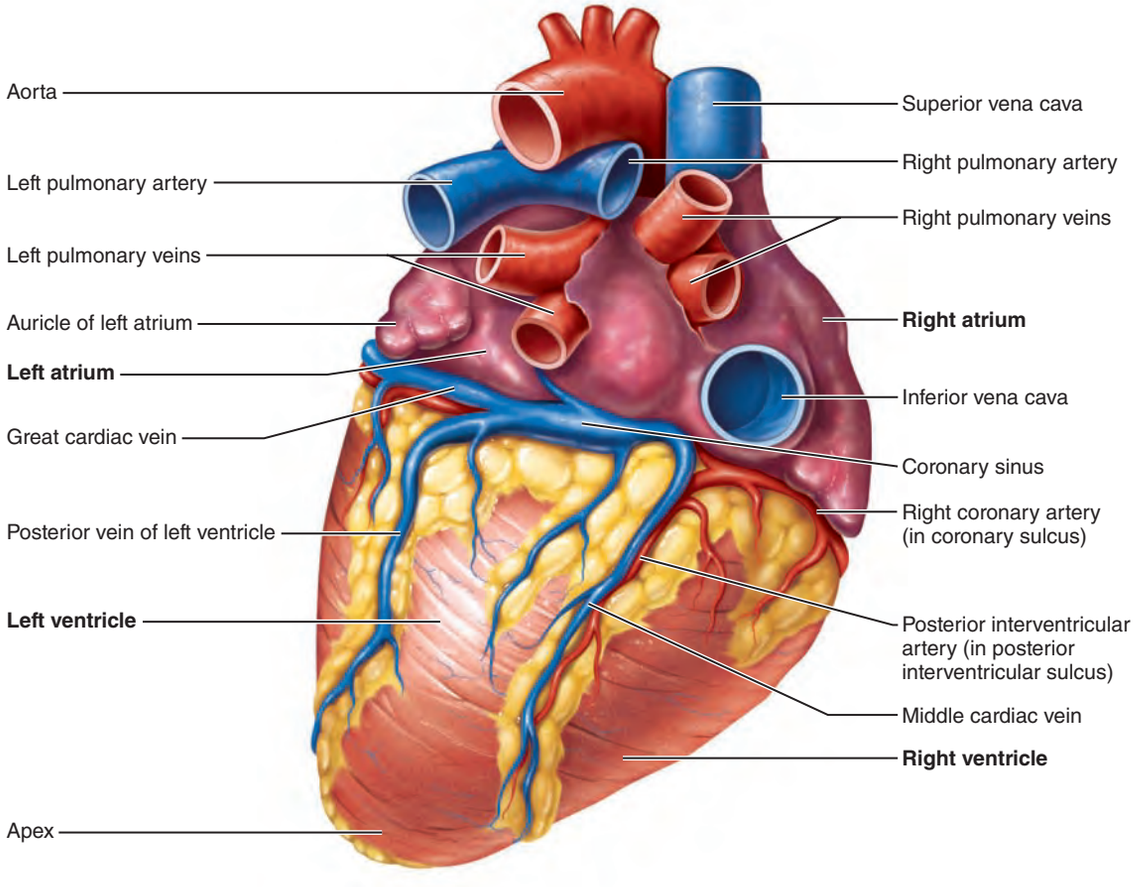


(b) Anterior view

Figure 18.5 Gross anatomy of the heart. In diagrammatic views, vessels transporting oxygen-rich blood are red; those transporting oxygen-poor blood are blue.

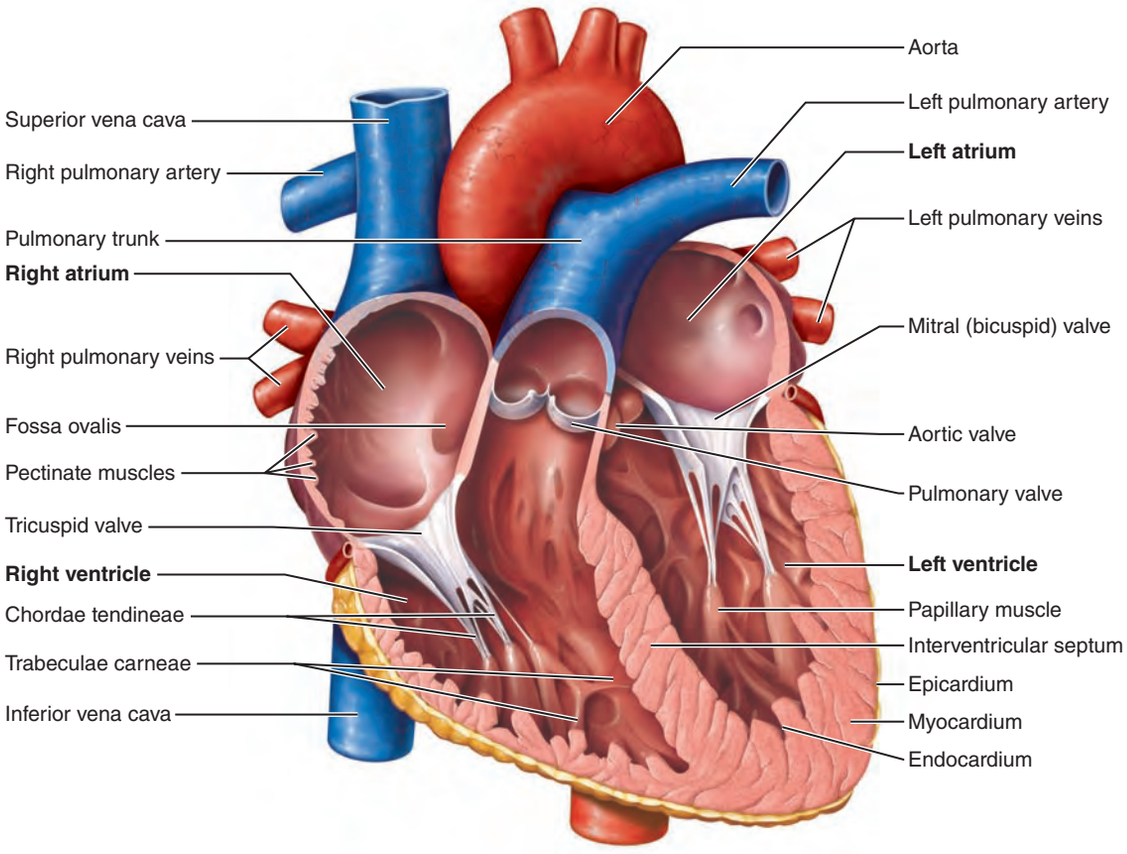


(c) Right anterior view of the internal aspect of the right atrium

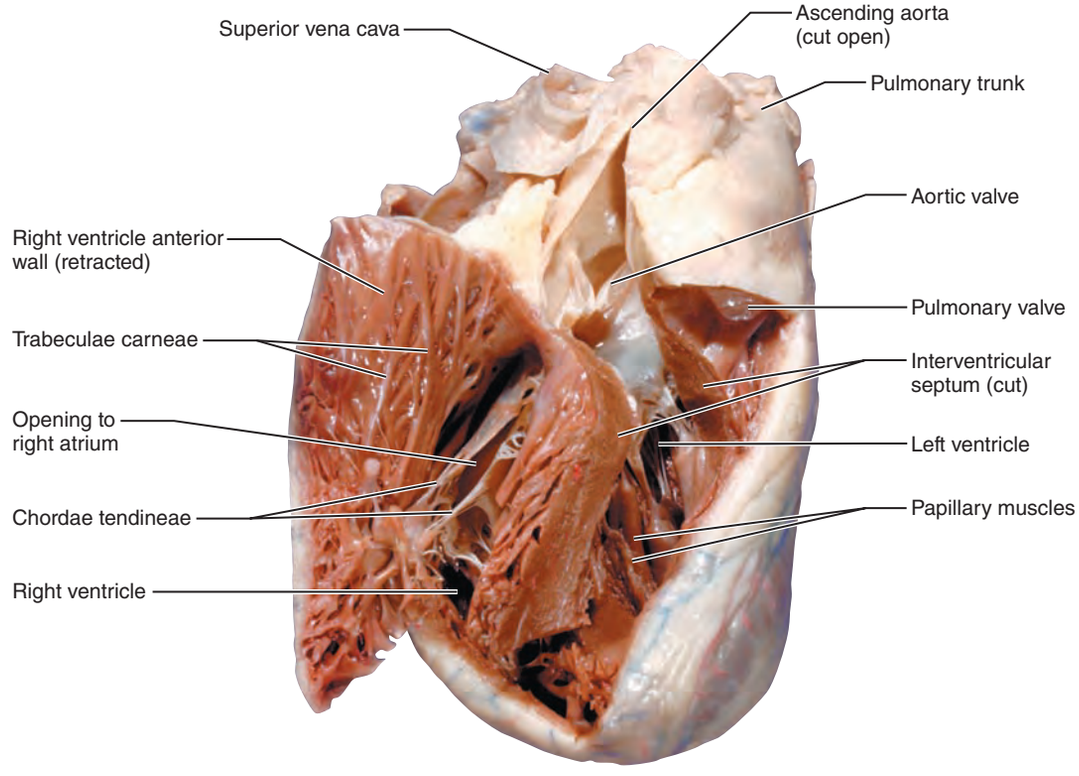


(d) Posterior surface view

Figure 18.5 *(continued)* **Gross anatomy of the heart.** In (c), the anterior wall of the atrium has been opened and folded inferiorly.

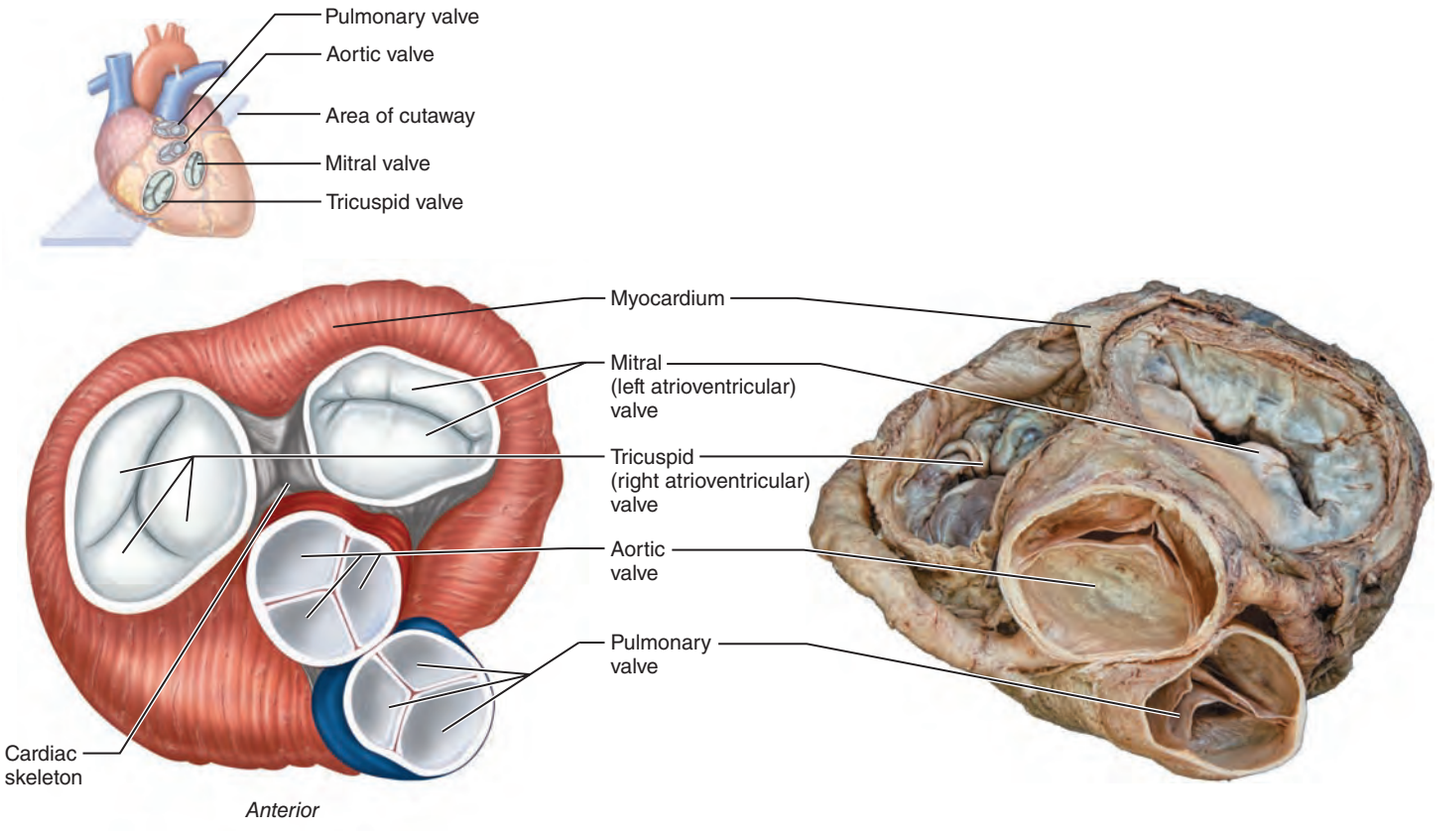


(e) Frontal section



(f) Photograph; view similar to (e)

Figure 18.5 *(continued)*



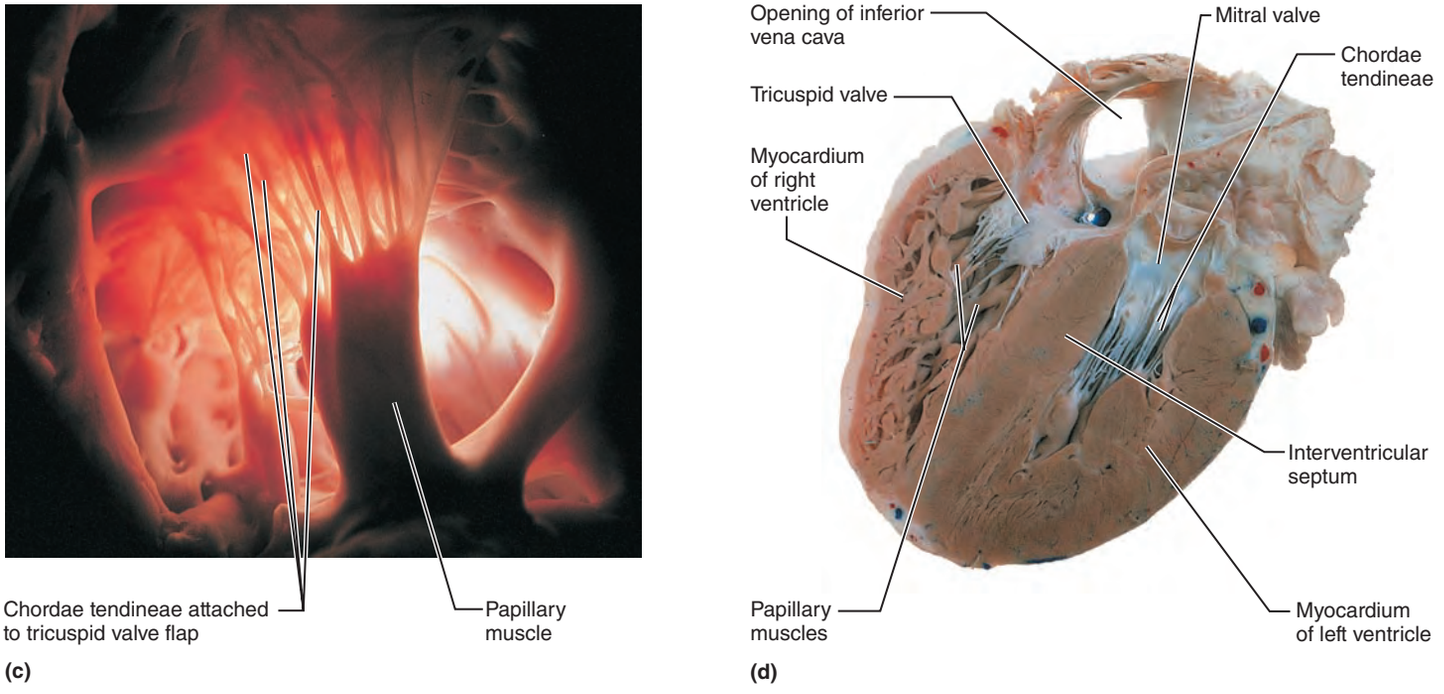


Figure 18.6 Heart valves. (a) Superior view of the two sets of heart valves (atria removed). The paired atrioventricular valves are located between atria and ventricles; the two semilunar valves are located at the junction of the ventricles and the arteries issuing from them. **(b)** Photograph of the heart valves, superior view. **(c)** Photograph of the tricuspid valve. This bottom-to-top view shows the valve as seen from the right ventricle. **(d)** Coronal section of the heart. (For related images, see *A Brief Atlas of the Human Body*, Figures 58 and 60.)

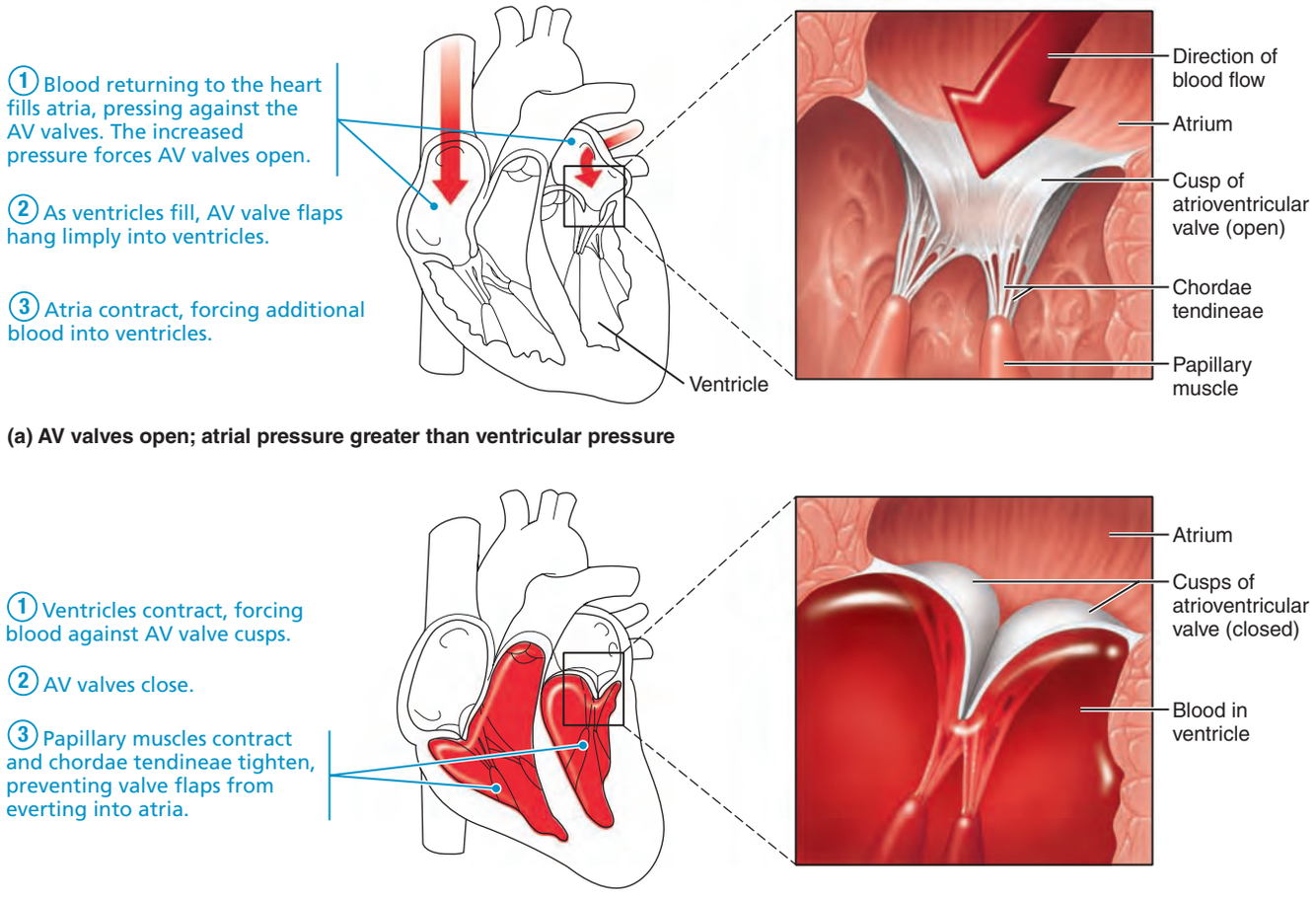


Figure 18.7 The atrioventricular (AV) valves.

Attached to each AV valve flap are tiny white collagen cords called **chordae tendineae** (kor′de ten″dĭ′ne-e; "tendinous cords"), "heart strings" which anchor the cusps to the papillary muscles protruding from the ventricular walls (Figure 18.6c, d).

When the heart is completely relaxed, the AV valve flaps hang limply into the ventricular chambers below and blood flows into the atria and then through the open AV valves into the ventricles **(Figure 18.7a)**. When the ventricles contract, compressing the blood in their chambers, the intraventricular pressure rises, forcing the blood superiorly against the valve flaps. As a result, the flap edges meet, closing the valve (Figure 18.7b).

The chordae tendineae and the papillary muscles serve as guy-wires that anchor the valve flaps in their *closed* position. If the cusps were not anchored, they would be blown upward (everted) into the atria, in the same way an umbrella is blown inside out by a gusty wind. The papillary muscles contract with the other ventricular musculature so that they take up the slack on the chordae tendineae as the full force of ventricular contraction hurls the blood against the AV valve flaps.

Semilunar (SL) Valves

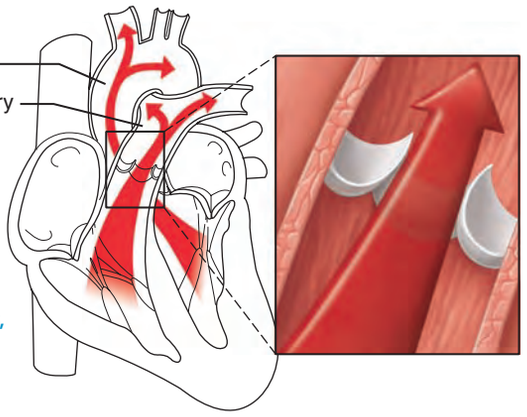
The **aortic** and **pulmonary (semilunar, SL) valves** guard the bases of the large arteries issuing from the ventricles (aorta and pulmonary trunk, respectively) and prevent backflow into the associated ventricles. Each SL valve is fashioned from three pocketlike cusps, each shaped roughly like a crescent moon (*semilunar* = half-moon).

Like the AV valves, the SL valves open and close in response to differences in pressure. When the ventricles contract and intraventricular pressure rises above the pressure in the aorta and pulmonary trunk, the SL valves are forced open and their cusps flatten against the arterial walls as blood rushes past them **(Figure 18.8a)**. When the ventricles relax, and the blood (no longer propelled forward by ventricular contraction) flows backward toward the heart, it fills the cusps and closes the valves (Figure 18.8b).

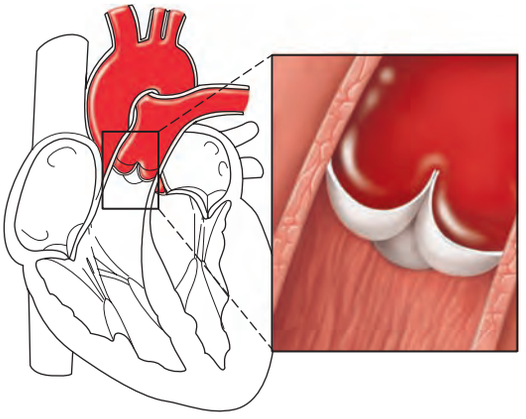
We complete the valve story by noting what seems to be an important omission—there are no valves guarding the entrances of the venae cavae and pulmonary veins into the right and left atria, respectively. Small amounts of blood *do* spurt back into these vessels during atrial contraction, but backflow is minimal because of the inertia of the blood and because as it contracts, the atrial myocardium compresses (and collapses) these venous entry points.

Homeostatic Imbalance 18.2

Heart valves are simple devices, and the heart—like any mechanical pump—can function with "leaky" valves as long as the impairment is not too great. However, severe valve deformities can seriously hamper cardiac function.



(a) Semilunar valves open



(b) Semilunar valves closed

Figure 18.8 The semilunar (SL) valves.

An *incompetent*, or *insufficient*, *valve* forces the heart to repump the same blood over and over because the valve does not close properly and blood backflows. In valvular *stenosis* ("narrowing"), the valve flaps become stiff (typically due to calcium salt deposits or scar tissue that forms following endocarditis) and constrict the opening. This stiffness compels the heart to contract more forcibly than normal. Both conditions increase the heart's workload and may weaken the heart severely over time.

The faulty valve (most often the mitral valve) can be replaced with a mechanical valve, a pig or cow heart valve chemically treated to prevent rejection, or cryopreserved valves from human cadavers. Heart valves tissue-engineered from a patient's own cells grown on a biodegradable scaffold are being developed. ✚

☑ Check Your Understanding

4. What is the function of the papillary muscles and chordae tendineae?

For answers, see Appendix H.

Pathway of Blood Through the Heart

✓ Trace the pathway of blood through the heart.

Having covered the basic anatomy of the heart, we can now follow the path that blood takes through the heart and its associated circuits. *Focus on Blood Flow Through the Heart* **(Figure 18.9)** follows a single "spurt" of blood as it passes through all four chambers of the heart and both blood circuits in its ever-repeating journey.

As you work your way through this figure, keep in mind that the left side of the heart is the *systemic circuit pump* and the right side of the heart is the *pulmonary circuit pump*. Notice how unique the pulmonary circuit is. Elsewhere in the body, veins carry relatively oxygen-poor blood to the heart, and arteries transport oxygen-rich blood from the heart. Exactly the opposite oxygenation conditions exist in veins and arteries of the pulmonary circuit.

Equal volumes of blood are pumped to the pulmonary and systemic circuits at any moment, but the two ventricles have very unequal workloads. The pulmonary circuit, served by the right ventricle, is a short, low-pressure circulation. In contrast, the systemic circuit, associated with the left ventricle, takes a long pathway through the entire body and encounters about five times as much friction, or resistance to blood flow.

This functional difference is revealed in the anatomy of the two ventricles (Figure 18.5e and **Figure 18.10**). The walls of the left ventricle are three times thicker than those of the right ventricle, and its cavity is nearly circular. The right ventricular cavity is flattened into a crescent shape that partially encloses the left ventricle, much the way a hand might loosely grasp a clenched fist. Consequently, the left ventricle can generate much more pressure than the right and is a far more powerful pump.

Coronary Circulation

✓ Name the major branches and describe the distribution of the coronary arteries.

Although the heart is more or less continuously filled with blood, this blood provides little nourishment to heart tissue. (The myocardium is too thick to make diffusion a practical means of delivering nutrients.) How, then, does the heart get nourishment? The **coronary circulation**, the functional blood supply of the heart, is the shortest circulation in the body.

Coronary Arteries

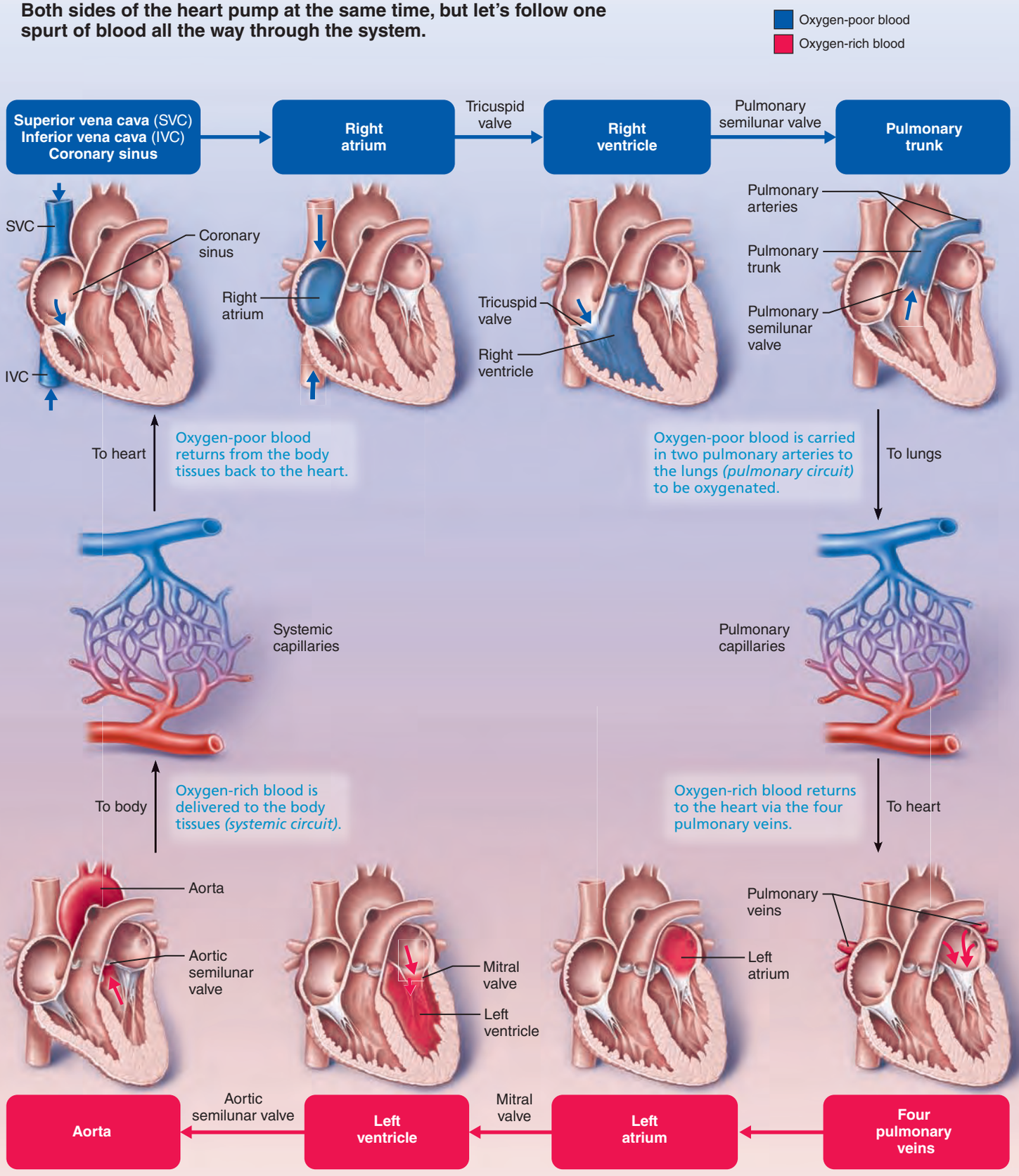
The *left* and *right coronary arteries* both arise from the base of the aorta and encircle the heart in the coronary sulcus. They provide the arterial supply of the coronary circulation **(Figure 18.11a)**.

The **left coronary artery** runs toward the left side of the heart and then divides into two major branches:

- The **anterior interventricular artery** (also known clinically as the *left anterior descending artery*) follows the anterior interventricular sulcus and supplies blood to the interventricular septum and anterior walls of both ventricles.
- The **circumflex artery** supplies the left atrium and the posterior walls of the left ventricle.

Figure 18.9 The heart is a double pump, each side supplying its own circuit.

Both sides of the heart pump at the same time, but let's follow one spurt of blood all the way through the system.



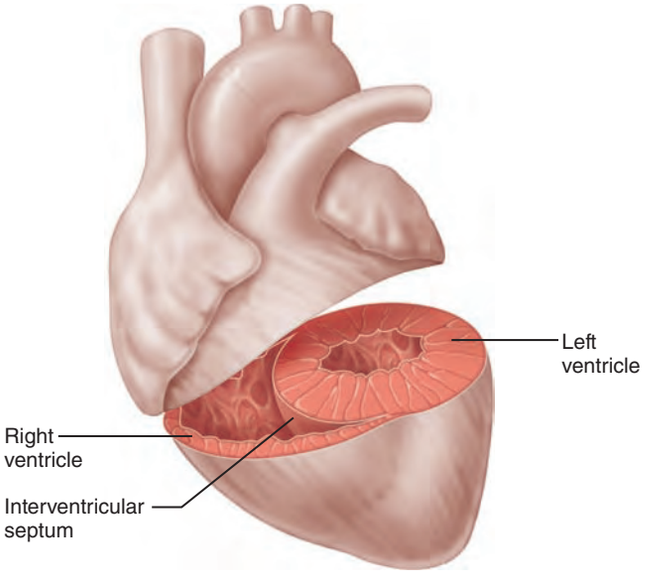


Figure 18.10 Anatomical differences between the right and left ventricles. The left ventricle has a thicker wall and its cavity is basically circular. The right ventricle cavity is crescent shaped and wraps around the left ventricle.

The **right coronary artery** courses to the right side of the heart, where it also gives rise to two branches:

- The **right marginal artery** serves the myocardium of the lateral right side of the heart.
- The **posterior interventricular artery** runs to the heart apex and supplies the posterior ventricular walls. Near the apex of the heart, this artery merges (anastomoses) with the anterior interventricular artery.

Together the branches of the right coronary artery supply the right atrium and nearly all the right ventricle.

The arterial supply of the heart varies considerably. For example, in 15% of people, the left coronary artery gives rise to *both* interventricular arteries. In about 4% of people, a single coronary artery supplies the whole heart. Additionally, there may be both right and left marginal arteries. There are many anastomoses (junctions) among the coronary arterial branches. These fusing networks provide additional (*collateral*) routes for blood delivery to the heart muscle, but are not robust enough to supply adequate nutrition when a coronary artery is suddenly occluded (blocked). Complete blockage leads to tissue death and heart attack.

The coronary arteries provide an intermittent, pulsating blood flow to the myocardium. These vessels and their main branches lie in the epicardium and send branches inward to nourish the myocardium. They deliver blood when the heart is relaxed, but are fairly ineffective when the ventricles are contracting because they are compressed by the contracting myocardium. Although the heart represents only about 1/200 of the body's weight, it requires about 1/20 of the body's blood supply. As might be expected, the left ventricle receives the most plentiful blood supply.

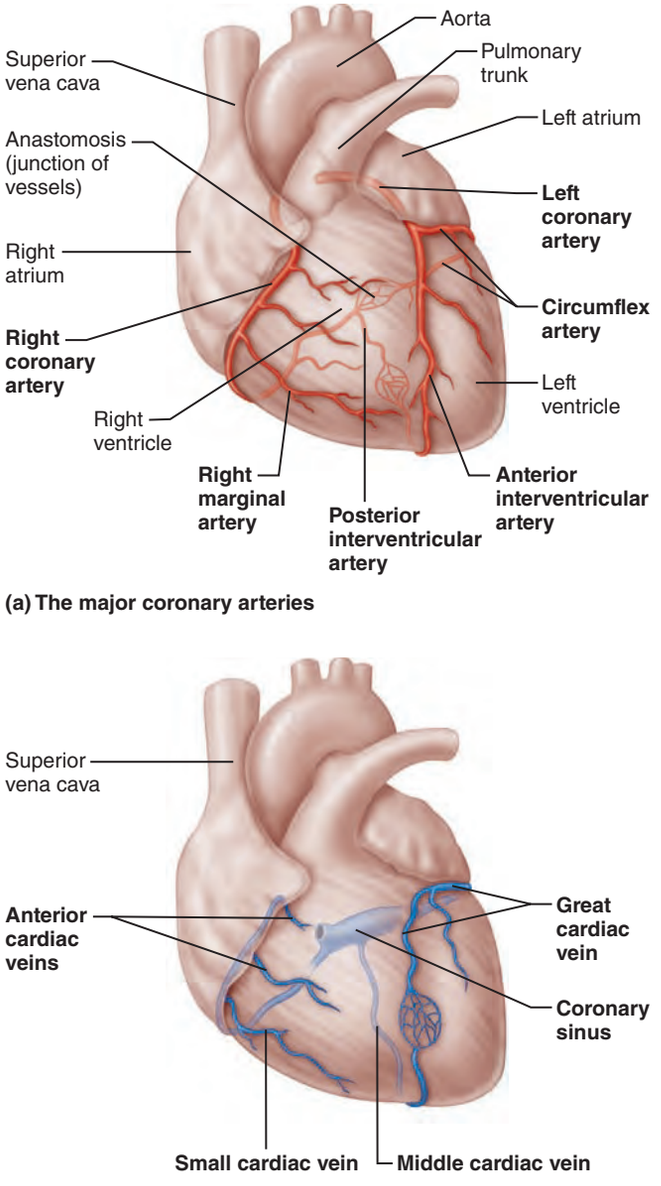


Figure 18.11 Coronary circulation. In both drawings, lighter-tinted vessels are more posterior in the heart.

Coronary Veins

After passing through the capillary beds of the myocardium, the venous blood is collected by the **cardiac veins**, whose paths roughly follow those of the coronary arteries. These veins join to form an enlarged vessel called the **coronary sinus**, which empties the blood into the right atrium. The coronary sinus is obvious on the posterior aspect of the heart (Figure 18.11b).

The sinus has three large tributaries: the **great cardiac vein** in the anterior interventricular sulcus; the **middle cardiac vein** in the posterior interventricular sulcus; and the **small cardiac vein**, running along the heart's right inferior margin. Additionally, several **anterior cardiac veins** empty directly into the right atrium anteriorly.

Homeostatic Imbalance 18.3

Blockage of the coronary arterial circulation can be serious and sometimes fatal. **Angina pectoris** (an-ji′nah pek′tor-is; "choked chest") is thoracic pain caused by a fleeting deficiency in blood delivery to the myocardium. It may result from stress-induced spasms of the coronary arteries or from increased physical demands on the heart. The myocardial cells are weakened by the temporary lack of oxygen but do not die.

Prolonged coronary blockage is far more serious because it can lead to a **myocardial infarction (MI)**, commonly called a **heart attack**, in which cells *do* die. Since adult cardiac muscle is essentially amitotic, most of the dead tissue is replaced with noncontractile scar tissue. Whether or not a person survives a myocardial infarction depends on the extent and location of the damage. Damage to the left ventricle—the systemic pump—is most serious. ✚

Check Your Understanding

5. Which side of the heart acts as the pulmonary pump? The systemic pump?
6. Which of the following statements are true? (a) The left ventricle wall is thicker than the right ventricle wall. (b) The left ventricle pumps blood at a higher pressure than the right ventricle. (c) The left ventricle pumps more blood with each beat than the right ventricle. Explain.
7. Name the two main branches of the right coronary artery.

For answers, see Appendix H.

Cardiac Muscle Fibers

- ✓ Describe the structural and functional properties of cardiac muscle, and explain how it differs from skeletal muscle.
- ✓ Briefly describe the events of cardiac muscle cell contraction.

Although similar to skeletal muscle, cardiac muscle displays some special anatomical features that reflect its unique blood-pumping role.

Microscopic Anatomy

Like skeletal muscle, **cardiac muscle** is striated and contracts by the sliding filament mechanism. However, in contrast to the long, cylindrical, multinucleate skeletal muscle fibers, cardiac cells are short, fat, branched, and interconnected. Each fiber contains one or at most two large, pale, *centrally* located nuclei **(Figure 18.12a)**. The intercellular spaces are filled with a loose connective tissue matrix (the *endomysium*) containing numerous capillaries. This delicate matrix is connected to the fibrous cardiac skeleton, which acts both as a tendon and as an insertion, giving the cardiac cells something to pull or exert their force against.

Skeletal muscle fibers are independent of one another both structurally and functionally. By contrast, the plasma membranes of adjacent cardiac cells interlock like the ribs of two sheets of corrugated cardboard at dark-staining junctions called **intercalated discs** (in-ter′kah-la″ted; *intercala* = insert) (Figure 18.12). Intercalated discs contain anchoring *desmosomes* and *gap junctions* (cell junctions discussed in Chapter 3). The desmosomes prevent adjacent cells from separating during contraction, and the gap junctions allow ions to pass from cell to cell, transmitting current across the entire heart. Because gap junctions electrically couple cardiac cells, the myocardium *behaves* as a single coordinated unit, or **functional syncytium** (sin-sit′e-um; *syn* = together, *cyt* = cell).

Large mitochondria account for 25–35% of the volume of cardiac cells (compared with only 2% in skeletal muscle), a characteristic that makes cardiac cells highly resistant to fatigue. Most of the remaining volume is occupied by myofibrils composed of fairly typical sarcomeres. The sarcomeres have Z discs, A bands, and I bands that reflect the arrangement of the thick (myosin) and thin (actin) filaments composing them. However, in contrast to skeletal muscle, the myofibrils of cardiac muscle cells vary greatly in diameter and branch extensively, accommodating the abundant mitochondria between them. This difference produces a banding pattern less dramatic than that seen in skeletal muscle.

The system for delivering Ca^{2+} is less elaborate in cardiac muscle cells. The T tubules are wider and fewer than in skeletal muscle and they enter the cells once per sarcomere at the Z discs. (Recall that T tubules are invaginations of the sarcolemma. In skeletal muscle, the T tubules invaginate twice per sarcomere, at the A band–I band junctions.) The cardiac sarcoplasmic reticulum is simpler and lacks the large terminal cisterns seen in skeletal muscle. Consequently, cardiac muscle fibers do not have *triads*.

Mechanism and Events of Contraction

Although both heart muscle and skeletal muscle are contractile tissues, they have three fundamental differences:

- **Means of stimulation.** Each skeletal muscle fiber must be stimulated to contract by a nerve ending, but some cardiac muscle cells are self-excitable. These cells can initiate not only their own depolarization, but that of the rest of the heart as well, in a spontaneous and rhythmic way. We describe this property, called **automaticity**, or **autorhythmicity**, in the next section.
- **Organ versus motor unit contraction.** In skeletal muscle, impulses do not spread from cell to cell. Only muscle fibers that are individually stimulated by nerve fibers contract. Skeletal muscles usually contract with only some of the muscle's motor units activated. In contrast, in cardiac muscle, either all fibers in the heart contract as a unit or the heart doesn't contract at all. This coordinated action occurs because gap junctions electrically tie all cardiac muscle cells together into a single contractile unit. Consequently, the depolarization wave travels across the heart from cell to cell via ion passage through the gap junctions.
- **Length of absolute refractory period.** Recall that the absolute refractory period is the inexcitable period when Na^+ channels are still open or inactivated. In skeletal muscle

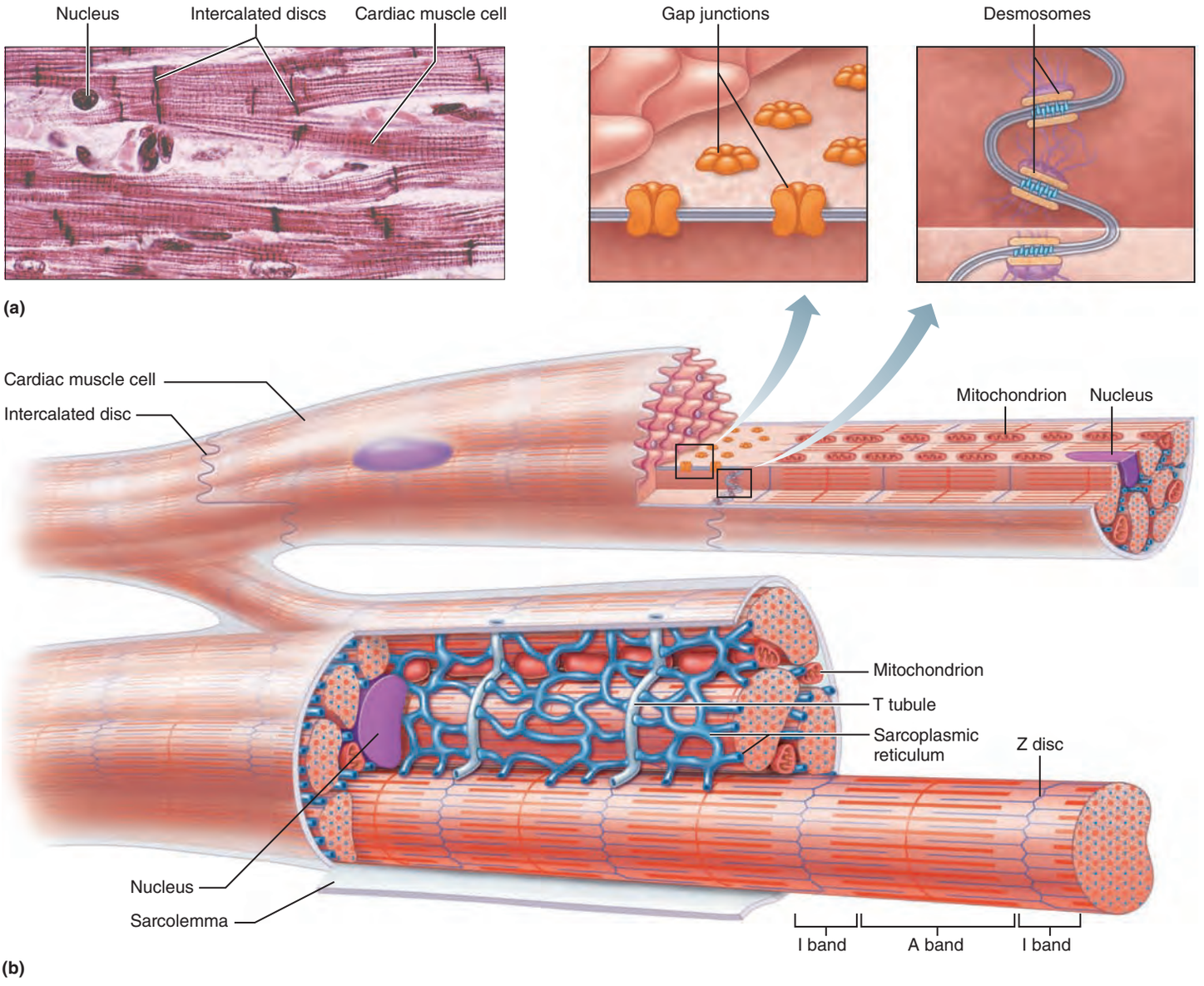
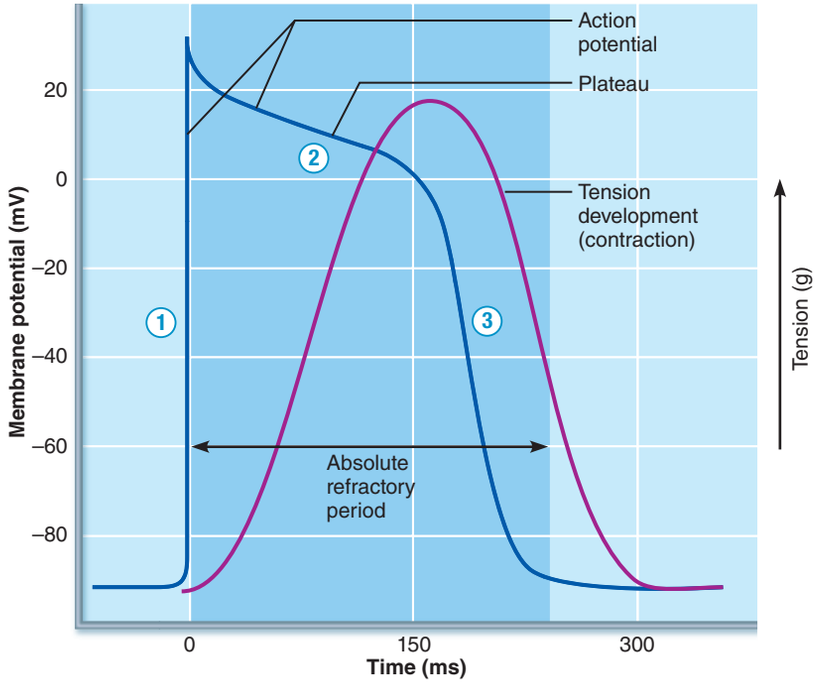


Figure 18.12 Microscopic anatomy of cardiac muscle. (a) Photomicrograph of cardiac muscle (600×). Notice that the cardiac muscle cells are short, branched, and striated. The dark-staining areas are intercalated discs, or junctions, between adjacent cells. **(b)** Components of intercalated discs and cardiac muscle fibers.

fibers, contractions last 15–100 ms with brief refractory periods of 1–2 ms. Contrast this to cardiac muscle cells, in which the absolute refractory period lasts over 200 ms, nearly as long as the contraction **(Figure 18.13)**. The long cardiac refractory period normally prevents tetanic contractions, which would stop the heart's pumping action.

Having probed the major differences between cardiac and skeletal muscle tissues, let's now look at their similarities. As with skeletal muscle, cardiac muscle contraction is triggered by action potentials that sweep across cell membranes. About 1% of cardiac fibers are *autorhythmic* ("self-rhythmic"), having the special ability to depolarize spontaneously and thus pace the heart. The bulk of heart muscle, however, is composed of *contractile muscle* fibers responsible for the heart's pumping activity. In these contractile muscle cells, the sequence of events leading to contraction is similar to that in skeletal muscle fibers:

1. Depolarization opens a few **fast voltage-gated Na^+ channels** in the sarcolemma, allowing extracellular Na^+ to enter. This influx initiates a positive feedback cycle that causes the rising phase of the action potential (and reversal of the membrane potential from −90 mV to nearly +30 mV; Figure 18.13 (1)). The period of Na^+ influx is very brief, because the sodium channels quickly inactivate and the Na^+ influx stops.



1 **Depolarization** is due to Na^+ influx through fast voltage-gated Na^+ channels. A positive feedback cycle rapidly opens many Na^+ channels, reversing the membrane potential. Channel inactivation ends this phase.

2 **Plateau phase** is due to Ca^{2+} influx through slow Ca^{2+} channels. This keeps the cell depolarized because few K^+ channels are open.

3 **Repolarization** is due to Ca^{2+} channels inactivating and K^+ channels opening. This allows K^+ efflux, which brings the membrane potential back to its resting voltage.

Figure 18.13 The action potential of contractile cardiac muscle cells. Relationship between the action potential, period of contraction, and absolute refractory period in a single ventricular cell.

2. Transmission of the depolarization wave down the T tubules (ultimately) causes the sarcoplasmic reticulum (SR) to release Ca^{2+} into the sarcoplasm.
3. Excitation-contraction coupling occurs as Ca^{2+} provides the signal (via troponin binding) for cross bridge activation and couples the depolarization wave to the sliding of the myofilaments.

These three steps are common to both skeletal and cardiac muscle cells (see Figure 9.11), but the two muscle types differ in how the SR is stimulated to release Ca^{2+}. Let's take a look.

Some 10–20% of the Ca^{2+} needed for the calcium pulse that triggers contraction enters the cardiac cells from the extracellular space. Once inside, it stimulates the SR to release the other 80% of the Ca^{2+} needed. Ca^{2+} is barred from entering nonstimulated cardiac fibers, but when Na^+-dependent membrane depolarization occurs, the voltage change also opens channels that allow Ca^{2+} to enter from the extracellular space. These channels are called **slow Ca^{2+} channels** because their opening is delayed a bit. The local influxes of Ca^{2+} through these channels trigger opening of nearby Ca^{2+}-sensitive channels in the SR tubules, which liberates bursts of Ca^{2+} ("calcium sparks") that dramatically increase the intracellular Ca^{2+} concentration.

Although Na^+ channels have inactivated and repolarization has begun by this point, the calcium surge across the sarcolemma prolongs the depolarization potential briefly, producing a **plateau** in the action potential tracing (Figure 18.13 2). At the same time, few K^+ channels are open, which also prolongs the plateau and prevents rapid repolarization. As long as Ca^{2+} is entering, the cells continue to contract. Notice in Figure 18.13 that muscle tension develops during the plateau, and peaks just after the plateau ends.

Notice also that the action potential and contractile phase lasts much longer in cardiac muscle than in skeletal muscle. In skeletal muscle, the action potential typically lasts 1–2 ms and the contraction (for a single stimulus) 15–100 ms. In cardiac muscle, the action potential lasts 200 ms or more (because of the plateau), and tension development persists for 200 ms or more, providing the sustained contraction needed to eject blood from the heart.

After about 200 ms, the slope of the action potential tracing falls rapidly (Figure 18.13 3). This repolarization results from inactivation of Ca^{2+} channels and opening of voltage-gated K^+ channels, which allows a rapid loss of potassium from the cell that restores the resting membrane potential. During repolarization, Ca^{2+} is pumped back into the SR and the extracellular space.

Energy Requirements

Cardiac muscle has more mitochondria than skeletal muscle does, reflecting its greater dependence on oxygen for its energy metabolism. The heart relies almost exclusively on aerobic respiration. As a result, cardiac muscle cannot operate effectively for long without oxygen. This is in contrast to skeletal muscle, which can contract for prolonged periods by carrying out anaerobic respiration, and then restore its reserves of oxygen and fuel using excess postexercise oxygen consumption (EPOC).

Both types of muscle tissue use multiple fuel molecules, including glucose and fatty acids. But cardiac muscle is much more adaptable and readily switches metabolic pathways to use whatever nutrients are available, including lactic acid generated

by skeletal muscle activity. Consequently, the real danger of an inadequate blood supply to the myocardium is not lack of nutrients, but lack of oxygen.

Homeostatic Imbalance 18.4

When a region of heart muscle is oxygen-starved (as during a heart attack), the ischemic cells (ischemic = blood deprived) begin to metabolize anaerobically, producing lactic acid. The rising H^+ level that results raises intracellular Ca^{2+}, damaging mitochondria and hindering cardiac cells' ability to produce ATP. High levels of intracellular H^+ and Ca^{2+} also cause the gap junctions (which are usually open) to close, isolating the damaged cells and forcing action potentials to find alternate routes to the cardiac cells beyond them. This may lead to fatal arrhythmias. ✚

Check Your Understanding

8. For each of the following, state whether it applies to skeletal muscle, cardiac muscle, or both: (a) refractory period is almost as long as the contraction; (b) source of Ca^{2+} for contraction is *only* SR; (c) AP exhibits a plateau phase; (d) has troponin; (e) has triads.
9. Cardiac muscle cannot go into tetany. Why?

For answers, see Appendix H.

Heart Physiology

Electrical Events

- ✓ Name the components of the conduction system of the heart, and trace the conduction pathway.
- ✓ Draw a diagram of a normal electrocardiogram tracing. Name the individual waves and intervals, and indicate what each represents.
- ✓ Name some abnormalities that can be detected on an ECG tracing.

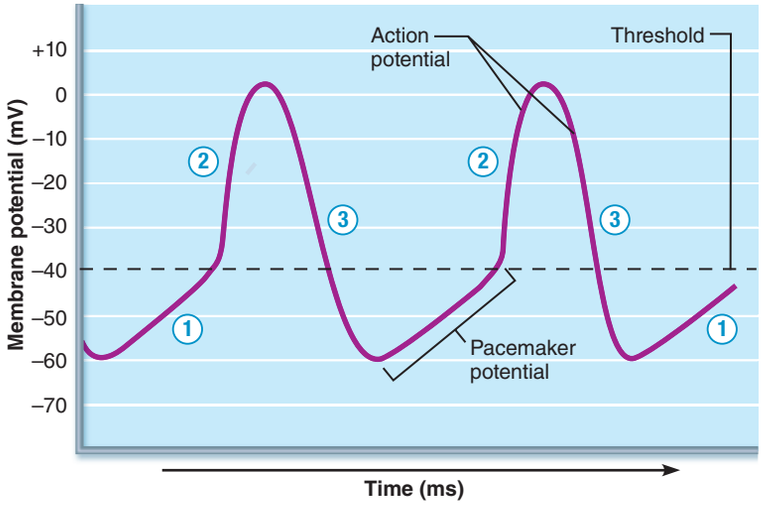
The ability of cardiac muscle to depolarize and contract is intrinsic. In other words, it is a property of heart muscle and does not depend on the nervous system. Even if all nerve connections to the heart are severed, the heart continues to beat rhythmically, as demonstrated by transplanted hearts. Nevertheless, the healthy heart is amply supplied with autonomic nerve fibers that can alter its basic rhythm.

Setting the Basic Rhythm: The Intrinsic Conduction System

The independent, but coordinated, activity of the heart is a function of (1) the presence of gap junctions, and (2) the activity of the heart's "in-house" conduction system. The **intrinsic cardiac conduction system** consists of noncontractile cardiac cells specialized to initiate and distribute impulses throughout the heart, so that it depolarizes and contracts in an orderly, sequential manner. Let's look at how this system works.

Action Potential Initiation by Pacemaker Cells Unstimulated contractile cells of the heart (and neurons and skeletal muscle fibers) maintain a stable resting membrane potential. Unlike them, the **cardiac pacemaker cells** (or *autorhythmic cells*) making up the intrinsic conduction system have an *unstable resting potential* that continuously depolarizes, drifting slowly toward threshold. These spontaneously changing membrane potentials, called **pacemaker potentials** or **prepotentials**, initiate the action potentials that spread throughout the heart to trigger its rhythmic contractions. Let's look at the three parts of an action potential in pacemaker cells as shown in **Figure 18.14**.

(1) **Pacemaker potential.** The pacemaker potential is due to the special properties of the ion channels in the sarcolemma. In these cells, hyperpolarization at the end of an action potential both closes K^+ channels and opens slow Na^+ channels. The Na^+ influx alters the balance between K^+ loss and Na^+ entry, and the membrane interior becomes less and less negative (more positive).

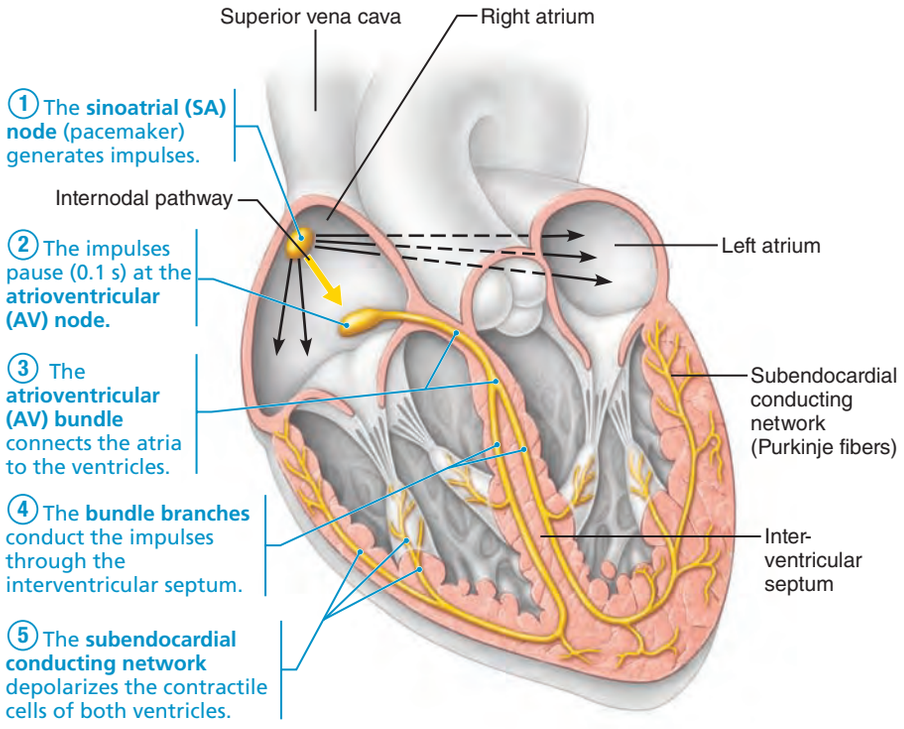


(1) **Pacemaker potential** This slow depolarization is due to both opening of Na^+ channels and closing of K^+ channels. Notice that the membrane potential is never a flat line.

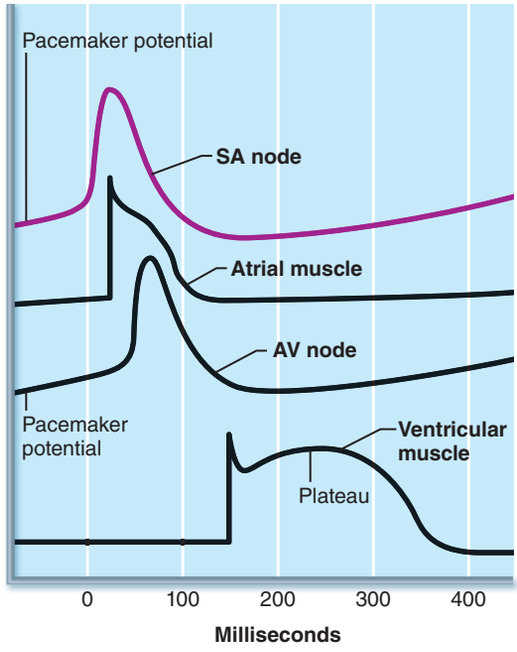
(2) **Depolarization** The action potential begins when the pacemaker potential reaches threshold. Depolarization is due to Ca^{2+} influx through Ca^{2+} channels.

(3) **Repolarization** is due to Ca^{2+} channels inactivating and K^+ channels opening. This allows K^+ efflux, which brings the membrane potential back to its most negative voltage.

Figure 18.14 **Pacemaker and action potentials of pacemaker cells in the heart.**



(a) Anatomy of the intrinsic conduction system showing the sequence of electrical excitation



(b) Comparison of action potential shape at various locations

Figure 18.15 **Intrinsic cardiac conduction system and action potential succession during one heartbeat.**

(2) **Depolarization.** Ultimately, at threshold (approximately −40 mV), **Ca^{2+} channels** open, allowing explosive entry of Ca^{2+} from the extracellular space. As a result, in pacemaker cells, it is the influx of Ca^{2+} (rather than Na^{+}) that produces the rising phase of the action potential and reverses the membrane potential.

(3) **Repolarization.** As in other excitable cells, the falling phase of the action potential and repolarization reflect opening of K^{+} channels and K^{+} efflux from the cell.

Once repolarization is complete, K^{+} channels close, K^{+} efflux declines, and the slow depolarization to threshold begins again.

Sequence of Excitation Cardiac pacemaker cells are found in the following areas (Figure 18.15): sinoatrial (si″no-a′tre-al) node, atrioventricular node, atrioventricular bundle, right and left bundle branches, and subendocardial conducting network (Purkinje fibers). Impulses pass across the heart in order from (1) to (5) following the yellow pathway in **Figure 18.15a**.

(1) **Sinoatrial (SA) node.** The crescent-shaped **sinoatrial node** is located in the right atrial wall, just inferior to the entrance of the superior vena cava. A minute cell mass with a mammoth job, the SA node typically generates impulses about 75 times every minute. (Its inherent rate in the absence of extrinsic neural and hormonal factors is closer to 100 times per minute.) The SA node sets the pace for the heart as a whole because no other region of the conduction system or the myocardium has a faster depolarization rate. For this reason, it is the heart's **pacemaker**, and its characteristic rhythm, called **sinus rhythm**, determines heart rate.

(2) **Atrioventricular (AV) node.** From the SA node, the depolarization wave spreads via gap junctions throughout the atria and via the *internodal pathway* to the **atrioventricular node**, located in the inferior portion of the interatrial septum immediately above the tricuspid valve. At the AV node, the impulse is delayed for about 0.1 s, allowing the atria to respond and complete their contraction before the ventricles contract. This delay reflects the smaller diameter of the fibers here and the fact that they have fewer gap junctions for current flow. Consequently, the AV node conducts impulses more slowly than other parts of the system, just as traffic slows when cars are forced to merge from four lanes into two. Once through the AV node, the signaling impulse passes rapidly through the rest of the system.

(3) **Atrioventricular (AV) bundle.** From the AV node, the impulse sweeps to the **atrioventricular bundle** (also called the **bundle of His**) in the superior part of the interventricular septum. Although the atria and ventricles abut each other, they are *not* connected by gap junctions. The AV bundle is the *only* electrical connection between them. The fibrous cardiac skeleton is nonconducting and insulates the rest of the AV junction.

4. **Right and left bundle branches.** The AV bundle persists only briefly before splitting into two pathways—the **right** and **left bundle branches**, which course along the interventricular septum toward the heart apex.
5. **Subendocardial conducting network.** Essentially long strands of barrel-shaped cells with few myofibrils, the **subendocardial conducting network**, also called **Purkinje fibers** (pur-kin′je), completes the pathway through the interventricular septum, penetrate into the heart apex, and then turn superiorly into the ventricular walls. The bundle branches excite the septal cells, but the bulk of ventricular depolarization depends on the large fibers of the conducting network and, ultimately, on cell-to-cell transmission of the impulse via gap junctions between the ventricular muscle cells. Because the left ventricle is much larger than the right, the subendocardial conducting network is more elaborate in that side of the heart.

The total time between initiation of an impulse by the SA node and depolarization of the last of the ventricular muscle cells is approximately 0.22 s (220 ms) in a healthy human heart.

Ventricular contraction almost immediately follows the ventricular depolarization wave. The wringing motion of contraction begins at the heart apex and moves toward the atria, following the direction of the excitation wave through the ventricle walls. This contraction ejects some of the contained blood *superiorly* into the large arteries leaving the ventricles.

The various cardiac pacemaker cells have different rates of spontaneous depolarization. The SA node normally drives the heart at a rate of 75 beats per minute. Without SA node input, the AV node would depolarize only about 50 times per minute. Without input from the AV node, the AV bundle and the subendocardial conducting network would depolarize only about 30 times per minute (though they conduct very rapidly). Note that these slower pacemakers cannot dominate the heart unless faster pacemakers stop functioning.

The cardiac conduction system coordinates and synchronizes heart activity. Without it, impulses would travel much more slowly—0.3 to 0.5 m/s as opposed to several meters per second in most parts of the conduction system. This slower rate would allow some muscle fibers to contract long before others, reducing pump effectiveness.

Homeostatic Imbalance 18.5

Defects in the intrinsic conduction system can cause irregular heart rhythms, or **arrhythmias** (ah-rith′me-ahz). They may also cause uncoordinated atrial and ventricular contractions, or even **fibrillation**, a condition of rapid and irregular or out-of-phase contractions in which control of heart rhythm is taken away from the SA node by rapid activity in other heart regions. The heart in fibrillation has been compared with a squirming bag of worms. Fibrillating ventricles are useless as pumps; and unless the heart is defibrillated quickly, circulation stops and brain death occurs.

Defibrillation is accomplished by electrically shocking the heart, which interrupts its chaotic twitching by depolarizing the entire myocardium. The hope is that "with the slate wiped clean" the SA node will begin to function normally and sinus rhythm will be reestablished. Implantable cardioverter defibrillators (ICDs) can continually monitor heart rhythms and slow an abnormally fast heart rate or emit an electrical shock if the heart begins to fibrillate.

A defective SA node may have several consequences. An **ectopic focus** (ek-top′ik), which is an abnormal pacemaker, may appear and take over the pacing of heart rate, or the AV node may become the pacemaker. The pace set by the AV node (**junctional rhythm**) is 40 to 60 beats per minute, slower than sinus rhythm but still adequate to maintain circulation.

Occasionally, ectopic pacemakers appear even when the SA node is operating normally. A small region of the heart becomes hyperexcitable, sometimes as a result of too much caffeine (several cups of coffee) or nicotine (excessive smoking), and generates impulses more quickly than the SA node. This leads to a *premature contraction* or **extrasystole** (ek″strah-sis′to-le) before the SA node initiates the next contraction. Then, because the heart has a longer time to fill, the next (normal) contraction is felt as a thud. As you might guess, premature *ventricular* contractions (PVCs) are most problematic.

The only route for impulse transmission from atria to ventricles is through the AV node. Thus any damage to the AV node interferes with the ability of the ventricles to receive pacing impulses, causing **heart block**. In total heart block no impulses get through and the ventricles beat at their intrinsic rate, which is too slow to maintain adequate circulation. In partial heart block, only some of the atrial impulses reach the ventricles. In both cases, artificial pacemakers are implanted to recouple the atria to the ventricles as necessary. These programmable devices speed up in response to increased physical activity just as a normal heart would, and many can send diagnostic information to the patient's doctor via telephone. ✚

Modifying the Basic Rhythm: Extrinsic Innervation of the Heart

Although the intrinsic conduction system sets the basic heart rate, fibers of the autonomic nervous system modify the march-like beat and introduce a subtle variability from one beat to the next. The sympathetic nervous system (the "accelerator") increases both the rate and the force of heartbeat. The parasympathetic activation (the "brakes") slows the heart. We explain these neural controls later—here we discuss the anatomy of the nerve supply to the heart.

The cardiac centers are located in the medulla oblongata. The **cardioacceleratory center** projects to sympathetic neurons in the T_1–T_5 level of the spinal cord. These preganglionic neurons, in turn, synapse with postganglionic neurons in the cervical and upper thoracic sympathetic trunk **(Figure 18.16)**. From there, postganglionic fibers run through the cardiac plexus to the heart where they innervate the SA and AV nodes, heart muscle, and coronary arteries.

The **cardioinhibitory center** sends impulses to the parasympathetic dorsal vagus nucleus in the medulla, which in turn sends inhibitory impulses to the heart via branches of the vagus nerves. Most parasympathetic postganglionic motor neurons lie

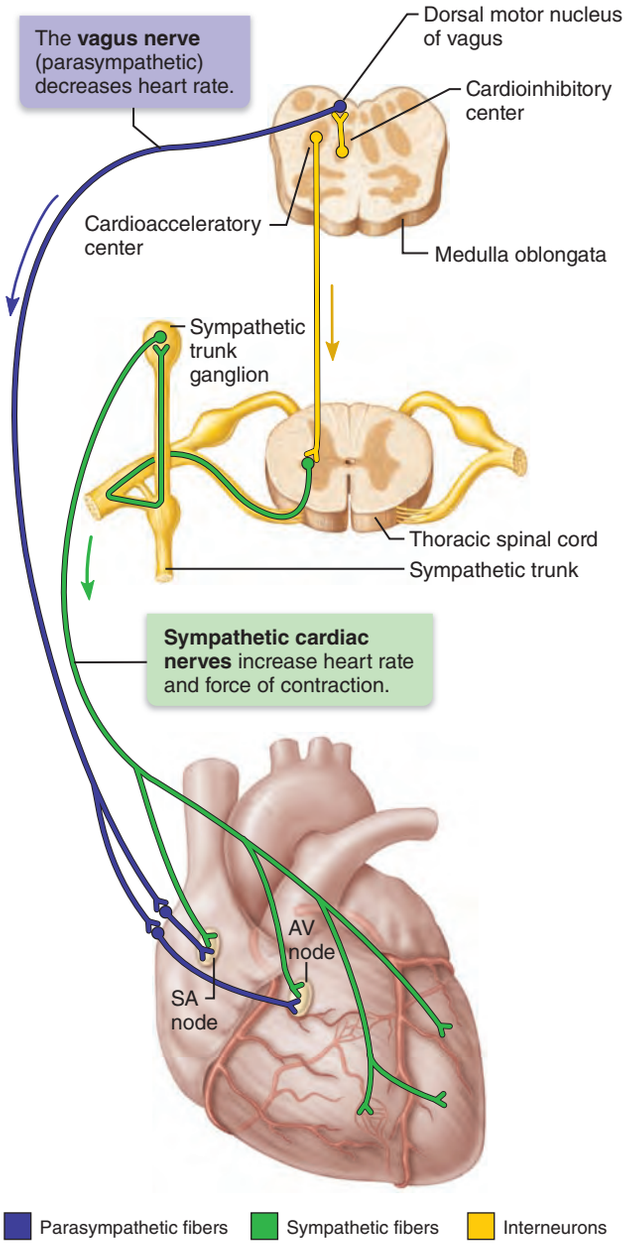


Figure 18.16 Autonomic innervation of the heart.

in ganglia in the heart wall and their fibers project most heavily to the SA and AV nodes.

Electrocardiography

The electrical currents generated in and transmitted through the heart spread throughout the body and can be detected with a device called an **electrocardiograph**. An **electrocardiogram (ECG)** is a graphic record of heart activity. An ECG is a composite of all the action potentials generated by nodal and contractile cells at a given time **(Figure 18.17)**—*not*, as sometimes assumed, a tracing of a single action potential.

To record an ECG, recording electrodes (typically 12 leads) are placed at various sites on the body surface. Three electrodes

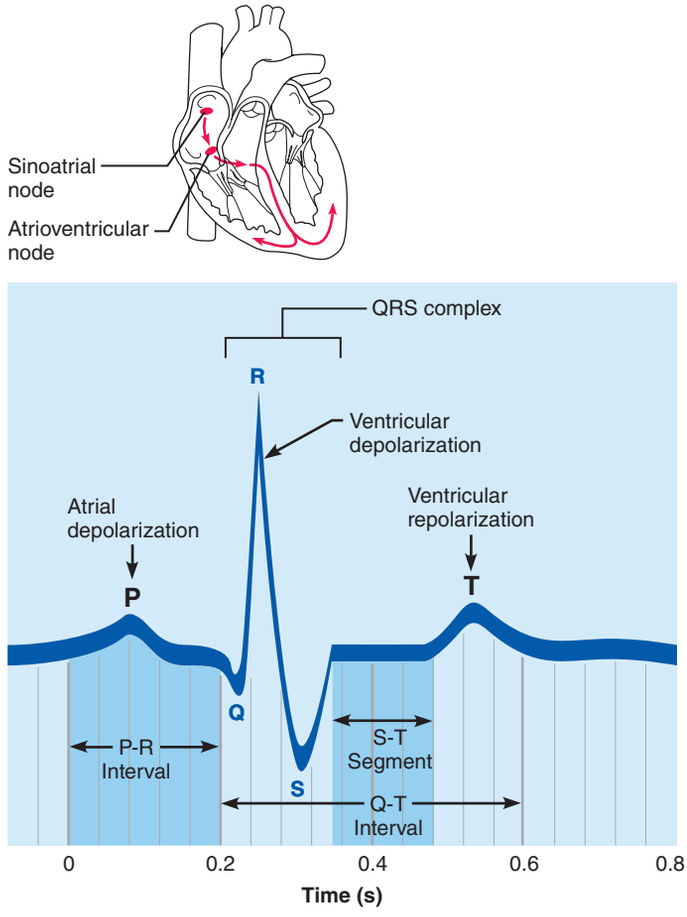


Figure 18.17 An electrocardiogram (ECG) tracing. The labels identify the three normally recognizable deflections (waves) and the important intervals.

are bipolar leads that measure the voltage difference either between the arms or between an arm and a leg, and nine are unipolar leads. Together the 12 leads provide a comprehensive picture of the heart's electrical activity.

A typical ECG has three almost immediately distinguishable waves or *deflections*: the P wave, the QRS complex, and the T wave (Figure 18.17). The first, the small **P wave**, lasts about 0.08 s and results from movement of the depolarization wave from the SA node through the atria. Approximately 0.1 s after the P wave begins, the atria contract.

The large **QRS complex** results from ventricular depolarization and precedes ventricular contraction. It has a complicated shape because the paths of the depolarization waves through the ventricular walls change continuously, producing corresponding changes in current direction. Additionally, the time required for each ventricle to depolarize depends on its size relative to the other ventricle. Average duration of the QRS complex is 0.08 s.

The **T wave,** caused by ventricular repolarization, typically lasts about 0.16 s. Repolarization is slower than depolarization, so the T wave is more spread out and has a lower amplitude (height) than the QRS complex. Because atrial repolarization takes place during the period of ventricular excitation, the wave

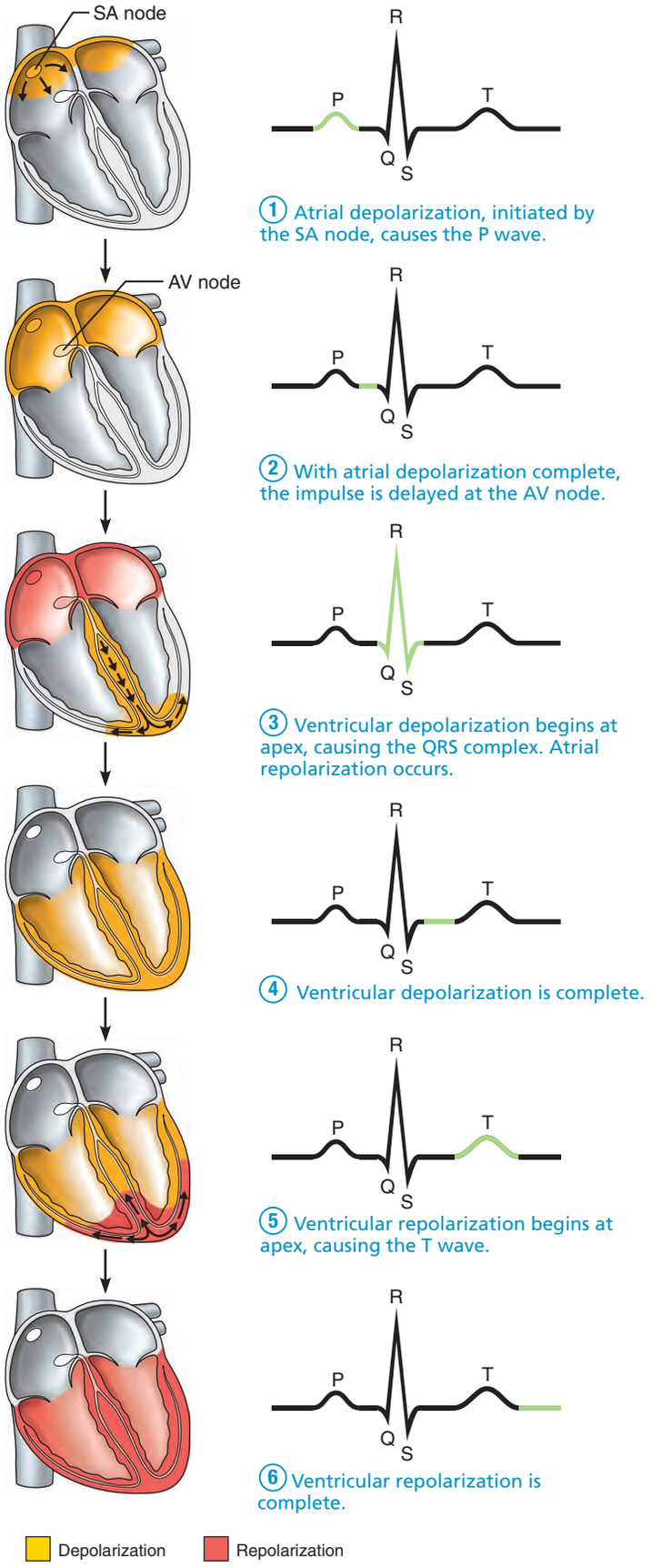


Figure 18.18 The sequence of depolarization and repolarization of the heart related to the deflection waves of an ECG tracing.

representing atrial repolarization is normally obscured by the large QRS complex being recorded at the same time.

The **P-R interval** is the time (about 0.16 s) from the beginning of atrial excitation to the beginning of ventricular excitation. If the Q wave is visible (which is often not the case), it marks the beginning of ventricular excitation, and for this reason this interval is sometimes called the **P-Q interval**. The P-R interval includes atrial depolarization (and contraction) as well as the passage of the depolarization wave through the rest of the conduction system.

During the **S-T segment** of the ECG, when the action potentials of the ventricular myocytes are in their plateau phases, the entire ventricular myocardium is depolarized. The **Q-T interval**, lasting about 0.38 s, is the period from the beginning of ventricular depolarization through ventricular repolarization.

Figure 18.18 relates the parts of an ECG to the sequence of depolarization and repolarization in the heart.

Homeostatic Imbalance 18.6

In a healthy heart, the size, duration, and timing of the deflection waves tend to be consistent. Changes in the pattern or timing of the ECG may reveal a diseased or damaged heart or problems with the heart's conduction system **(Figure 18.19)**. For example, an enlarged R wave hints of enlarged ventricles, an S-T segment that is elevated or depressed indicates cardiac ischemia, and a prolonged Q-T interval reveals a repolarization abnormality that increases the risk of ventricular arrhythmias. ✚

Check Your Understanding

10. Which part of the intrinsic conduction system directly excites ventricular myocardial cells? In which direction does the depolarization wave travel across the ventricles?
11. Describe the electrical event in the heart that occurs during each of the following: (a) the QRS wave of the ECG; (b) the T wave of the ECG; (c) the P-R interval of the ECG.

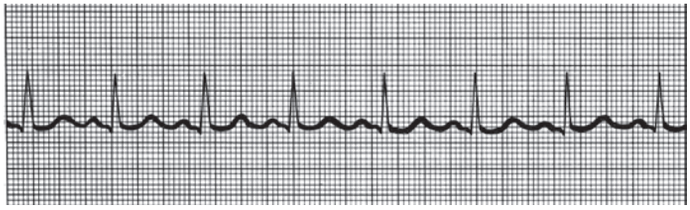
For answers, see Appendix H.

Heart Sounds

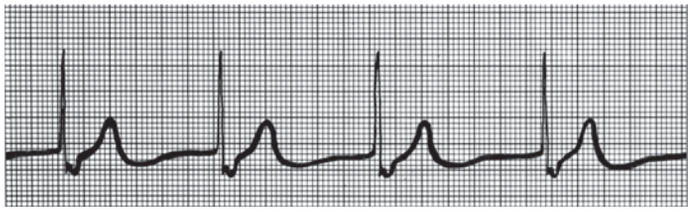
✓ Describe normal heart sounds, and explain how heart murmurs differ.

Auscultating (listening to) the thorax with a stethoscope will reveal two sounds during each heartbeat. These **heart sounds**, often described as lub-dup, are associated with the heart valves closing. (The top of Figure 18.21 shows the timing of heart sounds in the cardiac cycle.)

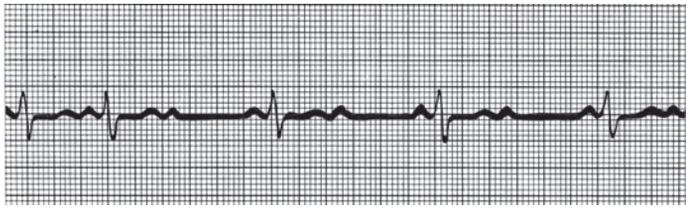
The basic rhythm of the heart sounds is lub-dup, pause, lub-dup, pause, and so on, with the pause indicating the period when the heart is relaxing. The first sound occurs as the AV valves close. It signifies the point when ventricular pressure rises above atrial pressure (the beginning of ventricular systole, discussed in the next section). The first sound tends to be louder, longer, and more resonant than the second. The second sound occurs as the SL valves snap shut at the beginning of ventricular relaxation (diastole) resulting in a short, sharp sound.



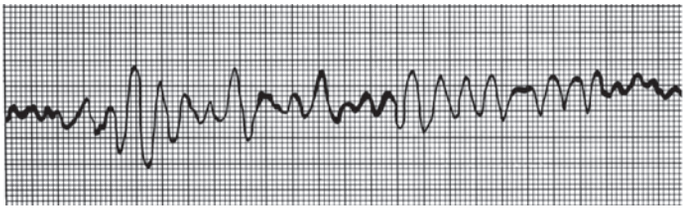
(a) Normal sinus rhythm.



(b) Junctional rhythm. The SA node is nonfunctional, P waves are absent, and the AV node paces the heart at 40–60 beats/min.



(c) Second-degree heart block. Some P waves are not conducted through the AV node; hence more P than QRS waves are seen. In this tracing, the ratio of P waves to QRS waves is mostly 2:1.



(d) Ventricular fibrillation. These chaotic, grossly irregular ECG deflections are seen in acute heart attack and electrical shock.

Figure 18.19 Normal and abnormal ECG tracings.

Because the mitral valve closes slightly before the tricuspid valve does, and the aortic SL valve generally snaps shut just before the pulmonary valve, it is possible to distinguish the individual valve sounds by auscultating four specific regions of the thorax **(Figure 18.20)**. Notice that these four points, while not directly superficial to the valves (because the sounds take oblique paths to reach the chest wall), do handily define the four corners of the normal heart. Knowing normal heart size and location is essential for recognizing an enlarged (and often diseased) heart.

Homeostatic Imbalance 18.7

Blood flows silently as long as its flow is smooth and uninterrupted. If blood strikes obstructions, however, its flow becomes turbulent and generates abnormal heart sounds, called **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.

Most often, however, murmurs indicate valve problems. An *insufficient* or *incompetent* valve fails to close completely. There is a swishing sound as blood backflows or regurgitates through the partially open valve *after* the valve has (supposedly) closed.

A *stenotic* valve fails to open completely and its narrow opening restricts blood flow *through* the valve. In a stenotic aortic valve, for instance, a high-pitched sound or click can be detected when the valve should be wide open during ventricular contraction, but is not. ✚

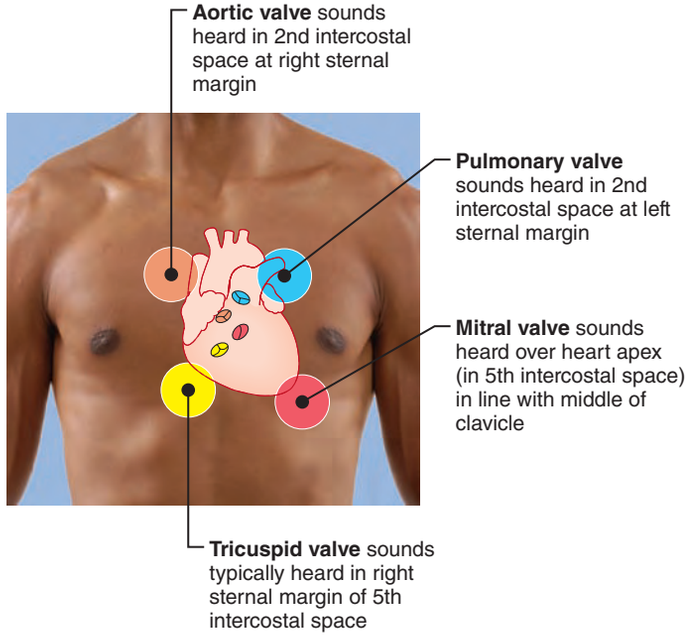


Figure 18.20 Areas of the thoracic surface where the sounds of individual valves can best be detected.

Mechanical Events: The Cardiac Cycle

✓ Describe the timing and events of the cardiac cycle.

The heart undergoes some dramatic writhing movements as it alternately contracts, forcing blood out of its chambers, and then relaxes, allowing its chambers to refill with blood. The term **systole** (sis′to-le) refers to these periods of contraction, and **diastole** (di-as′to-le) refers to those of relaxation. The **cardiac cycle** includes *all* events associated with the blood flow through the heart during one complete heartbeat—atrial systole and diastole followed by ventricular systole and diastole. These mechanical events always *follow* the electrical events seen in the ECG.

The cardiac cycle is marked by a succession of pressure and blood volume changes in the heart. Because blood circulates endlessly, we must choose an arbitrary starting point for one

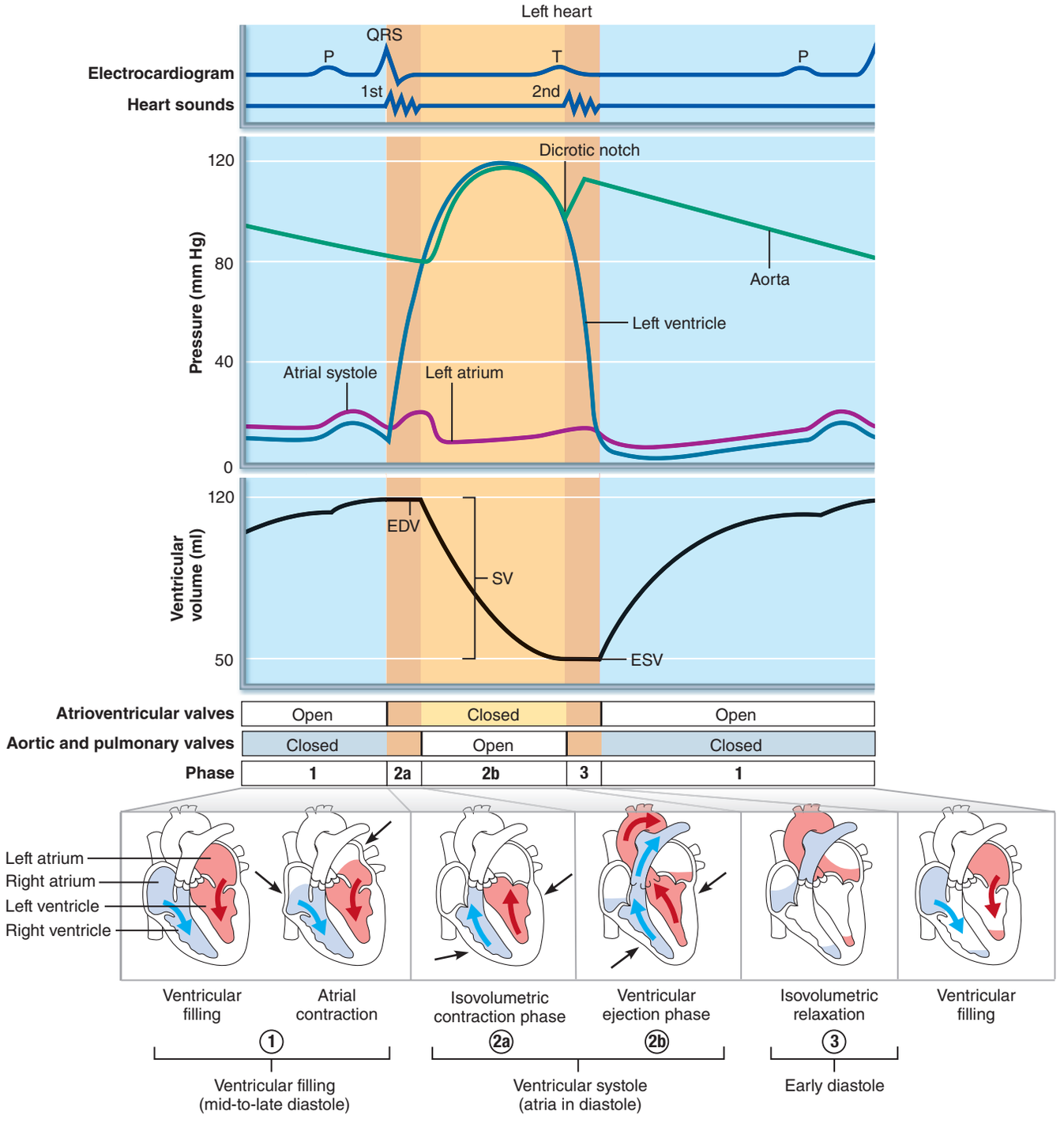


Figure 18.21 Summary of events during the cardiac cycle. An ECG tracing (*top*) correlated with graphs of pressure and volume changes (*center*) in the left side of the heart. Pressures are lower in the right side of the heart. Timing of heart sounds is also indicated. (*Bottom*) Events of phases 1 through 3 of the cardiac cycle. EDV = end diastolic volume, ESV = end systolic volume, SV = stroke volume.

18

turn of the cardiac cycle. As shown in **Figure 18.21**, which outlines what happens in the left side of the heart, we begin with the heart in total relaxation: Atria and ventricles are quiet, and it is mid-to-late diastole.

① **Ventricular filling: mid-to-late diastole.** Pressure in the heart is low, blood returning from the circulation is flowing passively through the atria and the open AV valves into the ventricles, and the aortic and pulmonary valves are closed. More than 80% of ventricular filling occurs during

this period, and the AV valve flaps begin to drift toward the closed position. (The remaining 20% is delivered to the ventricles when the atria contract toward the end of this phase.)

Now the stage is set for atrial systole. Following depolarization (P wave of ECG), the atria contract, compressing the blood in their chambers. This causes a sudden slight rise in atrial pressure, which propels residual blood out of the atria into the ventricles. At this point the ventricles are in the last part of their diastole and have the maximum volume of blood they will contain in the cycle, an amount called the *end diastolic volume* (*EDV*). Then the atria relax and the ventricles depolarize (QRS complex). Atrial diastole persists through the rest of the cycle.

② **Ventricular systole (atria in diastole).** As the atria relax, the ventricles begin contracting. Their walls close in on the blood in their chambers, and ventricular pressure rises rapidly and sharply, closing the AV valves. The split-second period when the ventricles are completely closed chambers and the blood volume in the chambers remains constant as the ventricles contract is the **isovolumetric contraction phase** (i″so-vol″u-met′rik).

Ventricular pressure continues to rise. When it finally exceeds the pressure in the large arteries issuing from the ventricles, the isovolumetric stage ends as the SL valves are forced open and blood rushes from the ventricles into the aorta and pulmonary trunk. During this ventricular ejection phase, the pressure in the aorta normally reaches about 120 mm Hg.

③ **Isovolumetric relaxation: early diastole.** During this brief phase following the T wave, the ventricles relax. Because the blood remaining in their chambers, referred to as the *end systolic volume* (*ESV*), is no longer compressed, ventricular pressure drops rapidly and blood in the aorta and pulmonary trunk flows back toward the heart, closing the SL valves. Closure of the aortic valve raises aortic pressure briefly as backflowing blood rebounds off the closed valve cusps, an event beginning at the **dicrotic notch** shown on the pressure graph. Once again the ventricles are totally closed chambers.

All during ventricular systole, the atria have been in diastole. They have been filling with blood and the intra-atrial pressure has been rising. When blood pressure on the atrial side of the AV valves exceeds that in the ventricles, the AV valves are forced open and ventricular filling, phase ①, begins again. Atrial pressure drops to its lowest point and ventricular pressure begins to rise, completing the cycle.

Assuming the average heart beats 75 times each minute, the cardiac cycle lasts about 0.8 s, with atrial systole accounting for 0.1 s and ventricular systole 0.3 s. The remaining 0.4 s is a period of total heart relaxation, the **quiescent period**.

Notice two important points: (1) Blood flow through the heart is controlled entirely by pressure changes and (2) blood flows down a pressure gradient through any available opening. The pressure changes, in turn, reflect the alternating contraction and relaxation of the myocardium and cause the heart valves to open, which keeps blood flowing in the forward direction.

The situation in the right side of the heart is essentially the same as in the left side *except* for pressure. The pulmonary circulation is a low-pressure circulation as evidenced by the much thinner myocardium of its right ventricle. So, typical systolic and diastolic pressures for the pulmonary artery are 24 and 10 mm Hg, compared to systolic and diastolic pressures of 120 and 80 mm Hg, respectively, for the aorta. However, the two sides of the heart eject the same blood volume with each heartbeat.

☑ Check Your Understanding

12. The second heart sound is associated with the closing of which valve(s)?
13. If the mitral valve were insufficient, would you expect to hear the murmur (of blood flowing through the valve that should be closed) during ventricular systole or diastole?
14. During the cardiac cycle, there are two periods when all four valves are closed. Name these two periods.

For answers, see Appendix H.

Cardiac Output (CO)

✓ Name and explain the effects of various factors regulating stroke volume and heart rate.

✓ Explain the role of the autonomic nervous system in regulating cardiac output.

Cardiac output (CO) is the amount of blood pumped out by *each* ventricle in 1 minute. It is the product of heart rate (HR) and stroke volume (SV). **Stroke volume** is defined as the volume of blood pumped out by one ventricle with each beat. In general, stroke volume correlates with the force of ventricular contraction.

Using normal resting values for heart rate (75 beats/min) and stroke volume (70 ml/beat), the average adult cardiac output can be computed:

$$\text{CO} = \text{HR} \times \text{SV} = \frac{75 \cancel{\text{beats}}}{\text{min}} \times \frac{70 \text{ ml}}{\cancel{\text{beat}}}$$
$$= \frac{5250 \text{ ml}}{\text{min}} = \frac{5.25 \text{ L}}{\text{min}}$$

The normal adult blood volume is about 5 L (a little more than 1 gallon). As you can see, the entire blood supply passes through each side of the heart once each minute.

Notice that cardiac output varies directly with SV and HR. This means that CO increases when the stroke volume increases or the heart beats faster or both, and it decreases when either or both of these factors decrease.

Cardiac output is highly variable and increases markedly in response to special demands, such as running to catch a bus. **Cardiac reserve** is the difference between resting and maximal CO. In nonathletic people, cardiac reserve is typically four to five times resting CO (20–25 L/min), but CO in trained athletes during competition may reach 35 L/min (seven times resting CO).

How does the heart accomplish such tremendous increases in output? To understand this feat, let's look at how stroke volume

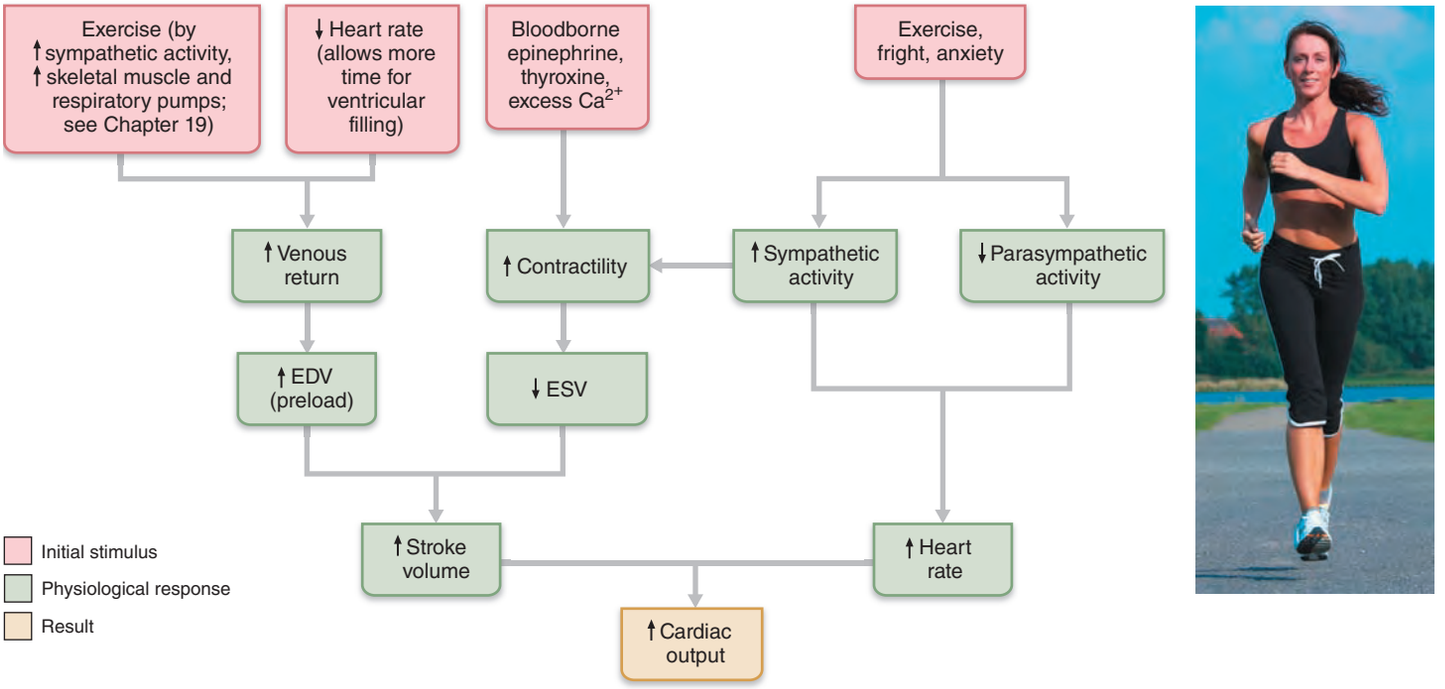


Figure 18.22 **Factors involved in determining cardiac output.**

and heart rate are regulated. As you read the next sections, refer to **Figure 18.22** for an overview of the factors that affect stroke volume and heart rate, and consequently, cardiac output.

Regulation of Stroke Volume

Mathematically, stroke volume (SV) represents the difference between **end diastolic volume (EDV)**, the amount of blood that collects in a ventricle during diastole, and **end systolic volume (ESV)**, the volume of blood remaining in a ventricle *after* it has contracted. The EDV, determined by how long ventricular diastole lasts and by venous pressure, is normally about 120 ml. (An increase in either factor *raises* EDV.) The ESV, determined by arterial blood pressure and the force of ventricular contraction, is approximately 50 ml. (The higher the arterial blood pressure, the higher the ESV.) To figure normal stroke volume, simply plug these values into this equation:

$$SV = EDV - ESV = \frac{120\ ml}{beat} - \frac{50\ ml}{beat} = \frac{70\ ml}{beat}$$

As you can see, each ventricle pumps out about 70 ml of blood with each beat, which is about 60% of the blood in its chambers.

So what is important here—how do we make sense out of this alphabet soup (SV, ESV, EDV)? Although many factors affect SV by altering EDV or ESV, the three most important are *preload, contractility*, and *afterload*. As we describe in detail next, preload affects EDV, whereas contractility and afterload affect the ESV.

Preload: Degree of Stretch of Heart Muscle The degree to which cardiac muscle cells are stretched just before they contract, which is called the **preload**, controls stroke volume. In a normal heart, the higher the preload, the higher the stroke volume will be. This relationship between preload and stroke volume is called the **Frank-Starling law of the heart**. Recall that at an *optimal length* of muscle fibers (and sarcomeres) (1) the maximum number of active cross bridge attachments is possible between actin and myosin, and (2) the force of contraction is maximal (see Figure 9.22, p. 302). Cardiac muscle, like skeletal muscle, exhibits a *length-tension relationship*.

Resting skeletal muscle fibers are kept near optimal length for developing maximal tension while resting cardiac cells are normally *shorter* than optimal length. As a result, stretching cardiac cells can produce dramatic increases in contractile force. The most important factor stretching cardiac muscle is **venous return**, the amount of blood returning to the heart and distending its ventricles.

Anything that increases the volume or speed of venous return, such as a slow heart rate or exercise, increases EDV and, consequently, SV and contraction force (Figure 18.22). A slow heartbeat allows more time for ventricular filling. Exercise speeds venous return because both increased sympathetic nervous system activity and the squeezing action of the skeletal muscles compress the veins, decreasing the volume of blood they contain and returning more blood to the heart. During vigorous exercise, SV may double as a result of increased venous return. Conversely, low venous return, such as might result from severe blood loss or an extremely rapid heart rate, decreases EDV, causing the heart to beat less forcefully and lowering SV.

Because the systemic and pulmonary circulations are in series, the intrinsic mechanism we just described ensures equal outputs of the two ventricles and proper distribution of blood volume between the two circuits. If one side of the heart suddenly

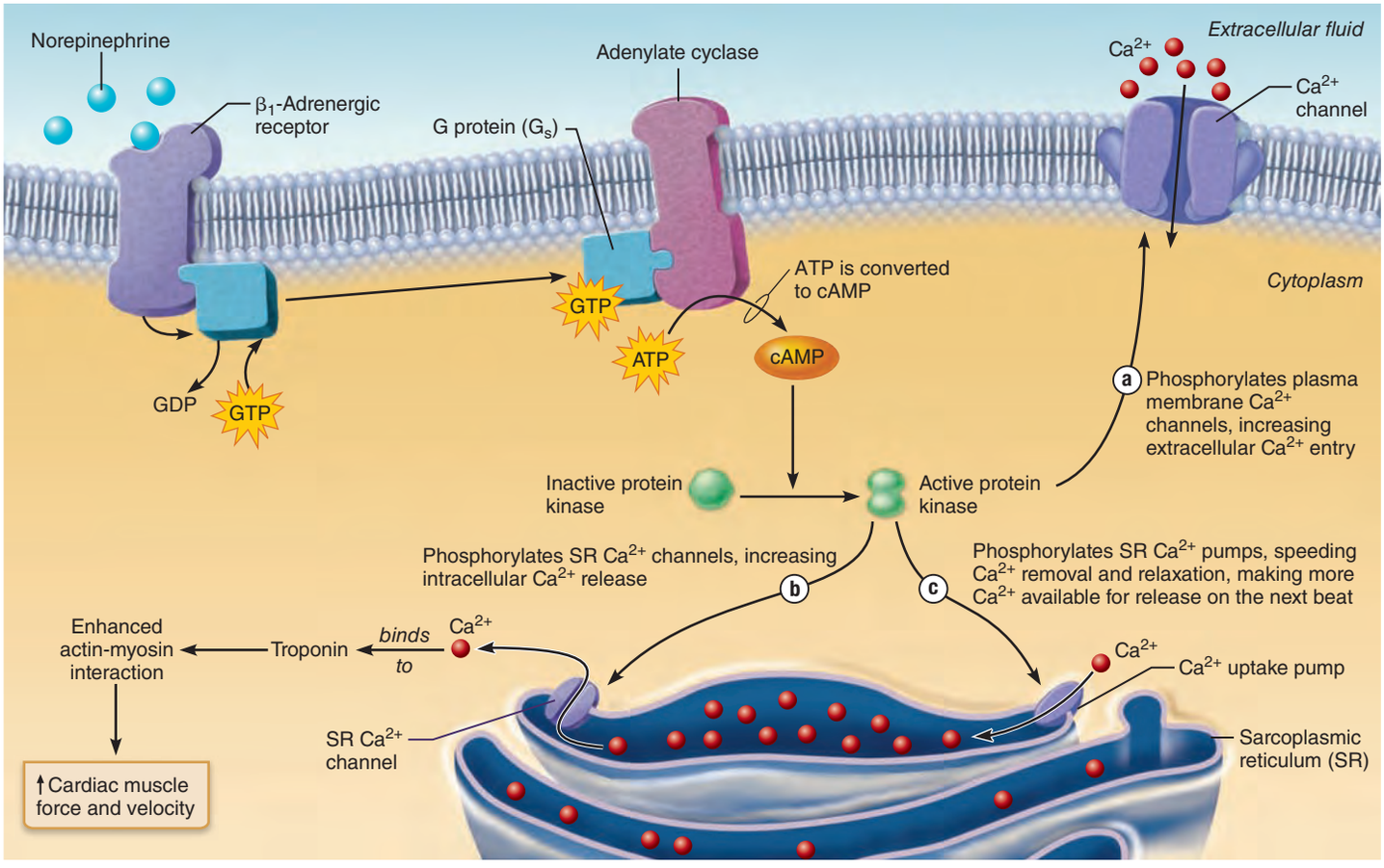


Figure 18.23 Norepinephrine increases heart contractility via a cyclic AMP second-messenger system. Cyclic AMP activates protein kinases that phosphorylate three different proteins, as shown in ⓐ, ⓑ, and ⓒ.

begins to pump more blood than the other, the increased venous return to the opposite ventricle forces that ventricle—through increased cardiac muscle stretch—to pump out an equal volume, preventing backup or accumulation of blood in the circulation.

Contractility EDV is the major *intrinsic factor* influencing SV, but *extrinsic factors* that increase heart muscle contractility can also enhance SV. **Contractility** is defined as the contractile strength achieved at a given muscle length. Note in Figure 18.22 that contractility is *independent* of muscle stretch and EDV. Contractility rises when more Ca^{2+} enters the cytoplasm from the extracellular fluid and the SR. Enhanced contractility means more blood is ejected from the heart (greater SV), hence a lower ESV.

Increased sympathetic stimulation increases contractility. As noted on p. 676, sympathetic fibers serve not only the intrinsic conduction system but the entire heart. One effect of norepinephrine or epinephrine binding is to initiate a cyclic AMP second-messenger system that increases Ca^{2+} entry, which in turn promotes more cross bridge binding and enhances ventricular contractility **(Figure 18.23)**.

A battery of other chemicals also influence contractility. Substances that increase contractility are called *positive inotropic agents* (*ino* = muscle, fiber). The hormones epinephrine, thyroxine, and glucagon; the drug digitalis; and high levels of extracellular Ca^{2+} are all positive inotropic agents. *Negative inotropic agents,* which impair or decrease contractility, include acidosis (excess H^+), rising extracellular K^+ levels, and drugs called calcium channel blockers.

Afterload: Back Pressure Exerted by Arterial Blood **Afterload** is the pressure that the ventricles must overcome to eject blood. It is essentially the back pressure that arterial blood exerts on the aortic and pulmonary valves—about 80 mm Hg in the aorta and 10 mm Hg in the pulmonary trunk.

In healthy individuals, afterload is not a major determinant of stroke volume because it is relatively constant. However, in people with hypertension (high blood pressure), afterload is important indeed because it reduces the ability of the ventricles to eject blood. Consequently, more blood remains in the heart after systole, increasing ESV and reducing stroke volume.

Regulation of Heart Rate

Given a healthy cardiovascular system, SV tends to be relatively constant. However, when blood volume drops sharply or the heart is seriously weakened, SV declines and CO is maintained by increasing HR and contractility. Temporary stressors can

also influence HR—and consequently CO—by acting through homeostatic mechanisms induced neurally, chemically, and physically. Factors that increase HR are called *positive chronotropic* (*chrono* = time) factors, and those that decrease HR are *negative chronotropic* factors.

Autonomic Nervous System Regulation of Heart Rate The autonomic nervous system exerts the most important extrinsic controls affecting heart rate, as shown on the right side of Figure 18.22. When emotional or physical stressors (such as fright, anxiety, or exercise) activate the sympathetic nervous system, sympathetic nerve fibers release norepinephrine at their cardiac synapses. Norepinephrine binds to β_1-adrenergic receptors in the heart, causing threshold to be reached more quickly. As a result, the SA node fires more rapidly and the heart responds by beating faster.

Sympathetic stimulation also enhances contractility and speeds relaxation. It does this by enhancing Ca^{2+} movements in the contractile cells as we described above and in Figure 18.23. Enhanced contractility lowers ESV, so SV does not decline as it would if only heart *rate* increased. (Remember, when the heart beats faster, there is less time for ventricular filling and so a lower EDV.)

The parasympathetic division opposes sympathetic effects and effectively reduces heart rate when a stressful situation has passed. Parasympathetic-initiated cardiac responses are mediated by acetylcholine, which hyperpolarizes the membranes of its effector cells by *opening* K^+ channels. Because vagal innervation of the ventricles is sparse, parasympathetic activity has little or no effect on cardiac contractility.

Under resting conditions, both autonomic divisions continuously send impulses to the SA node of the heart, but the *dominant* influence is inhibitory. For this reason, the heart is said to exhibit **vagal tone**, and heart rate is generally slower than it would be if the vagal nerves were not innervating it. Cutting the vagal nerves results in an almost immediate increase in heart rate of about 25 beats/min, reflecting the inherent rate (100 beats/min) of the pacemaking SA node.

When sensory input from various parts of the cardiovascular system activates either division of the autonomic nervous system more strongly, the other division is temporarily inhibited. Most such sensory input is generated by *baroreceptors* which respond to changes in systemic blood pressure, as we will discuss in Chapter 19. Another example, the **atrial (Bainbridge) reflex**, is an autonomic reflex initiated by increased venous return and increased atrial filling. Stretching the atrial walls increases heart rate by stimulating both the SA node and the atrial stretch receptors. Stretch receptor activation triggers reflexive adjustments of autonomic output to the SA node, increasing heart rate.

Increased or decreased CO results in corresponding changes to systemic blood pressure, so blood pressure regulation often involves reflexive controls of heart rate. In Chapter 19 we describe in more detail neural mechanisms that regulate blood pressure.

Chemical Regulation of Heart Rate Chemicals normally present in the blood and other body fluids may influence heart rate, particularly if they become excessive or deficient.

- **Hormones.** *Epinephrine*, liberated by the adrenal medulla during sympathetic nervous system activation, produces the same cardiac effects as norepinephrine released by the sympathetic nerves: It enhances heart rate and contractility.

  Thyroxine is a thyroid gland hormone that increases metabolic rate and production of body heat. When released in large quantities, it causes a sustained increase in heart rate. Thyroxine acts directly on the heart but also *enhances* the effects of epinephrine and norepinephrine.
- **Ions.** Normal heart function depends on having normal levels of intracellular and extracellular ions. Plasma electrolyte imbalances pose real dangers to the heart.

Homeostatic Imbalance 18.8

Reduced Ca^{2+} blood levels (*hypocalcemia*) depress the heart. Conversely, above-normal levels (*hypercalcemia*) increase heart rate and contractility—up to a point. Very high Ca^{2+} levels disrupt heart function and life-threatening arrhythmias can occur.

High or low blood K^+ levels are particularly dangerous and arise in a number of clinical conditions. Excessive K^+ (*hyperkalemia*) alters electrical activity in the heart by depolarizing the resting potential, and may lead to heart block and cardiac arrest. *Hypokalemia* is also life threatening, in that the heart beats feebly and arrhythmically. ✚

Other Factors That Regulate Heart Rate Age, gender, exercise, and body temperature also influence HR, although they are less important than neural factors. Resting heart rate is fastest in the fetus (140–160 beats/min) and gradually declines throughout life. Average heart rate is faster in females (72–80 beats/min) than in males (64–72 beats/min).

Exercise raises HR by acting through the sympathetic nervous system (Figure 18.22). Exercise also increases systemic blood pressure and routes more blood to the working muscles. However, resting HR in the physically fit tends to be substantially lower than in those who are out of condition, and in trained athletes it may be as slow as 40 beats/min. We explain this apparent paradox below.

Heat increases HR by enhancing the metabolic rate of cardiac cells. This explains the rapid, pounding heartbeat you feel when you have a high fever and also accounts, in part, for the effect of exercise on HR (remember, working muscles generate heat). Cold directly decreases heart rate.

Homeostatic Imbalance 18.9

HR varies with changes in activity, but marked and persistent rate changes usually signal cardiovascular disease.

Tachycardia (tak″e-kar′de-ah; "heart hurry") is an abnormally fast heart rate (more than 100 beats/min) that may result from elevated body temperature, stress, certain drugs, or heart disease. Persistent tachycardia is considered pathological because tachycardia occasionally promotes fibrillation.

Bradycardia (brad″e-kar′de-ah; *brady* = slow) is a heart rate slower than 60 beats/min. It may result from low body temperature, certain drugs, or parasympathetic nervous activation.

It is a known, and desirable, consequence of endurance training. With physical and cardiovascular conditioning, the heart hypertrophies and SV increases, allowing a lower resting heart rate while still providing the same cardiac output. However, in poorly conditioned people persistent bradycardia may result in grossly inadequate blood circulation to body tissues, and bradycardia is often a warning of brain edema after head trauma. ✚

Homeostatic Imbalance of Cardiac Output

The heart's pumping action ordinarily maintains a balance between cardiac output and venous return. Were this not so, a dangerous damming up of blood (blood congestion) would occur in the veins returning blood to the heart.

In **congestive heart failure (CHF)**, the heart is such an inefficient pump that blood circulation is inadequate to meet tissue needs. This progressively worsening disorder reflects weakening of the myocardium by various conditions that damage it in different ways. Let's take a look.

- **Coronary atherosclerosis.** Coronary atherosclerosis, essentially fatty buildup that clogs the coronary arteries, impairs blood and oxygen delivery to cardiac cells. The heart becomes increasingly hypoxic and begins to contract ineffectively.
- **Persistent high blood pressure.** Normally, pressure in the aorta during diastole is 80 mm Hg, and the left ventricle exerts only slightly over that amount of force to eject blood from its chamber. When aortic diastolic blood pressure rises to 90 mm Hg or more, the myocardium must exert more force to open the aortic valve and pump out the same amount of blood. If afterload is chronically elevated, ESV rises and the myocardium hypertrophies. Eventually, the stress takes its toll and the myocardium becomes progressively weaker.
- **Multiple myocardial infarctions.** A succession of MIs (heart attacks) depresses pumping efficiency because noncontractile fibrous (scar) tissue replaces the dead heart cells.
- **Dilated cardiomyopathy (DCM)** (kar″de-o-my-ah′path-e). The cause of this condition, in which the ventricles stretch (dilate) and become flabby and the myocardium deteriorates, is often unknown. Drug toxicity (alcohol, cocaine, excess catecholamines, chemotherapeutic agents) and inflammation of the heart following an infection are implicated in some cases.

  The heart's attempts to work harder result in increasing levels of Ca^{2+} in cardiac cells. The Ca^{2+} activates calcineurin, a calcium-sensitive enzyme that initiates a cascade which switches on genes that enlarge the heart. CO is poor because ventricular contractility is impaired, and the cardiomyopathy progressively worsens.

Because the heart is a double pump, each side can initially fail independently of the other. If the left side fails, **pulmonary congestion** occurs. The right side continues to propel blood to the lungs, but the left side does not adequately eject the returning blood into the systemic circulation. Blood vessels in the lungs become engorged with blood, the pressure in them increases, and fluid leaks from the circulation into the lung tissue, causing pulmonary edema. If the congestion is untreated, the person suffocates.

If the right side of the heart fails, **peripheral congestion** occurs. Blood stagnates in body organs, and pooled fluids in the tissue spaces impair the ability of body cells to obtain adequate nutrients and oxygen and rid themselves of wastes. The resulting edema is most noticeable in the extremities (feet, ankles, and fingers).

Failure of one side of the heart puts a greater strain on the other side, and ultimately the whole heart fails. A seriously weakened, or *decompensated*, heart is irreparable. Treatment is directed primarily toward (1) removing the excess leaked fluid with *diuretics* (drugs that increase the kidneys' excretion of Na^+ and water), (2) reducing afterload with drugs that drive down blood pressure, and (3) increasing contractility with digitalis derivatives. Heart transplants and other surgical or mechanical remedies to replace damaged heart muscle provide additional hope for some cardiac patients.

☑ Check Your Understanding

15. After running to catch a bus, Josh noticed that his heart was beating faster than normally and was pounding forcefully in his chest. How did his increased HR and SV come about?
16. What problem of cardiac output might ensue if the heart beats far too rapidly for an extended period, that is, if tachycardia occurs? Why?

For answers, see Appendix H.

Developmental Aspects of the Heart

✓ Describe the development of the heart, and indicate how the fetal heart differs from the adult heart.

✓ Provide examples of age-related changes in heart function.

The human heart, derived from mesoderm and guided by powerful signaling molecules, begins as two simple endothelial tubes. They quickly fuse to form a single chamber or heart tube that is busily pumping blood by the 22nd day of gestation **(Figure 18.24)**.

Before Birth

The tube develops four slightly bulged areas that represent the earliest heart chambers. From tail to head, following the direction of blood flow, the four primitive chambers are the following (Figure 18.24b):

1. **Sinus venosus** (ven-o′sus). This chamber initially receives all the venous blood of the embryo. It will become the smooth-walled part of the right atrium and the coronary sinus. It also gives rise to the sinoatrial node, which "takes the baton" and sets heart rate early in embryonic development.
2. **Atrium.** This embryonic chamber eventually becomes the pectinate muscle–ridged parts of the atria.

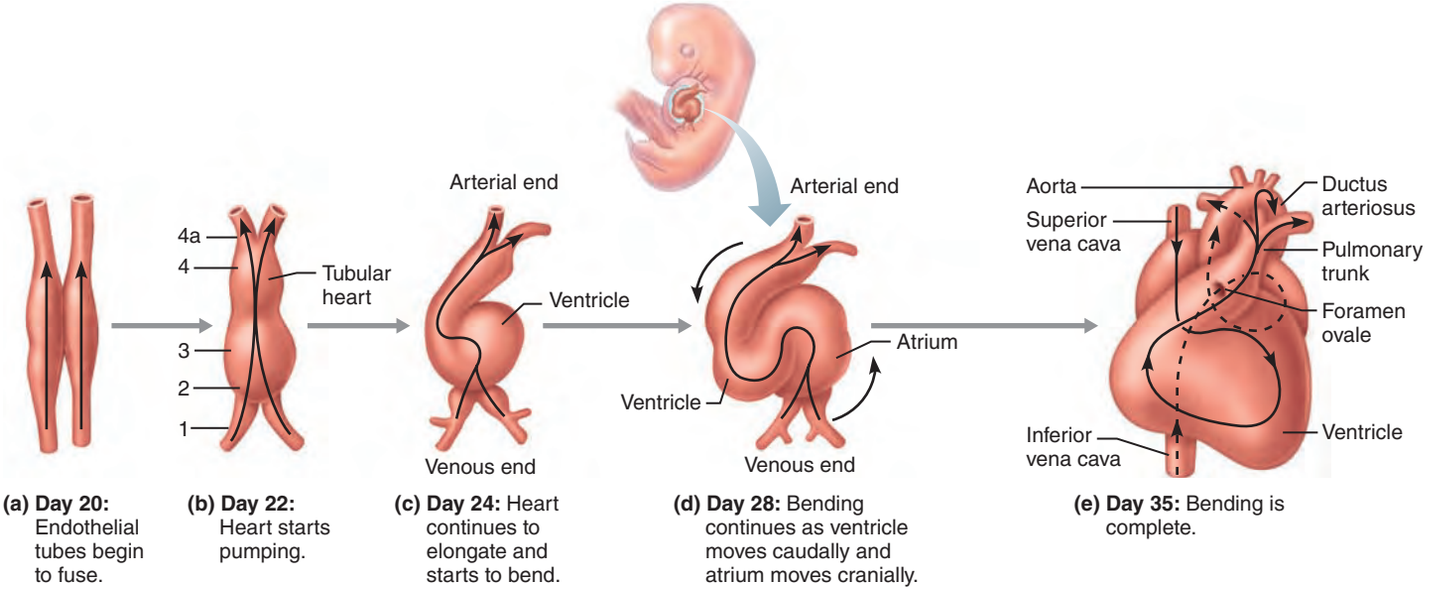


Figure 18.24 Development of the human heart. Ventral views, with the cranial direction toward the top of the figures. Arrows show the direction of blood flow. Days are approximate. **(b)** 1 is the sinus venosus; 2, the atrium; 3, the ventricle; 4, the bulbus cordis; and 4a, the truncus arteriosus.

3. **Ventricle.** The strongest pumping chamber of the early heart, the ventricle gives rise to the *left* ventricle.
4. **Bulbus cordis.** This chamber plus its cranial extension, the *truncus arteriosus* (labeled 4a in Figure 18.24b), give rise to the pulmonary trunk, the first part of the aorta, and most of the *right* ventricle.

During the next three weeks, the heart "tube" exhibits dramatic contortions as it undergoes rightward looping, and major structural changes convert it into a four-chambered organ capable of acting as a double pump—all without missing a beat! The ventricle moves caudally and the atrium cranially, assuming their adult positions. The heart divides into its four definitive chambers (via a number of stages), the midline septum forms, and the bulbus cordis splits into the pulmonary trunk and ascending aorta. After the second month, few changes other than growth occur until birth.

The interatrial septum of the fetal heart is incomplete. The **foramen ovale** (literally, "oval door") connects the two atria and allows blood entering the right heart to bypass the pulmonary circuit and the collapsed, nonfunctional fetal lungs (Figure 18.24e). Another lung bypass, the **ductus arteriosus**, exists between the pulmonary trunk and the aorta. At or shortly after birth, these shunts close, completing the separation between the right and left sides of the heart.

In the adult heart, the fossa ovalis reveals the position of the foramen ovale, and the **ligamentum arteriosum** is the fibrous remnant of the ductus arteriosus (see Figure 18.5b). We give a more complete description of the fetal and newborn circulation in Chapter 28 (see Figure 28.14).

Homeostatic Imbalance 18.10

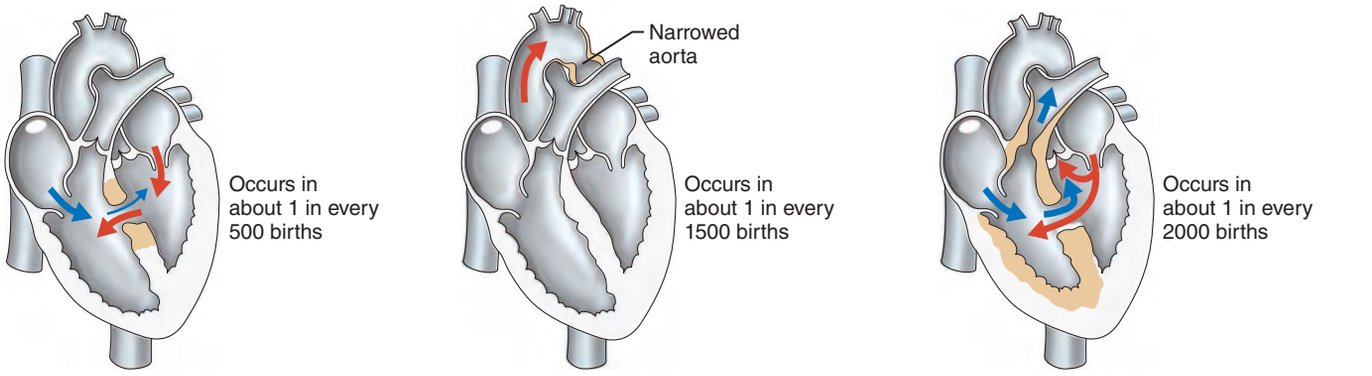
Building a perfect heart is difficult. Each year about 30,000 infants are born in the U.S. with one or more of 30 different **congenital heart defects**, making them the most common of all birth defects. Some congenital heart problems are traceable to environmental influences, such as maternal infection or drug intake during month 2 when the major events of heart formation occur.

The most prevalent abnormalities produce two basic kinds of disorders in the newborn. They either (1) lead to mixing of oxygen-poor blood with oxygenated blood (so that inadequately oxygenated blood reaches the body tissues) or (2) involve narrowed valves or vessels that greatly increase the workload on the heart.

Examples of the first type of defect are *septal defects* **(Figure 18.25a)** and *patent ductus arteriosus*, in which the connection between the aorta and pulmonary trunk remains open. *Coarctation of the aorta* (Figure 18.25b) is an example of the second type of problem. *Tetralogy of Fallot* (te-tral′o-je ov fal-o′), a serious condition in which the baby becomes cyanotic within minutes of birth, encompasses both types of disorders (Figure 18.25c). Modern surgical techniques can usually correct these congenital defects. ✚

Heart Function Throughout Life

In the absence of congenital heart problems, the heart functions admirably throughout a long lifetime for most people. Homeostatic mechanisms are normally so efficient that people rarely notice when the heart is working harder.



(a) Ventricular septal defect. The superior part of the interventricular septum fails to form, allowing blood to mix between the two ventricles. More blood is shunted from left to right because the left ventricle is stronger.

(b) Coarctation of the aorta. A part of the aorta is narrowed, increasing the workload of the left ventricle.

(c) Tetralogy of Fallot. Multiple defects (*tetra* = four): (1) Pulmonary trunk too narrow and pulmonary valve stenosed, resulting in (2) hypertrophied right ventricle; (3) ventricular septal defect; (4) aorta opens from both ventricles.

Figure 18.25 Three examples of congenital heart defects. Tan areas indicate the locations of the defects.

In people who exercise regularly and vigorously, the heart gradually adapts to the increased demand by enlarging and becoming more efficient and more powerful. Aerobic exercise also helps clear fatty deposits from blood vessel walls throughout the body, retarding atherosclerosis and coronary heart disease. Barring some chronic illnesses, this beneficial cardiac response to exercise persists into ripe old age.

The key word on benefiting from exercise is *regularity*. Regular exercise gradually enhances myocardial endurance and strength. For example, 30 minutes a day of moderately vigorous activity (brisk walking, biking, or yard work) offers significant health benefits to most adults. However, intermittent vigorous exercise, enjoyed by weekend athletes, may push an unconditioned heart beyond its ability to respond to the unexpected demands and bring on a myocardial infarction.

Because of the incredible amount of work the heart does over the course of a lifetime, certain structural changes are inevitable. Age-related changes affecting the heart include the following:

- **Valve flaps thicken and become sclerotic (stiff).** This change occurs particularly where the stress of blood flow is greatest (mitral valve). For this reason, heart murmurs are more common in elderly people.
- **Cardiac reserve declines.** Although the passing years seem to cause little change in resting heart rate, the aged heart is less able to respond to both sudden and prolonged stressors that demand increased output. In addition, the maximum HR declines as sympathetic control of the heart becomes less efficient. These changes are less of a problem in physically active seniors.
- **Cardiac muscle becomes fibrosed (scarred).** As a person ages, more and more cardiac cells die and are replaced with fibrous tissue. As a result, the heart stiffens and fills less efficiently for each heartbeat, reducing stroke volume. The nodes of the heart's conduction system may also become fibrosed, which increases the incidence of arrhythmias and other conduction problems.
- **Atherosclerosis.** The insidious progress of atherosclerosis begins in childhood, but inactivity, smoking, and stress accelerate it. The most serious consequences to the heart are hypertensive heart disease and coronary artery occlusion, both of which increase the risk of heart attack and stroke. Although the aging process itself leads to changes in blood vessel walls that promote atherosclerosis, many investigators feel that diet, not aging, is the single most important contributor to cardiovascular disease. We can lower our risk by consuming less animal fat, cholesterol, and salt.

Check Your Understanding

17. Name the two components of the fetal heart that allow blood to bypass the lungs.
18. In the past decade, many people over 70 have competed in the Ironman World Championships in Hawaii. In what way might age-related changes of the heart limit the performance of these athletes?

For answers, see Appendix H.

The heart is an exquisitely engineered double pump that operates with precision to propel blood into the large arteries leaving its chambers. However, continuous circulation of blood also depends critically on the pressure dynamics in the blood vessels. Chapter 19 considers the structure and function of these vessels and relates this information to the work of the heart to provide a complete picture of cardiovascular functioning.

Chapter Summary

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The Pulmonary and Systemic Circuits (p. 659)

1. The right side of the heart is the pulmonary circuit pump. It pumps blood through the lungs, where the blood picks up oxygen and dumps carbon dioxide. The left side of the heart is the systemic circuit pump. It pumps blood through the body's tissues, supplying them with oxygen and nutrients and removing carbon dioxide.

Heart Anatomy (pp. 659–671)

Size, Location, and Orientation (p. 659)

1. The human heart, about the size of a clenched fist, is located obliquely within the mediastinum of the thorax.

Coverings of the Heart (pp. 660–661)

2. The heart is enclosed within a double sac made up of the outer fibrous pericardium and the inner serous pericardium (parietal and visceral layers). The pericardial cavity between the serous layers contains lubricating serous fluid.

Layers of the Heart Wall (pp. 661–662)

3. Layers of the heart wall, from the interior out, are the endocardium, myocardium (reinforced by a fibrous cardiac skeleton), and epicardium (visceral layer of the serous pericardium).

Chambers and Associated Great Vessels (p. 662)

4. The heart has two superior atria and two inferior ventricles. Functionally, the heart is a double pump.
5. Entering the right atrium are the superior vena cava, inferior vena cava, and coronary sinus. Four pulmonary veins enter the left atrium.
6. The right ventricle discharges blood into the pulmonary trunk; the left ventricle pumps blood into the aorta.

Heart Valves (pp. 662–668)

7. The atrioventricular (AV) valves (tricuspid and mitral) prevent backflow into the atria when the ventricles are contracting; the semilunar (SL) valves (pulmonary and aortic) prevent backflow into the ventricles when the ventricles are relaxing.

Pathway of Blood Through the Heart (p. 668)

8. Oxygen-poor systemic blood enters the right atrium, passes into the right ventricle, through the pulmonary trunk to the lungs, and back to the left atrium via the pulmonary veins. Oxygen-laden blood entering the left atrium from the lungs flows into the left ventricle and then into the aorta, which provides the functional supply of all body organs. Systemic veins return the oxygen-depleted blood to the right atrium.

Coronary Circulation (pp. 668–671)

9. The right and left coronary arteries branch from the aorta and via their main branches (anterior and posterior interventricular, right marginal, and circumflex arteries) supply the heart itself. Venous blood, collected by the cardiac veins (great, middle, and small), empties into the coronary sinus.
10. Blood delivery to the myocardium occurs during heart relaxation.

iP **Cardiovascular System; Topic: Anatomy Review: The Heart, pp. 1–8.**

Cardiac Muscle Fibers (pp. 671–674)

Microscopic Anatomy (p. 671)

1. Cardiac muscle cells are branching, striated, generally uninucleate cells. They contain myofibrils consisting of typical sarcomeres.
2. Intercalated discs containing desmosomes and gap junctions connect adjacent cardiac cells. The myocardium behaves as a functional syncytium because of electrical coupling provided by gap junctions.

Mechanism and Events of Contraction (pp. 671–673)

3. As in skeletal muscle, the membrane depolarization of contractile myocytes causes opening of sodium channels and allows sodium to enter, which is responsible for the rising phase of the action potential curve. Depolarization also opens slow Ca^{2+} channels; Ca^{2+} entry prolongs the period of depolarization (creates the plateau). Ca^{2+} released by the SR and entering from the extracellular space couples the action potential to sliding of the myofilaments. Compared to skeletal muscle, cardiac muscle has a prolonged refractory period that prevents tetany.

iP **Cardiovascular System; Topic: Cardiac Action Potential, pp. 11–18.**

Energy Requirements (pp. 673–674)

4. Cardiac muscle has abundant mitochondria and depends almost entirely on aerobic respiration to form ATP.

Heart Physiology (pp. 674–685)

Electrical Events (pp. 674–678)

1. Certain noncontractile cardiac muscle cells exhibit automaticity and rhythmicity and can independently initiate action potentials. Such cells have an unstable resting potential called a pacemaker potential that gradually depolarizes, drifting toward threshold for firing. These cells compose the intrinsic conduction system of the heart.
2. The conduction system of the heart consists of the SA and AV nodes, the AV bundle and bundle branches, and the subendocardial conducting network. This system coordinates the depolarization of the heart and ensures that the heart beats as a unit. The SA node has the fastest rate of spontaneous depolarization and acts as the heart's pacemaker; it sets the sinus rhythm.
3. Defects in the intrinsic conduction system can cause arrhythmias, fibrillation, and heart block.
4. The autonomic nervous system innervates the heart. Cardiac centers in the medulla include the cardioacceleratory center, which projects to the T_1–T_5 region of the spinal cord, which in turn projects to the cervical and upper thoracic sympathetic

trunk. Postganglionic fibers innervate the SA and AV nodes and the cardiac muscle fibers. The cardioinhibitory center exerts its influence via the parasympathetic vagus nerves (X), which project to the heart wall. Most parasympathetic fibers serve the SA and AV nodes.

5. An electrocardiogram (ECG) is a graphic representation of the cardiac conduction cycle. The P wave reflects atrial depolarization. The QRS complex indicates ventricular depolarization; the T wave represents ventricular repolarization.

iP Cardiovascular System; Topic: Intrinsic Conduction System, pp. 1–7; Topic: Cardiac Action Potential, pp. 1–10.

Heart Sounds (pp. 678–679)

6. Normal heart sounds arise chiefly from turbulent blood flow during the closing of heart valves. Abnormal heart sounds, called murmurs, usually reflect valve problems.

Mechanical Events: The Cardiac Cycle (pp. 679–681)

7. A cardiac cycle consists of the events occurring during one heartbeat. During mid-to-late diastole, the ventricles fill and the atria contract. Ventricular systole consists of the isovolumetric contraction phase and the ventricular ejection phase. During early diastole, the ventricles are relaxed and are closed chambers until the atrial pressure exceeds the ventricular pressure, forcing the AV valves open. Then the cycle begins again. At a normal heart rate of 75 beats/min, a cardiac cycle lasts 0.8 s.
8. Pressure changes promote blood flow and valve opening and closing.

iP Cardiovascular System; Topic: Cardiac Cycle, pp. 1–19.

Cardiac Output (pp. 681–685)

9. Cardiac output, typically 5 L/min, is the amount of blood pumped out by each ventricle in 1 minute. Stroke volume is the amount of blood pumped out by a ventricle with each contraction. Cardiac output = heart rate × stroke volume.
10. Stroke volume depends to a large extent on the degree to which venous return stretches cardiac muscle. Approximately 70 ml, it is the difference between end diastolic volume (EDV) and end systolic volume (ESV). Anything that influences heart rate or blood volume influences venous return, hence stroke volume.
11. Activation of the sympathetic nervous system increases heart rate and contractility; parasympathetic activation decreases heart rate but has little effect on contractility. Ordinarily, the heart exhibits vagal tone.
12. Chemical regulation of the heart is effected by hormones (epinephrine and thyroxine) and ions (particularly potassium and calcium). Ion imbalances severely impair heart activity.
13. Other factors influencing heart rate are age, sex, exercise, and body temperature.
14. Congestive heart failure occurs when the pumping ability of the heart cannot provide adequate circulation to meet body needs. Right heart failure leads to systemic edema; left heart failure results in pulmonary edema.

iP Cardiovascular System; Topic: Cardiac Output, pp. 1–11.

Developmental Aspects of the Heart (pp. 685–687)

Before Birth (pp. 685–686)

1. The heart begins as a simple (mesodermal) tube that is pumping blood by the fourth week of gestation. The fetal heart has two lung bypasses: the foramen ovale and the ductus arteriosus.
2. Congenital heart defects are the most common of all birth defects. The most common of these disorders lead to inadequate oxygenation of blood or increase the workload of the heart.

Heart Function Throughout Life (pp. 686–687)

3. Age-related changes include sclerosis and thickening of the valve flaps, declines in cardiac reserve, fibrosis of cardiac muscle, and atherosclerosis.
4. Risk factors for cardiac disease include dietary factors, excessive stress, cigarette smoking, and lack of exercise.

Review Questions

Multiple Choice/Matching

(Some questions have more than one correct answer. Select the best answer or answers from the choices given.)

1. When the semilunar valves are open, which of the following are occurring? **(a)** 2, 3, 5, 6, **(b)** 1, 2, 3, 7, **(c)** 1, 3, 5, 6, **(d)** 2, 4, 5, 7.

   ____ **(1)** coronary arteries fill
   ____ **(2)** AV valves are closed
   ____ **(3)** ventricles are in systole
   ____ **(4)** ventricles are in diastole
   ____ **(5)** blood enters aorta
   ____ **(6)** blood enters pulmonary arteries
   ____ **(7)** atria contract

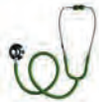
2. The portion of the intrinsic conduction system located in the superior interventricular septum is the **(a)** AV node, **(b)** SA node, **(c)** AV bundle, **(d)** subendocardial conducting network.
3. An ECG provides information about **(a)** cardiac output, **(b)** movement of the excitation wave across the heart, **(c)** coronary circulation, **(d)** valve impairment.
4. The sequence of contraction of the heart chambers is **(a)** random, **(b)** left chambers followed by right chambers, **(c)** both atria followed by both ventricles, **(d)** right atrium, right ventricle, left atrium, left ventricle.
5. The fact that the left ventricular wall is thicker than the right reveals that it **(a)** pumps a greater volume of blood, **(b)** pumps blood against greater resistance, **(c)** expands the thoracic cage, **(d)** pumps blood through a smaller valve.
6. The chordae tendineae **(a)** close the atrioventricular valves, **(b)** prevent the AV valve flaps from everting, **(c)** contract the papillary muscles, **(d)** open the semilunar valves.
7. In the heart, which of the following apply? **(1)** Action potentials are conducted from cell to cell across the myocardium via gap junctions, **(2)** the SA node sets the pace for the heart as a whole, **(3)** spontaneous depolarization of cardiac cells can occur in the absence of nerve stimulation, **(4)** cardiac muscle can continue to contract for long periods in the absence of oxygen. **(a)** all of the above, **(b)** 1, 3, 4, **(c)** 1, 2, 3, **(d)** 2, 3.
8. The activity of the heart depends on intrinsic properties of cardiac muscle and on neural factors. Thus, **(a)** vagus nerve stimulation of the heart reduces heart rate, **(b)** sympathetic nerve

stimulation of the heart decreases time available for ventricular filling, **(c)** sympathetic stimulation of the heart increases its force of contraction, **(d)** all of the above.

9. Freshly oxygenated blood is first received by the **(a)** right atrium, **(b)** left atrium, **(c)** right ventricle, **(d)** left ventricle.

Short Answer Essay Questions

10. Describe the location and position of the heart in the body.
11. Describe the pericardium and distinguish between the fibrous and the serous pericardia relative to histological structure and location.
12. Trace one drop of blood from the time it enters the right atrium until it enters the left atrium. What is this circuit called?
13. (a) Describe how heart contraction and relaxation influence coronary blood flow. (b) Name the major branches of the coronary arteries, and note the heart regions served by each.
14. The refractory period of cardiac muscle is much longer than that of skeletal muscle. Why is this a desirable functional property?
15. (a) Name the elements of the intrinsic conduction system of the heart in order, beginning with the pacemaker. (b) What is the important function of this conduction system?
16. Draw a normal ECG pattern. Label and explain the significance of its deflection waves.
17. Define cardiac cycle, and follow the events of one cycle.
18. What is cardiac output, and how is it calculated?
19. Discuss how the Frank-Starling law of the heart helps to explain the influence of venous return on stroke volume.
20. (a) Describe the common function of the foramen ovale and the ductus arteriosus in a fetus. (b) What problems result if these shunts remain patent (open) after birth?



Critical Thinking and Clinical Application Questions

1. A gang member was stabbed in the chest during a street fight. He was cyanotic and unconscious from lack of blood delivery to the brain. The diagnosis was cardiac tamponade. What is cardiac tamponade and how does it cause the observed symptoms?
2. You have been called upon to demonstrate the technique for listening to valve sounds. (a) Explain where you would position your stethoscope to auscultate (1) the aortic valve of a patient with severe aortic valve insufficiency and (2) a stenotic mitral valve. (b) During which period(s) would you hear these abnormal valve sounds most clearly? (During atrial diastole, ventricular systole, ventricular diastole, or atrial systole?) (c) What cues would you use to differentiate between an insufficient and a stenotic valve?
3. Florita Santos, a middle-aged woman, is admitted to the coronary care unit with a diagnosis of left ventricular failure resulting from a myocardial infarction. Her history indicated that she was aroused in the middle of the night by severe chest pain. Her skin is pale and cold, and moist sounds are heard over the lower regions of both lungs. Explain how failure of the left ventricle can cause these signs and symptoms.
4. Heather, a newborn baby, needs surgery because she was born with an aorta that arises from the right ventricle and a pulmonary trunk that issues from the left ventricle, a condition called transposition of the great vessels. What are the physiological consequences of this defect?
5. Gabriel, a heroin addict, feels tired, is weak and feverish, and has vague aches and pains. Terrified that he has AIDS, he goes to a doctor and is informed that he is suffering not from AIDS, but from a heart murmur accompanied by endocarditis. What is the most likely way that Gabriel contracted endocarditis? (Hint: See Related Clinical Terms.)
6. As Cara worked at her dissection, she became frustrated that several of the structures she had to learn about had more than one common name. Provide another name for each of these structures: (a) atrioventricular groove, (b) tricuspid valve, (c) bicuspid valve (give two synonyms), and (d) atrioventricular bundle.

AT THE CLINIC

18

Related Clinical Terms

Asystole (a-sis′to-le) Situation in which the heart fails to contract.

Cardiac catheterization Diagnostic procedure that involves passing a fine catheter (tubing) through a blood vessel into the heart. Oxygen content of blood, blood flow, and pressures within the heart can be measured. Findings help to detect valve problems, heart deformities, and other heart malfunctions.

Commotio cordis ("concussion of the heart") Situation in which a relatively mild blow to the chest causes heart failure and sudden death because it occurs during a vulnerable interval (2 ms) when the heart is repolarizing. Explains those rare instances when youngsters drop dead on the playing field after being hit in the chest by a ball.

Cor pulmonale (kor pul-mun-nă′le; *cor* = heart, *pulmo* = lung) A condition of right-sided heart failure resulting from elevated blood pressure in the pulmonary circuit (pulmonary hypertension). Acute cases may develop suddenly due to a pulmonary embolism; chronic cases are usually associated with chronic lung disorders such as emphysema.

Endocarditis (en″do-kar-di′tis) Inflammation of the endocardium, usually confined to the endocardium of the heart valves. Endocarditis often results from infection by bacteria that have entered the bloodstream but may result from fungal infection or an autoimmune response. Drug addicts may develop endocarditis by injecting themselves with contaminated needles.

Heart palpitation A heartbeat that is unusually strong, fast, or irregular so that the person becomes aware of it; may be caused by certain drugs, emotional pressures ("nervous heart"), or heart disorders.

Hypertrophic cardiomyopathy (HCM) The leading cause of sudden death in young athletes, this condition, which is usually inherited, causes the cardiac muscle cells to enlarge, thickening the heart wall. The heart pumps strongly but doesn't relax well during diastole when the heart is filling.

Mitral valve prolapse Valve disorder affecting up to 1% of the population; most often seen in young women. It appears to have a genetic basis resulting in abnormal chordae tendineae

Related Clinical Terms *(continued)*

or a malfunction of the papillary muscles. One or more of the mitral valve flaps become incompetent and billow into the left atrium during ventricular systole, allowing blood regurgitation. Occasionally requires valve replacement surgery.

Myocarditis (mi″o-kar-di′tis; *myo* = muscle, *card* = heart, *itis* = inflammation) Inflammation of the cardiac muscle layer (myocardium) of the heart; sometimes follows an untreated streptococcal infection in children. May weaken the heart and impair its ability to pump effectively.

Paroxysmal atrial tachycardia (PAT) Bursts of atrial contractions with little pause between them.

Ventricular tachycardia (VT or **V-tac)** Rapid ventricular contractions that are not coordinated with atrial activity.

Case Study Cardiovascular System: The Heart

Donald Ayers, a 49-year-old male, was the driver of the bus involved in the accident on Route 91. He was brought into the ER with blunt trauma to the chest. Paramedics noted that the driver's seatbelt had broken and that he was found lying under the instrument panel. Initially unresponsive, Mr. Ayers regained consciousness and complained of chest, epigastric, and left upper quadrant pain. Examination revealed mild tachycardia (110 bpm) and a blood pressure of 105/75 mm Hg. An exam 10 minutes later showed a rapid change in blood pressure (80/55 mm Hg) and HR (130 bpm) along with muffled heart sounds, a thready (weak) pulse, and bulging neck veins. Soon after, the patient began to complain of a sudden onset of pain that radiated into his back from the injury site. The patient described the pain as "sharp, stabbing, and tearing" and it continued to increase.

1. Mr. Ayers's pulse is described as "thready." What might this indicate with respect to this patient's stroke volume?
2. Mr. Ayers's HR increased from 110 to 130 bpm. What effect will this have on his cardiac output? Explain your reasoning.

Mr. Ayers's blood pressure continued to drop, so doctors ordered a chest X ray, ECG, and spiral CT scan (a rapid CT technique). These diagnostic tests revealed four fractured ribs, an enlarged mediastinum, and pericardial effusions (fluid in the pericardium) producing cardiac tamponade.

Mr. Ayers was scheduled for emergency surgery.

3. Beginning with the concept of end diastolic volume (EDV), explain the effect that the fluid in the pericardium is having on the stroke volume of Mr. Ayers's heart.
4. Muffled heart sounds are quieter and less distinct. Explain how changes in EDV can result in muffled heart sounds.
5. The final diagnosis in this case is a dissection (tear) of the aorta. From what you know about the anatomy of the heart, where in the aorta do you think the tear is located? Explain your answer.
6. Why did Mr. Ayers's neck veins bulge?

(Answers in Appendix H)

inspired experiments of William Harvey, an English physician. Prior to that time, people thought, as proposed by the ancient Greek physician Galen, that blood moved through the body like an ocean tide, first moving out from the heart and then ebbing back in the same vessels.

PART 1
Blood Vessel Structure and Function

The three major types of blood vessels are *arteries, capillaries*, and *veins*. As the heart contracts, it forces blood into the large arteries leaving the ventricles. The blood then moves into successively smaller arteries, finally reaching their smallest branches, the *arterioles* (ar-te′re-ōlz; "little arteries"), which feed into the capillary beds of body organs and tissues. Blood drains from the capillaries into *venules* (ven′ūlz), the smallest veins, and then on into larger and larger veins that merge to form the large veins that ultimately empty into the heart. Altogether, the blood vessels in the adult human stretch for about 100,000 km (60,000 miles) through the internal body landscape!

Arteries carry blood *away from* the heart, so they are said to "branch," "diverge," or "fork" as they form smaller and smaller divisions. **Veins**, by contrast, carry blood *toward* the heart and so are said to "join," "merge," and "converge" into the successively larger vessels approaching the heart. In the systemic circulation, arteries always carry oxygenated blood and veins always carry oxygen-poor blood. The opposite is true in the pulmonary circulation, where the arteries, still defined as the vessels leading away from the heart, carry oxygen-poor blood to the lungs, and the veins carry oxygen-rich blood from the lungs to the heart. The special umbilical vessels of a fetus also differ in the roles of veins and arteries.

Of all the blood vessels, only the capillaries have intimate contact with tissue cells and directly serve cellular needs. Exchanges between the blood and tissue cells occur primarily through the gossamer-thin capillary walls.

Structure of Blood Vessel Walls

✓ Describe the three layers that typically form the wall of a blood vessel, and state the function of each.

✓ Define vasoconstriction and vasodilation.

The walls of all blood vessels, except the very smallest, have three distinct layers, or *tunics* ("coverings"), that surround a central blood-containing space, the vessel **lumen** (Figure 19.1).

The innermost tunic is the **tunica intima** (in′tĭ-mah). The name is easy to remember once you know that this tunic is in *intimate* contact with the blood in the lumen. The tunica intima contains the **endothelium**, the simple squamous epithelium that lines the lumen of all vessels. The endothelium is continuous with the endocardial lining of the heart, and its flat cells fit closely together, forming a slick surface that minimizes friction as blood moves through the lumen. In vessels larger than 1 mm in diameter, a *subendothelial layer*, consisting of a basement membrane and loose connective tissue, supports the endothelium.

The middle tunic, the **tunica media** (me′de-ah), is mostly circularly arranged smooth muscle cells and sheets of elastin. The activity of the smooth muscle is regulated by sympathetic *vasomotor nerve fibers* of the autonomic nervous system and a whole battery of chemicals. Depending on the body's needs at any given moment, regulation causes either **vasoconstriction** (lumen diameter decreases as the smooth muscle contracts) or **vasodilation** (lumen diameter increases as the smooth muscle relaxes). The activities of the tunica media are critical in regulating circulatory dynamics because small changes in vessel diameter greatly influence blood flow and blood pressure. Generally, the tunica media is the bulkiest layer in arteries, which bear the chief responsibility for maintaining blood pressure and circulation.

The outermost layer of a blood vessel wall, the **tunica externa** (also called the *tunica adventitia*; ad″ven-tish′e-ah; "coming from outside"), is composed largely of loosely woven collagen fibers that protect and reinforce the vessel, and anchor it to surrounding structures. The tunica externa is infiltrated with nerve fibers, lymphatic vessels, and, in larger veins, a network of elastic fibers. In larger vessels, the tunica externa contains a system of tiny blood vessels, the **vasa vasorum** (va′sah va-sor′um)—literally, "vessels of the vessels"—that nourish the more external tissues of the blood vessel wall. The innermost (luminal) portion of the vessel obtains nutrients directly from blood in the lumen.

The three vessel types vary in length, diameter, wall thickness, and tissue makeup (see Table 19.1 on p. 696). Figure 19.2 summarizes how these vascular channels relate to one another and to vessels of the lymphatic system. The lymphatic system recovers fluids that leak from the circulation and is described in Chapter 20.

☑ Check Your Understanding

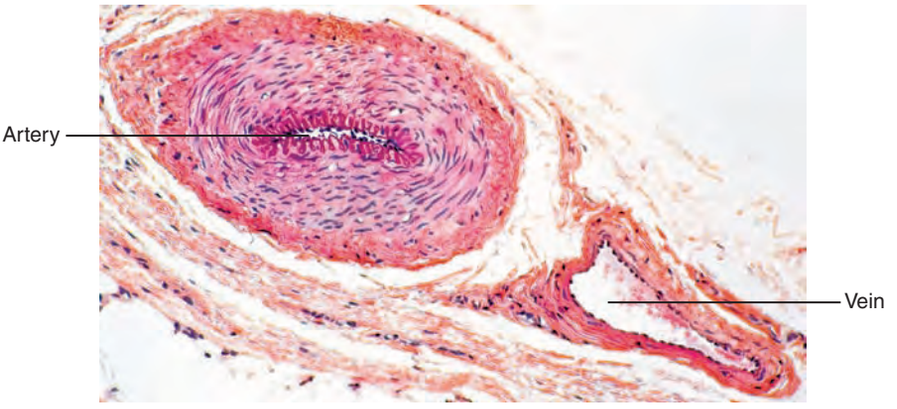
1. Which branch of the autonomic nervous system innervates blood vessels? Which layer of the blood vessel wall do these nerves innervate? What are the effectors (cells that carry out the response)?
2. When vascular smooth muscle contracts, what happens to the diameter of the blood vessel? What is this called?

For answers, see Appendix H.

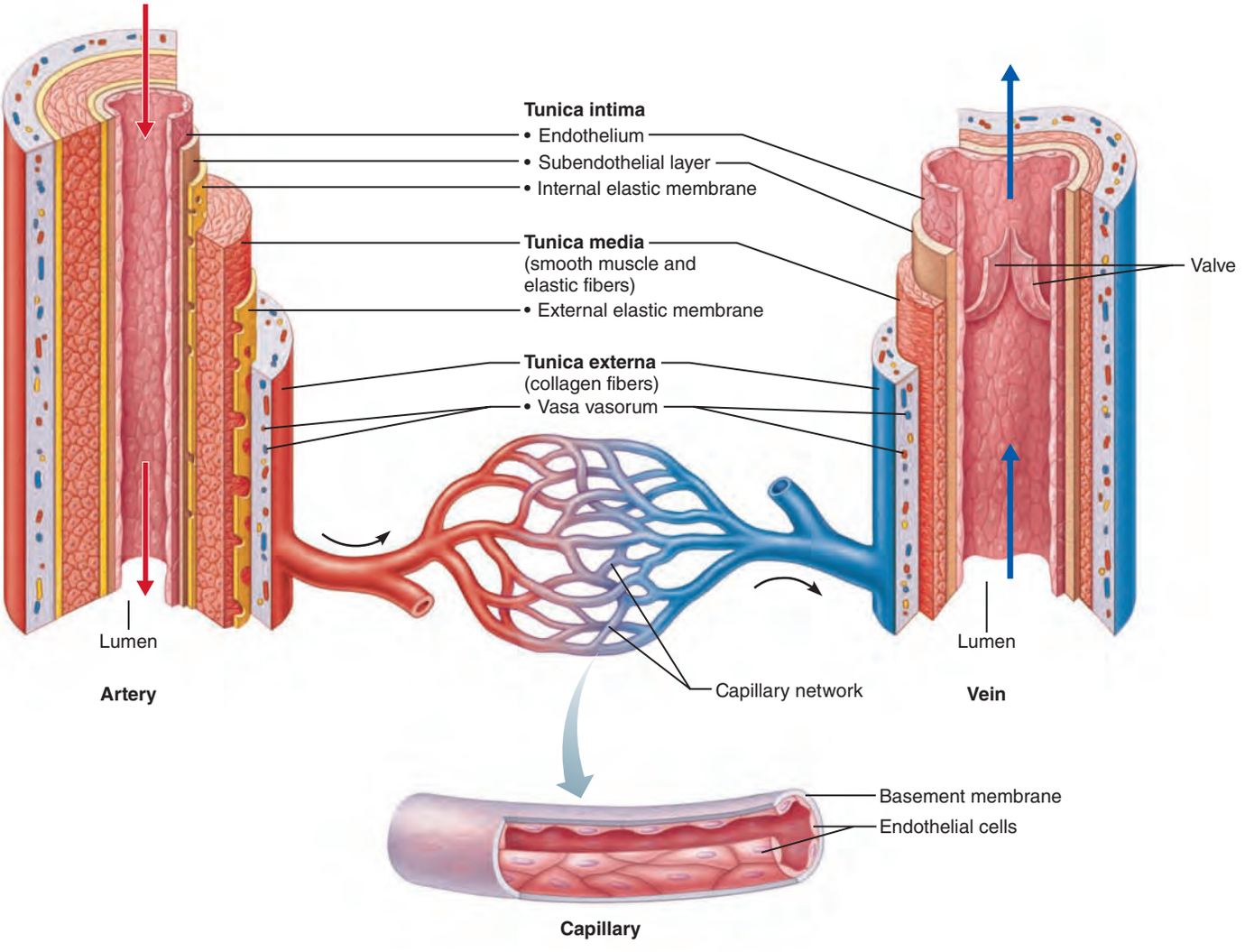
Arterial System

✓ Compare and contrast the structure and function of the three types of arteries.

In terms of relative size and function, arteries can be divided into three groups—elastic arteries, muscular arteries, and arterioles.



(a)



(b)

Figure 19.1 Generalized structure of arteries, veins, and capillaries. (a) Light photomicrograph of a muscular artery and the corresponding vein in cross section (100×). **(b)** Comparison of wall structure of arteries, veins, and capillaries. Note that the tunica media is thicker than the tunica externa in arteries and that the opposite is true in veins.

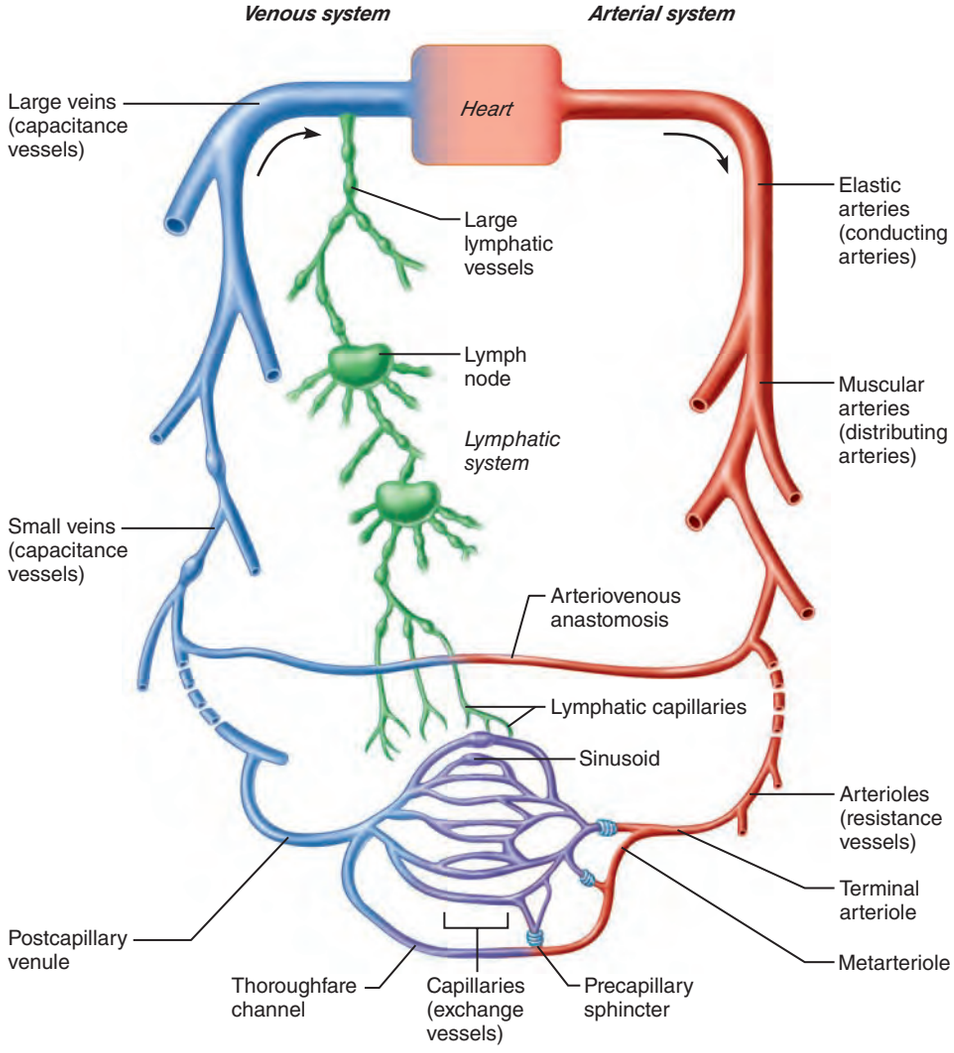


Figure 19.2 The relationship of blood vessels to each other and to lymphatic vessels.
Lymphatic vessels recover excess tissue fluid and return it to the blood.

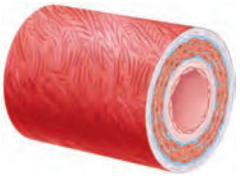
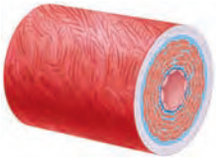
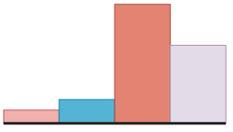
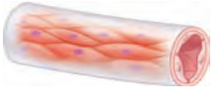
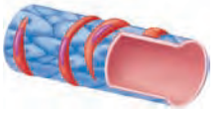
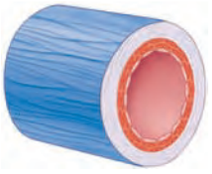
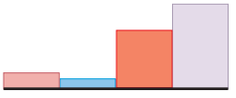
Elastic Arteries

Elastic arteries are the thick-walled arteries near the heart—the aorta and its major branches. These arteries are the largest in diameter, ranging from 2.5 cm to 1 cm, and the most elastic (Table 19.1). Because their large lumens make them low-resistance pathways that conduct blood from the heart to medium-sized arteries, elastic arteries are sometimes called *conducting arteries* (Figure 19.2).

Elastic arteries contain more elastin than any other vessel type. It is present in all three tunics, but the tunica media contains the most. There the elastin constructs concentric "holey" sheets of elastic connective tissue that look like slices of Swiss cheese sandwiched between layers of smooth muscle cells. Although elastic arteries also contain substantial amounts of smooth muscle, they are relatively inactive in vasoconstriction. Thus, in terms of function, they can be visualized as simple elastic tubes.

Elastic arteries are pressure reservoirs, expanding and recoiling as the heart ejects blood. Consequently, blood flows fairly continuously rather than starting and stopping with the pulsating rhythm of the heartbeat. If the blood vessels become hard and unyielding, as in atherosclerosis, blood flows more intermittently, similar to the way water flows through a hard rubber garden hose attached to a faucet. When the faucet is on, the high pressure makes the water gush out of the hose. But when the faucet is shut off, the water flow abruptly becomes a trickle and then stops, because the hose walls cannot recoil to keep the water under pressure. Also, without the pressure-smoothing effect of the elastic arteries, the walls of arteries throughout the body experience higher pressures. Battered by high pressures, the arteries eventually weaken and may balloon out or even burst. (These problems are discussed in *A Closer Look* on pp. 700–701.)

Table 19.1 Summary of Blood Vessel Anatomy

VESSEL TYPE/ ILLUSTRATION*	AVERAGE LUMEN DIAMETER (D) AND WALL THICKNESS (T)	RELATIVE TISSUE MAKEUP			
		Endothelium	*Elastic Tissues*	*Smooth Muscles*	*Fibrous (Collagenous) Tissues*
 Elastic artery	D: 1.5 cm T: 1.0 mm				
 Muscular artery	D: 6.0 mm T: 1.0 mm				
 Arteriole	D: 37.0 µm T: 6.0 µm				
 Capillary	D: 9.0 µm T: 0.5 µm				
 Venule	D: 20.0 µm T: 1.0 µm				
 Vein	D: 5.0 mm T: 0.5 mm				

*Size relationships are not proportional. Smaller vessels are drawn relatively larger so detail can be seen. See column 2 for actual dimensions.

Muscular Arteries

Distally the elastic arteries give way to the **muscular arteries**, which deliver blood to specific body organs (and so are sometimes called *distributing arteries*). Muscular arteries account for most of the named arteries studied in the anatomy laboratory. Their internal diameter ranges from that of a little finger to that of a pencil lead.

Proportionately, muscular arteries have the thickest tunica media of all vessels. Their tunica media contains relatively more smooth muscle and less elastic tissue than do elastic arteries (Table 19.1). For this reason, they are more active in vasoconstriction and less distensible (capable of stretching). In muscular arteries, however, there *is* an *elastic membrane* on each face of the tunica media.

Arterioles

The smallest of the arteries, **arterioles** have a lumen diameter ranging from 0.3 mm down to 10 µm. Larger arterioles have all three tunics, but their tunica media is chiefly smooth muscle with a few scattered elastic fibers. Smaller arterioles, which lead into the capillary beds, are little more than a single layer of smooth muscle cells spiraling around the endothelial lining.

As we will describe shortly, minute-to-minute blood flow into the capillary beds is determined by arteriolar diameter, which varies in response to changing neural, hormonal, and local chemical influences. When arterioles constrict, the tissues served are largely bypassed. When arterioles dilate, blood flow into the local capillaries increases dramatically.

Capillaries

✓ Describe the structure and function of a capillary bed.

The microscopic **capillaries** are the smallest blood vessels. Their exceedingly thin walls consist of just a thin tunica intima (see Figure 19.1b). In some cases, one endothelial cell forms the entire circumference of the capillary wall. At strategic locations along the outer surface of some capillaries are spider-shaped **pericytes**, smooth muscle–like cells that stabilize the capillary wall and help control capillary permeability **(Figure 19.3a).**

Average capillary length is 1 mm and average lumen diameter is 8–10 µm, just large enough for red blood cells to slip through in single file. Most tissues have a rich capillary supply, but there are exceptions. Tendons and ligaments are poorly vascularized. Cartilage and epithelia lack capillaries, but receive nutrients from blood vessels in nearby connective tissues, and the avascular cornea and lens of the eye receive nutrients from the aqueous humor.

If we compare arteries and arterioles to expressways and roads, capillaries are the back alleys and driveways that provide direct access to nearly every cell in the body. Given their location and thin walls, capillaries are ideally suited for their role—exchange of materials (gases, nutrients, hormones, and so on) between the blood and the interstitial fluid (Figure 19.2 and Table 19.1). We describe these exchanges later in this chapter. Here, we focus on capillary structure.

Types of Capillaries

Structurally, there are three types of capillaries—*continuous, fenestrated*, and *sinusoid*.

Continuous Capillaries

Continuous capillaries, abundant in the skin and muscles, are most common (Figure 19.3a). They are continuous in the sense that their endothelial cells are joined together by *tight junctions*, providing an uninterrupted lining. However, these junctions are usually incomplete and leave gaps of unjoined membrane called **intercellular clefts**, which are just large enough to allow limited passage of fluids and small solutes. Typically, the endothelial cell cytoplasm contains numerous pinocytotic vesicles that ferry fluids across the capillary wall.

Brain capillaries, however, are unique. There the tight junctions of the continuous capillaries are complete and extend around the entire perimeter of the endothelial cells, constituting the structural basis of the *blood brain barrier* that we described in Chapter 12.

Fenestrated Capillaries

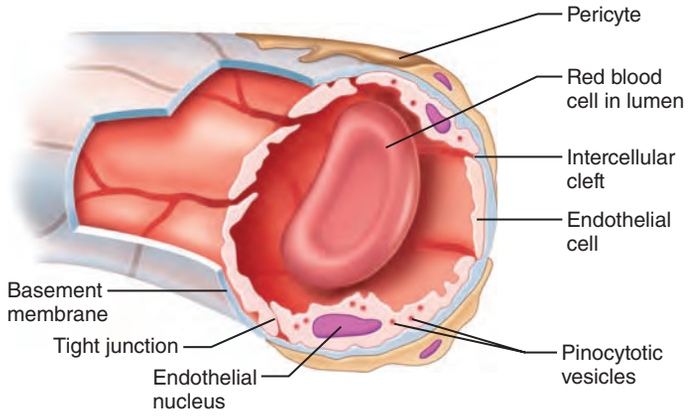
Fenestrated capillaries (fen′es-tra-tid) are similar to the continuous variety except that the endothelial cells in fenestrated capillaries are riddled with oval *pores*, or *fenestrations* (*fenestra* = window) (Figure 19.3b). A delicate membrane, or diaphragm (probably condensed basal lamina material), usually covers the fenestrations. Even so, fenestrated capillaries are much more permeable to fluids and small solutes than continuous capillaries are.

Fenestrated capillaries are found wherever active capillary absorption or filtrate formation occurs. For example, fenestrated capillaries in the small intestine receive nutrients from digested food, and those in endocrine organs allow hormones rapid entry into the blood. Fenestrated capillaries with perpetually open pores occur in the kidneys, where rapid filtration of blood plasma is essential.

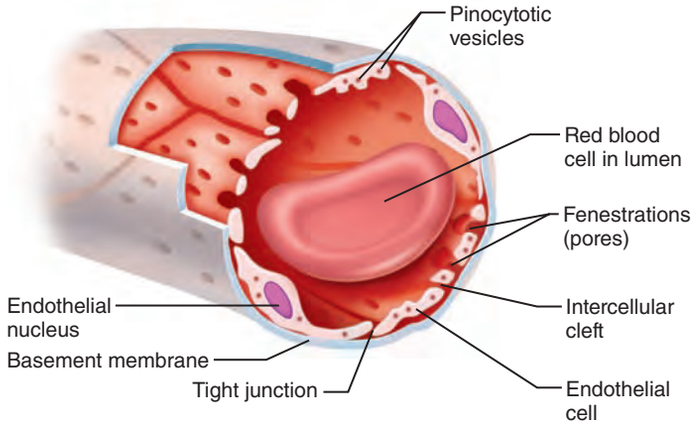
Sinusoid Capillaries (Sinusoids)

Sinusoid capillaries, or **sinusoids** (si′nŭ-soyds), are highly modified, leaky capillaries found only in the liver, bone marrow, spleen, and adrenal medulla. Sinusoids have large, irregularly shaped lumens and are usually fenestrated. Their endothelial lining has fewer tight junctions and larger intercellular clefts than ordinary capillaries (Figure 19.3c).

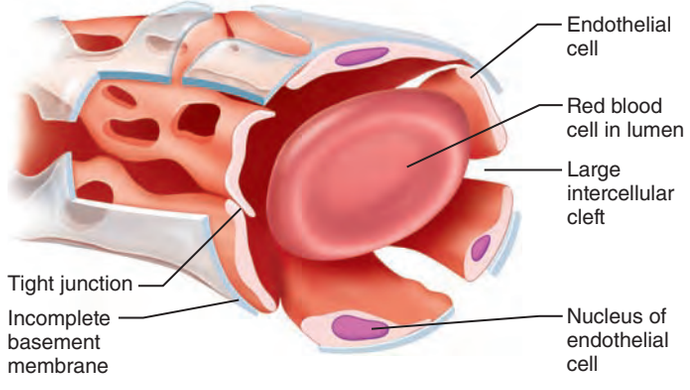
These structural adaptations allow large molecules and even blood cells to pass between the blood and surrounding tissues. In the liver, the endothelium of the sinusoids is *discontinuous* and its lining includes large **stellate macrophages** (hepatic macrophages), which remove and destroy any bacteria. In other organs, such as the spleen, phagocytes located just outside the sinusoids stick cytoplasmic extensions through the intercellular clefts into the sinusoid lumen to get at their "prey." Blood flows sluggishly through the tortuous sinusoid channels, allowing time for it to be modified in various ways.



(a) Continuous capillary. Least permeable, and most common (e.g., skin, muscle).

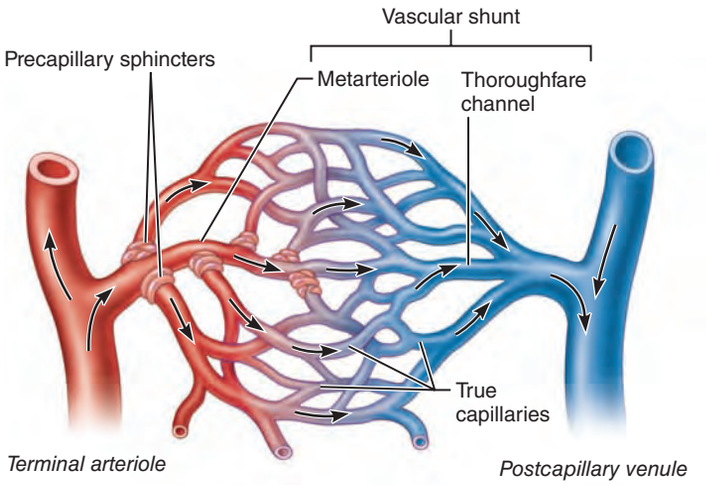


(b) Fenestrated capillary. Large fenestrations (pores) increase permeability. Occurs in areas of active absorption or filtration (e.g., kidney, small intestine).

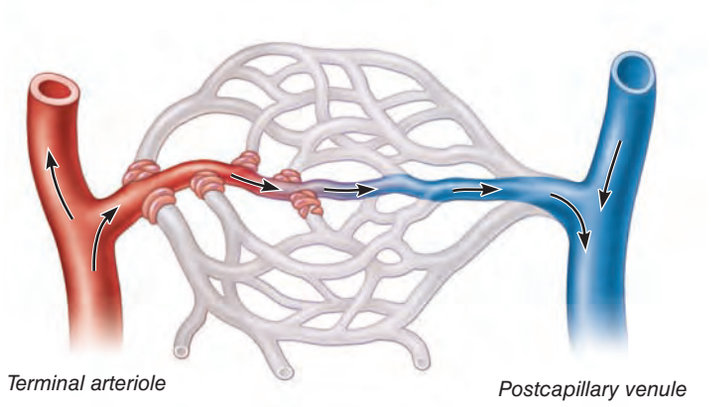


(c) Sinusoid capillary. Most permeable. Occurs in special locations (e.g., liver, bone marrow, spleen).

Figure 19.3 Capillary structure. Note that the basement membrane is incomplete only in (c) and that pericytes most often occur on continuous capillaries.



(a) Sphincters open—blood flows through true capillaries.



(b) Sphincters closed—blood flows through metarteriole–thoroughfare channel and bypasses true capillaries.

Figure 19.4 Anatomy of a capillary bed.

Capillary Beds

Capillaries do not function independently. Instead they form interweaving networks called **capillary beds**. The flow of blood from an arteriole to a venule—that is, through a capillary bed—is called the **microcirculation**. In most body regions, a capillary bed consists of two types of vessels: (1) a *vascular shunt* (metarteriole–thoroughfare channel), a short vessel that directly connects the arteriole and venule at opposite ends of the bed, and (2) *true capillaries*, the actual *exchange vessels* **(Figure 19.4)**.

The **terminal arteriole** feeding the bed leads into a **metarteriole** (a vessel structurally intermediate between an arteriole and a capillary), which is continuous with the **thoroughfare channel** (intermediate between a capillary and a venule). The thoroughfare channel, in turn, joins the **postcapillary venule** that drains the bed.

The **true capillaries** number 10 to 100 per capillary bed, depending on the organ or tissues served. They usually branch off the metarteriole (proximal end of the shunt) and return to the thoroughfare channel (the distal end), but occasionally they spring from the terminal arteriole and empty directly into the venule. A cuff of smooth muscle fibers, called a **precapillary sphincter**, surrounds the root of each true capillary at the metarteriole and acts as a valve to regulate blood flow into the capillary.

Blood flowing through a terminal arteriole may go either through the true capillaries or through the shunt. When the precapillary sphincters are relaxed (open), as in Figure 19.4a, blood flows through the true capillaries and takes part in exchanges with tissue cells. When the sphincters are contracted (closed), as in Figure 19.4b, blood flows through the shunts and bypasses the tissue cells.

Local chemical conditions and arteriolar vasomotor nerve fibers regulate the amount of blood entering a capillary bed. A bed may be flooded with blood or almost completely bypassed, depending on conditions in the body or in that specific organ. For example, suppose you have just eaten and are sitting relaxed, listening to your favorite musical group. Food is being digested, and blood is circulating freely through the true capillaries of your gastrointestinal organs to receive the breakdown products of digestion. Between meals, however, most of these same capillary pathways are closed.

To take another example, when you exercise vigorously, blood is rerouted from your digestive organs (food or no food) to the capillary beds of your skeletal muscles where it is more immediately needed. This rerouting helps explain why vigorous exercise right after a meal can cause indigestion or abdominal cramps.

Venous System

✓ Describe the structure and function of veins, and explain how veins differ from arteries.

Veins carry blood from the capillary beds toward the heart. Along the route, the diameter of successive venous vessels increases, and their walls gradually thicken as they progress from venules to larger and larger veins.

Venules

Capillaries unite to form **venules**, which range from 8 to 100 μm in diameter. The smallest venules, the *postcapillary venules*, consist entirely of endothelium around which pericytes congregate. Postcapillary venules are extremely porous (more like capillaries than veins in this way), and fluid and white blood cells move easily from the bloodstream through their walls. Indeed, a well-recognized sign of inflammation is adhesion of white blood cells to the postcapillary venule endothelium, followed by their migration through the wall into the inflamed tissue.

Larger venules have one or two layers of smooth muscle cells (a scanty tunica media) and a thin tunica externa as well.

Veins

Venules join to form *veins*. Veins usually have three distinct tunics, but their walls are always thinner and their lumens larger than those of corresponding arteries (see Figure 19.1 and Table 19.1). Consequently, in histological preparations, veins are usually collapsed and their lumens appear slitlike.

There is relatively little smooth muscle or elastin in the tunica media, which is poorly developed and tends to be thin even in the largest veins. The tunica externa is the heaviest wall layer. Consisting of thick longitudinal bundles of collagen fibers and elastic networks, it is often several times thicker than the tunica media. In the largest veins—the venae cavae, which return blood directly to the heart—longitudinal bands of smooth muscle make the tunica externa even thicker.

With their large lumens and thin walls, veins can accommodate a fairly large blood volume. Veins are called **capacitance vessels** and **blood reservoirs** because they can hold up to 65% of the body's blood supply at any time **(Figure 19.5)**. Even so, they are normally only partially filled.

The walls of veins can be much thinner than arterial walls without danger of bursting because the blood pressure in veins is low. However, the low-pressure condition demands several structural adaptations to ensure that veins return blood to the heart at the same rate it was pumped into the circulation. One such adaptation is their large-diameter lumens, which offer relatively little resistance to blood flow.

Venous Valves

Another adaptation is valves that prevent blood from flowing backward. **Venous valves**, formed from folds of the tunica intima, resemble the semilunar valves of the heart in both structure and function (see Figure 19.1). Venous valves are most abundant in the veins of the limbs, where gravity opposes the upward flow of blood. They are usually absent in veins of the thoracic and abdominal body cavities.

The effectiveness of venous valves is demonstrated by this simple experiment: Hang one hand by your side until the blood vessels on its dorsal aspect distend with blood. Next place two fingertips against one of the distended veins, and pressing firmly, move the superior finger proximally along the vein and then release that finger. The vein will remain collapsed (flat) despite the pull of gravity. Finally, remove your distal fingertip and watch the vein refill with blood.

Homeostatic Imbalance 19.1

Varicose veins are veins that are tortuous and dilated because of incompetent (leaky) valves. More than 15% of adults suffer from varicose veins, usually in the lower limbs.

Several factors contribute, including heredity and conditions that hinder venous return, such as prolonged standing in one position, obesity, or pregnancy. Both the "potbelly" of an overweight person and the enlarged uterus of a pregnant woman exert downward pressure on vessels of the groin, restricting return of blood to the heart. Consequently, blood pools in the lower limbs, and with time, the valves weaken and the venous walls stretch and become floppy. Superficial veins, which receive little support from surrounding tissues, are especially susceptible.

Elevated venous pressure can also cause varicose veins. For example, straining to deliver a baby or have a bowel movement raises intra-abdominal pressure, preventing blood from draining from anal veins. The resulting varicosities in the anal veins are called *hemorrhoids* (hem′ŏ-roidz). ✚

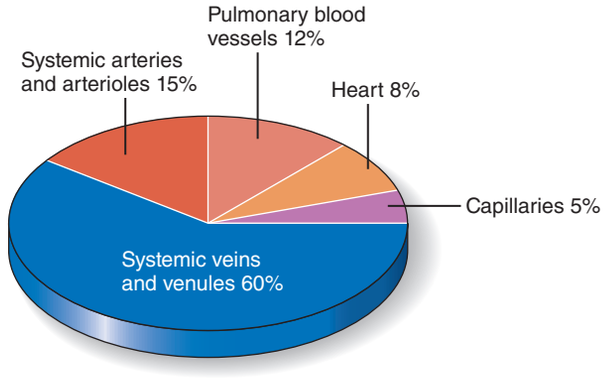


Figure 19.5 Relative proportion of blood volume throughout the cardiovascular system. The systemic veins are called capacitance vessels because they are distensible and contain a large proportion of the blood volume. Pulmonary blood vessels supply the lungs; systemic blood vessels supply the rest of the body.

Venous Sinuses

Venous sinuses, such as the *coronary sinus* of the heart and the *dural venous sinuses* of the brain, are highly specialized, flattened veins with extremely thin walls composed only of endothelium. They are supported by the tissues that surround them, rather than by any additional tunics. The dural venous sinuses, which receive cerebrospinal fluid and blood draining from the brain, are reinforced by the tough dura mater that covers the brain surface.

Vascular Anastomoses

Blood vessels form special interconnections called **vascular anastomoses** (ah-nas″to-mo′sēz; "coming together"). Most organs receive blood from more than one arterial branch, and arteries supplying the same territory often merge, forming **arterial anastomoses**. These anastomoses provide alternate pathways, called **collateral channels**, for blood to reach a given body region. If one branch is cut or blocked by a clot, the collateral channel can often provide sufficient blood to the area.

Arterial anastomoses occur around joints, where active movement may hinder blood flow through one channel. They are also common in abdominal organs, the heart, and the brain (for example, the *cerebral arterial circle* in Figure 19.22d on p. 727). Arteries that supply the retina, kidneys, and spleen either do not anastomose or have a poorly developed collateral circulation. If their blood flow is interrupted, cells supplied by such vessels die.

The metarteriole–thoroughfare channel shunts of capillary beds that connect arterioles and venules are examples of **arteriovenous anastomoses**. Veins interconnect much more freely than arteries, and **venous anastomoses** are common. (You may be able to see venous anastomoses through the skin on the dorsum of your hand.) Because venous anastomoses are abundant, an occluded vein rarely blocks blood flow or leads to tissue death.

Atherosclerosis? Get Out the Cardiovascular Drāno

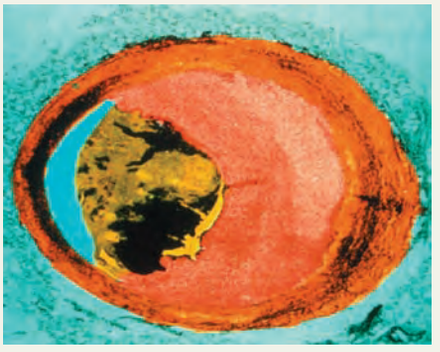
When pipes get **clogged**, it is usually because we've dumped something down the drain that shouldn't be there—a greasy mass or a hairball. Sometimes, pipes get blocked when something is growing inside them (tree roots, for example), trapping the normal sludge coming through (see top photo). In **arteriosclerosis**, the walls of our arteries become thicker and stiffer, and **hypertension** results. In **atherosclerosis**, the most common form of arteriosclerosis, small patchy thickenings called *atheromas* form that can intrude into the vessel lumen, making it easy for **arterial spasms** or a roaming **blood clot** to close the vessel completely.

Although all arteries are susceptible to atherosclerosis, those most often affected are the aorta and the coronary and carotid arteries.

Onset and Stages

Atherosclerosis indirectly causes half of the deaths in the Western world. How does this scourge of blood vessels come about? The development of a full-blown atheroma is believed to occur in several stages.

1. **The endothelium is injured.** According to the *response to injury hypothesis*, the initial event is damage to the tunica intima caused by bloodborne chemicals, hypertension, components of cigarette smoke, or viral or bacterial infections. Researchers suspect that almost any type of chronic infection—even periodontal problems—could set the stage for atherosclerosis. How a bacterium such as *Chlamydophila pneumoniae* (found in some plaques) triggers atheroma development is not completely understood, but we know that any injury to the endothelium sets off the alarm summoning the immune system and the inflammatory process to repair the damage.
2. **Lipids accumulate and oxidize in the tunica intima.** Injured endothelial cells release chemotactic agents and growth (mitosis-inducing) factors, and begin to transport and modify lipids picked up from the blood, particularly low-density lipoproteins (LDLs) that deliver cholesterol to tissue cells via the bloodstream. This accumulated LDL oxidizes in the hostile inflammatory environment. This not only damages neighboring cells, but also acts as a chemotactic agent, attracting macrophages. Some of these macrophages become so engorged with LDLs that they are transformed into lipid-laden *foam cells*. Accumulating foam cells form a **fatty streak**, the first visible sign of an atheroma.
3. **Smooth muscle cells proliferate and a fibrous cap forms.** Smooth muscle cells migrate from the tunica media and deposit collagen and elastic fibers, thickening the intima and producing fibrous lesions with a core of dead and dying foam cells called **fibrous** or **atherosclerotic plaques**. At first the vessel walls accommodate the growing plaque by expanding outward, but eventually these fatty mounds begin to protrude into the vessel lumen, producing full-blown atherosclerosis (see bottom photo).
4. **The plaque becomes unstable.** As the plaque continues to enlarge, the cells at its center die. Calcium is deposited, and collagen fiber production by smooth muscle cells declines. Now called a **complicated plaque**, it is unstable and prone to rupture.



Top **A pipe clogged by accumulated deposits.** ***Bottom*** **Atherosclerotic plaques nearly close a human artery.**

Consequences

The presence of plaques stiffens artery walls and results in *hypertension*. The increased pressure stresses the plaques, making them even more unstable. Plaques also constrict the vessel and cause the arterial walls to fray and ulcerate, conditions that encourage blood sludging and backup, platelet adhesion, and thrombus formation.

Two other factors also promote thrombus formation: (1) Endothelial cells damaged by plaques release less nitric oxide and prostacyclin—chemicals that would otherwise promote vasodilation and inhibit platelet aggregation. (2) *Lipoprotein (a)*, an altered form of LDL found in some individuals, inhibits fibrinolysis by competing with plasminogen.

Plaque formation increases the risk of myocardial infarction, strokes, and aneurysms, and is responsible for the pain (angina) that occurs when heart muscle is ischemic. We often think of large complicated plaques as being the culprits for heart attacks and strokes, but plaques of any size may rupture and form a clot. At least one-third of all heart attacks are caused by plaques too small to be seen on traditional angiograms. They cause no warning symptoms, and victims appear perfectly healthy until they drop dead! One goal of current research is to find ways to identify these vulnerable plaques.

Risk Factors

Why are some of us so troubled by atherosclerosis while others are seemingly immune to its ravages? A large number of interacting risk factors determine the progress of atheroma development. Risk factors include increasing age, male sex, a family history of atherosclerosis, high blood cholesterol, hypertension, cigarette smoking, lack of exercise, diabetes, obesity, stress, and intake of trans fats.

A growing body of evidence links systemic inflammation with the formation

and subsequent rupture of atherosclerotic plaques. *C-reactive protein* is a marker of systemic inflammation that is measured to predict the likelihood of future heart attacks and strokes.

Prevention and Treatment

Some risk factors are under our control. We can avoid smoking, lose weight, exercise regularly to increase blood levels of high-density lipoprotein (HDL, the "good" lipoprotein that removes cholesterol from vessel walls and carries it to the liver), and eat a healthy diet low in saturated and trans fats.

But for many of us, these measures are not enough and a pharmaceutical approach is needed. At first it was hoped that cholesterol-lowering drugs called statins would act as cardiovascular Drāno, in effect washing fatty plaques off the walls. Statins do lower LDL, but decrease plaque size by only a small amount. A significant part of their action, though, is their unexpected side benefit—anti-inflammatory activity, which appears to help stabilize existing plaques and keep them from rupturing.

The humble aspirin can also play a role. The American Heart Association recommends that people at high risk for heart attack or stroke take one baby aspirin (81 mg) daily to prevent clot formation when plaques do rupture.

Larger plaques that partially block arteries are treated in much the same way we would treat a blocked sewer pipe—dig it up and replace it or call Roto-Rooter to drill through the obstruction. In *coronary bypass surgery*, veins removed from the legs or small arteries removed from the thoracic cavity are implanted in the heart to restore myocardial circulation. In *balloon angioplasty*, a catheter with a balloon tightly packed into its tip is threaded through the vessels. When the catheter reaches the obstruction, the balloon is inflated to compress the fatty mass against the vessel wall.

Angioplasty temporarily clears the path, but *restenoses* (new blockages) often occur. *Stents*, short metal-mesh tubes that look like a ziti noodle, are inserted into the newly dilated vessels in order to hold the vessel open. Stents that slowly release drugs that inhibit smooth muscle proliferation help reduce restenosis, but these often become clogged as well. Treating the area with bursts of radiation (*brachytherapy*) can help.

When an atheroma ruptures and induces clot formation, *thrombolytic* (*clot-dissolving*) *agents* can help. A genetically engineered form of the naturally occurring *tissue plasminogen activator* (*tPA*) is injected directly into the blocked vessel. tPA restores blood flow quickly and puts an early end to many heart attacks and strokes in progress.

Of course, it's best to prevent atherosclerosis from progressing in the first place by changing our lifestyles. Americans like their burgers and butter. But if heart disease can be prevented by reversing atherosclerosis, many people with diseased arteries may be willing to trade lifelong habits for a healthy old age!

☑ Check Your Understanding

3. Name the type of artery that matches each description: major role in dampening the pulsatile pressure of heart contractions; vasodilation or constriction determines blood flow to individual capillary beds; have the thickest tunica media relative to their lumen size.
4. Look at Figure 19.4 on p. 698 and assume that the capillary bed depicted is in your calf muscle. Which condition—(a) or (b)—would the bed be in if you were doing calf raises at the gym?
5. What is the function of venous valves? What forms the valves?
6. In the systemic circuit, which contains more blood—arteries or veins—or is it the same?

For answers, see Appendix H.

PART 2
Physiology of Circulation

Have you ever climbed a mountain? Well, get ready to climb a hypothetical mountain as you learn about circulatory dynamics. Like scaling a mountain, tackling blood pressure regulation and other topics of cardiovascular physiology is challenging while you're doing it, and exhilarating when you succeed. Let's begin the climb.

To sustain life, blood must be kept circulating. By now, you are aware that the heart is the pump, the arteries are pressure reservoirs and conduits, the arterioles are resistance vessels that control distribution, the capillaries are exchange sites, and the veins are conduits and blood reservoirs. Now for the dynamics of this system.

Introduction to Blood Flow, Blood Pressure, and Resistance

✓ Define blood flow, blood pressure, and resistance, and explain the relationships between these factors.

First we need to define three physiologically important terms—blood flow, blood pressure, and resistance—and examine how these factors relate to the physiology of blood circulation.

Definition of Terms

Blood Flow

Blood flow is the volume of blood flowing through a vessel, an organ, or the entire circulation in a given period (ml/min). If we consider the entire vascular system, blood flow is equivalent to cardiac output (CO), and under resting conditions, it is relatively constant. At any given moment, however, blood flow through *individual* body organs may vary widely according to their immediate needs.

Blood Pressure (BP)

Blood pressure (BP), the force per unit area exerted on a vessel wall by the contained blood, is expressed in millimeters of mercury (mm Hg). For example, a blood pressure of 120 mm Hg is equal to the pressure exerted by a column of mercury 120 mm high.

Unless stated otherwise, the term *blood pressure* means systemic arterial blood pressure in the largest arteries near the heart. The pressure gradient—the *differences* in blood pressure within the vascular system—provides the driving force that keeps blood moving, always from an area of higher pressure to an area of lower pressure, through the body.

Resistance

Resistance is opposition to flow and is a measure of the amount of friction blood encounters as it passes through the vessels. Because most friction is encountered in the peripheral (systemic) circulation, well away from the heart, we generally use the term **peripheral resistance**.

There are three important sources of resistance: blood viscosity, vessel length, and vessel diameter.

Blood Viscosity The internal resistance to flow that exists in all fluids is *viscosity* (vis-kos′ĭ-te) and is related to the thickness or "stickiness" of a fluid. The greater the viscosity, the less easily molecules slide past one another and the more difficult it is to get and keep the fluid moving. Blood is much more viscous than water. Because it contains formed elements and plasma proteins, it flows more slowly under the same conditions.

Blood viscosity is fairly constant, but conditions such as polycythemia (excessive numbers of red blood cells) can increase blood viscosity and, hence, resistance. On the other hand, if the red blood cell count is low, as in some anemias, blood is less viscous and peripheral resistance declines.

Total Blood Vessel Length The relationship between total blood vessel length and resistance is straightforward: the longer the vessel, the greater the resistance. For example, an infant's blood vessels lengthen as he or she grows to adulthood, and so both peripheral resistance and blood pressure increase.

Blood Vessel Diameter Because blood viscosity and vessel length are normally unchanging, the influence of these factors can be considered constant in healthy people. However, blood vessel diameter changes frequently and significantly alters peripheral resistance. How so? The answer lies in principles of fluid flow. Fluid close to the wall of a tube or channel is slowed by friction as it passes along the wall, whereas fluid in the center of the tube flows more freely and faster. You can verify this by watching the flow of water in a river. Water close to the bank hardly seems to move, while that in the middle of the river flows quite rapidly.

In a tube of a given size, the relative speed and position of fluid in the different regions of the tube's cross section remain constant, a phenomenon called *laminar flow* or *streamlining*. The smaller the tube, the greater the friction, because relatively more of the fluid contacts the tube wall, where its movement is impeded.

Resistance varies *inversely* with the *fourth power* of the vessel radius (one-half the diameter). This means, for example, that if the radius of a vessel doubles, the resistance drops to one-sixteenth of its original value ($r^4 = 2 \times 2 \times 2 \times 2 = 16$ and $1/r^4 = 1/16$). For this reason, the large arteries close to the heart, which do not change dramatically in diameter, contribute little to peripheral resistance. Instead, the small-diameter arterioles, which can enlarge or constrict in response to neural and chemical controls, are the major determinants of peripheral resistance.

When blood encounters either an abrupt change in vessel diameter or rough or protruding areas of the tube wall (such as the fatty plaques of atherosclerosis), the smooth laminar blood flow is replaced by *turbulent flow*, that is, irregular fluid motion where blood from the different laminae mixes. Turbulence dramatically increases resistance.

Relationship Between Flow, Pressure, and Resistance

Now that we have defined these terms, let's summarize the relationships between them.

- Blood flow (F) is *directly* proportional to the difference in blood pressure (ΔP) between two points in the circulation, that is, the blood pressure, or hydrostatic pressure, gradient. Thus, when ΔP increases, blood flow speeds up, and when ΔP decreases, blood flow declines.
- Blood flow is *inversely* proportional to the peripheral resistance (R) in the systemic circulation; if R increases, blood flow decreases.

We can express these relationships by the formula

$$F = \frac{\Delta P}{R}$$

Of these two factors influencing blood flow, R is far more important than ΔP in influencing local blood flow because R can easily be changed by altering blood vessel diameter. For example, when the arterioles serving a particular tissue dilate (thus decreasing the resistance), blood flow to that tissue increases, even though the systemic pressure is unchanged or may actually be falling.

Check Your Understanding

7. List three factors that determine resistance in a vessel. Which of these factors is physiologically most important?
8. Suppose vasoconstriction decreases the diameter of a vessel to one-third its size. What happens to the rate of flow through that vessel? Calculate the expected size of the change.

For answers, see Appendix H.

Systemic Blood Pressure

✓ Describe how blood pressure differs in the arteries, capillaries, and veins.

Any fluid driven by a pump through a circuit of closed channels operates under pressure, and the nearer the fluid is to the pump, the greater the pressure exerted on the fluid. Blood flow in blood vessels is no exception, and blood flows through the blood vessels along a pressure gradient, always moving from higher- to lower-pressure areas. Fundamentally, *the pumping action of the heart generates blood flow. Pressure results when flow is opposed by resistance.*

As illustrated in **Figure 19.6**, systemic blood pressure is highest in the aorta and declines throughout the pathway to finally reach 0 mm Hg in the right atrium. The steepest drop in blood pressure occurs in the arterioles, which offer the greatest

resistance to blood flow. However, as long as a pressure gradient exists, no matter how small, blood continues to flow until it completes the circuit back to the heart.

Arterial Blood Pressure

Arterial blood pressure reflects two factors: (1) how much the elastic arteries close to the heart can stretch (their *compliance* or *distensibility*) and (2) the volume of blood forced into them at any time. If the amounts of blood entering and leaving the elastic arteries in a given period were equal, arterial pressure would be constant. Instead, as Figure 19.6 reveals, blood pressure is *pulsatile*—it rises and falls in a regular fashion—in the elastic arteries near the heart.

As the left ventricle contracts and expels blood into the aorta, it imparts kinetic energy to the blood, which stretches the elastic aorta as aortic pressure reaches its peak. Indeed, if the aorta were opened during this period, blood would spurt upward 5 or 6 feet! This pressure peak generated by ventricular contraction is called the **systolic pressure** (sis-tah′lik) and averages 120 mm Hg in healthy adults. Blood moves forward into the arterial bed because the pressure in the aorta is higher than the pressure in the more distal vessels.

During diastole, the aortic valve closes, preventing blood from flowing back into the heart. The walls of the aorta (and other elastic arteries) recoil, maintaining sufficient pressure to keep the blood flowing forward into the smaller vessels. During this time, aortic pressure drops to its lowest level (approximately 70 to 80 mm Hg in healthy adults), called the **diastolic pressure** (di-as-tah′lik). You can picture the elastic arteries as pressure reservoirs that operate as auxiliary pumps to keep blood circulating throughout the period of diastole, when the heart is relaxing. Essentially, the volume and energy of blood stored in the elastic arteries during systole are given back during diastole.

The difference between the systolic and diastolic pressures is called the **pulse pressure**. It is felt as a throbbing pulsation in an artery (a *pulse*) during systole, as ventricular contraction forces blood into the elastic arteries and expands them. Increased stroke volume and faster blood ejection from the heart (a result of increased contractility) raise pulse pressure *temporarily*. Atherosclerosis chronically increases pulse pressure because the elastic arteries become less stretchy.

Because aortic pressure fluctuates up and down with each heartbeat, the important pressure figure to consider is the **mean arterial pressure (MAP)**—the pressure that propels the blood to the tissues. Diastole usually lasts longer than systole, so MAP is not simply the value halfway between systolic and diastolic pressures. Instead, it is roughly equal to the diastolic pressure plus one-third of the pulse pressure.

$$\text{MAP} = \text{diastolic pressure} + \frac{\text{pulse pressure}}{3}$$

For a person with a systolic blood pressure of 120 mm Hg and a diastolic pressure of 80 mm Hg:

$$\text{MAP} = 80 \text{ mm Hg} + \frac{40 \text{ mm Hg}}{3} = 93 \text{ mm Hg}$$

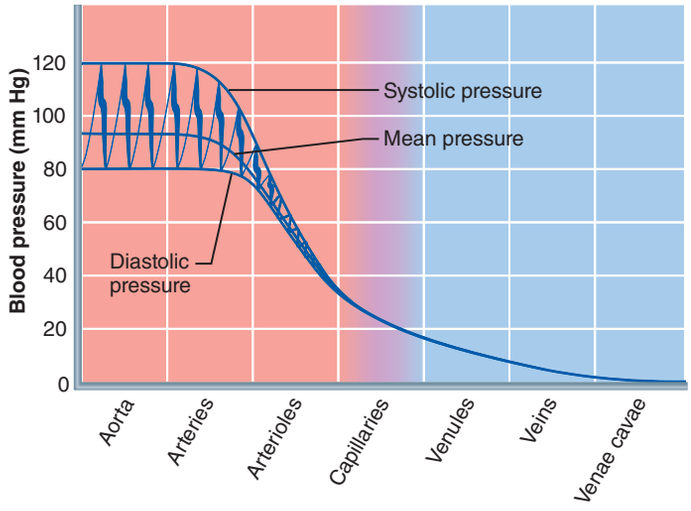


Figure 19.6 Blood pressure in various blood vessels of the systemic circulation.

MAP and pulse pressure both decline with increasing distance from the heart. The MAP loses ground to the never-ending friction between the blood and the vessel walls, and the pulse pressure is gradually phased out in the less elastic muscular arteries, where elastic rebound of the vessels ceases to occur. At the end of the arterial tree, blood flow is steady and the pulse pressure has disappeared.

Capillary Blood Pressure

As Figure 19.6 shows, by the time blood reaches the capillaries, blood pressure has dropped to approximately 35 mm Hg and by the end of the capillary beds is only around 17 mm Hg. Such low capillary pressures are desirable because (1) capillaries are fragile and high pressures would rupture them, and (2) most capillaries are extremely permeable and thus even the low capillary pressure can force solute-containing fluids (filtrate) out of the bloodstream into the interstitial space.

As we describe later in this chapter, these fluid flows are important for continuously refreshing the interstitial fluid.

Venous Blood Pressure

Unlike arterial pressure, which pulsates with each contraction of the left ventricle, venous blood pressure is steady and changes very little during the cardiac cycle. The pressure gradient in the veins, from venules to the termini of the venae cavae, is only about 15 mm Hg (that from the aorta to the ends of the arterioles is about 60 mm Hg).

The difference in pressure between an artery and a vein becomes very clear when the vessels are cut. If a vein is cut, the blood flows evenly from the wound, but a lacerated artery spurts blood. The very low pressure in the venous system reflects the cumulative effects of peripheral resistance, which dissipates most of the energy of blood pressure (as heat) during each circuit.

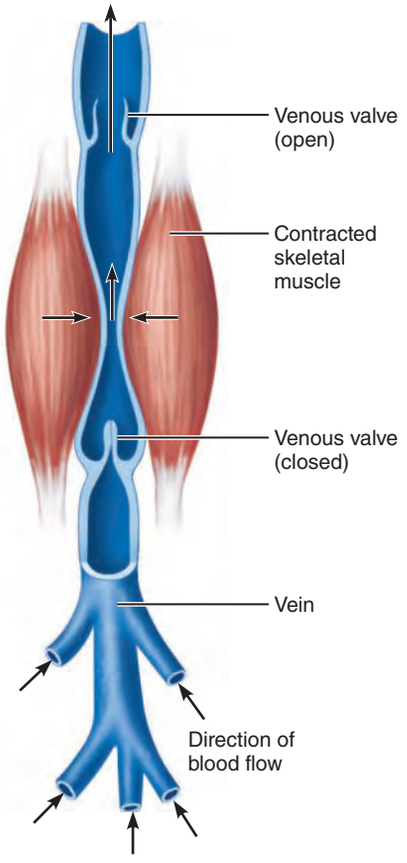


Figure 19.7 The muscular pump. When contracting skeletal muscles press against a vein, they force open the valves proximal to the area of contraction and blood is propelled toward the heart. Backflowing blood closes the valves distal to the area of contraction.

Despite the structural modifications of veins (large lumens and valves), venous pressure is normally too low to promote adequate venous return. For this reason, three functional adaptations are critically important to venous return:

- **The muscular pump.** The **muscular pump** consists of skeletal muscle activity. As the skeletal muscles surrounding the deep veins contract and relax, they "milk" blood toward the heart, and once blood passes each successive valve, it cannot flow back **(Figure 19.7)**. People who earn their living in "standing professions," such as hairdressers and dentists, often have swollen ankles because blood pools in their feet and legs. Indeed, standing for prolonged periods may cause fainting because skeletal muscle inactivity reduces venous return.
- **The respiratory pump.** The **respiratory pump** moves blood up toward the heart as pressure changes in the ventral body cavity during breathing. As we inhale, abdominal pressure increases, squeezing local veins and forcing blood toward the heart. At the same time, the pressure in the chest decreases, allowing thoracic veins to expand and speeding blood entry into the right atrium.
- **Sympathetic venoconstriction.** Sympathetic venoconstriction reduces the volume of blood in the veins—the capacitance vessels. As the layer of smooth muscle around the veins constricts under sympathetic control, venous volume is reduced and blood is pushed toward the heart.

All three of these functional adaptations increase venous return, which increases stroke volume (by the Frank-Starling mechanism) and therefore increases cardiac output.

Maintaining Blood Pressure

- ✓ List and explain the factors that influence blood pressure, and describe how blood pressure is regulated.
- ✓ Define hypertension. Describe its manifestations and consequences.

Maintaining a steady flow of blood from the heart to the toes is vital for organs to function properly. But making sure a person jumping out of bed in the morning does not keel over from inadequate blood flow to the brain requires the finely tuned cooperation of the heart, blood vessels, and kidneys—all supervised by the brain.

Central among the homeostatic mechanisms that regulate cardiovascular dynamics are those that maintain blood pressure, principally *cardiac output*, *peripheral resistance*, and *blood volume*. If we rearrange the formula pertaining to blood flow presented on p. 702, we can see how cardiac output (blood flow of the entire circulation) and peripheral resistance relate to blood pressure:

$$F = \Delta P/R \quad \text{or} \quad CO = \Delta P/R \quad \text{or} \quad \Delta P = CO \times R$$

Clearly, blood pressure varies *directly* with CO and *R*. Additionally, blood pressure varies directly with blood volume because CO depends on blood volume (the heart can't pump out what doesn't enter its chambers).

So in theory, a change (increase or decrease) in any of these variables would cause a corresponding change in blood pressure. However, what *really* happens in the body is that changes in one variable that threaten blood pressure homeostasis are quickly compensated for by changes in the other variables.

As we described in Chapter 18, CO is equal to *stroke volume* (ml/beat) times *heart rate* (beats/min), and normal CO is 5.0 to 5.5 L/min. **Figure 19.8** shows the main factors determining cardiac output—venous return and the neural and hormonal controls. Remember that the cardioinhibitory center in the medulla is "in charge" of heart rate most of the time and, via the parasympathetic vagus nerves, maintains the *resting heart rate*. During "resting" periods, venous return (end diastolic volume) largely controls stroke volume. During stress, the cardioacceleratory center takes over, activating the sympathetic nervous system and increasing both heart rate (by acting on the SA node) and stroke volume (by enhancing cardiac muscle contractility, which decreases end systolic volume). The enhanced CO, in turn, increases MAP.

In the following discussion we explore factors that regulate blood pressure. *Short-term regulation* by the nervous system and bloodborne hormones alters blood pressure by changing peripheral resistance and CO. *Long-term regulation* alters blood volume via the kidneys. Figure 19.11 (p. 709) summarizes the influence of nearly all of the important factors.

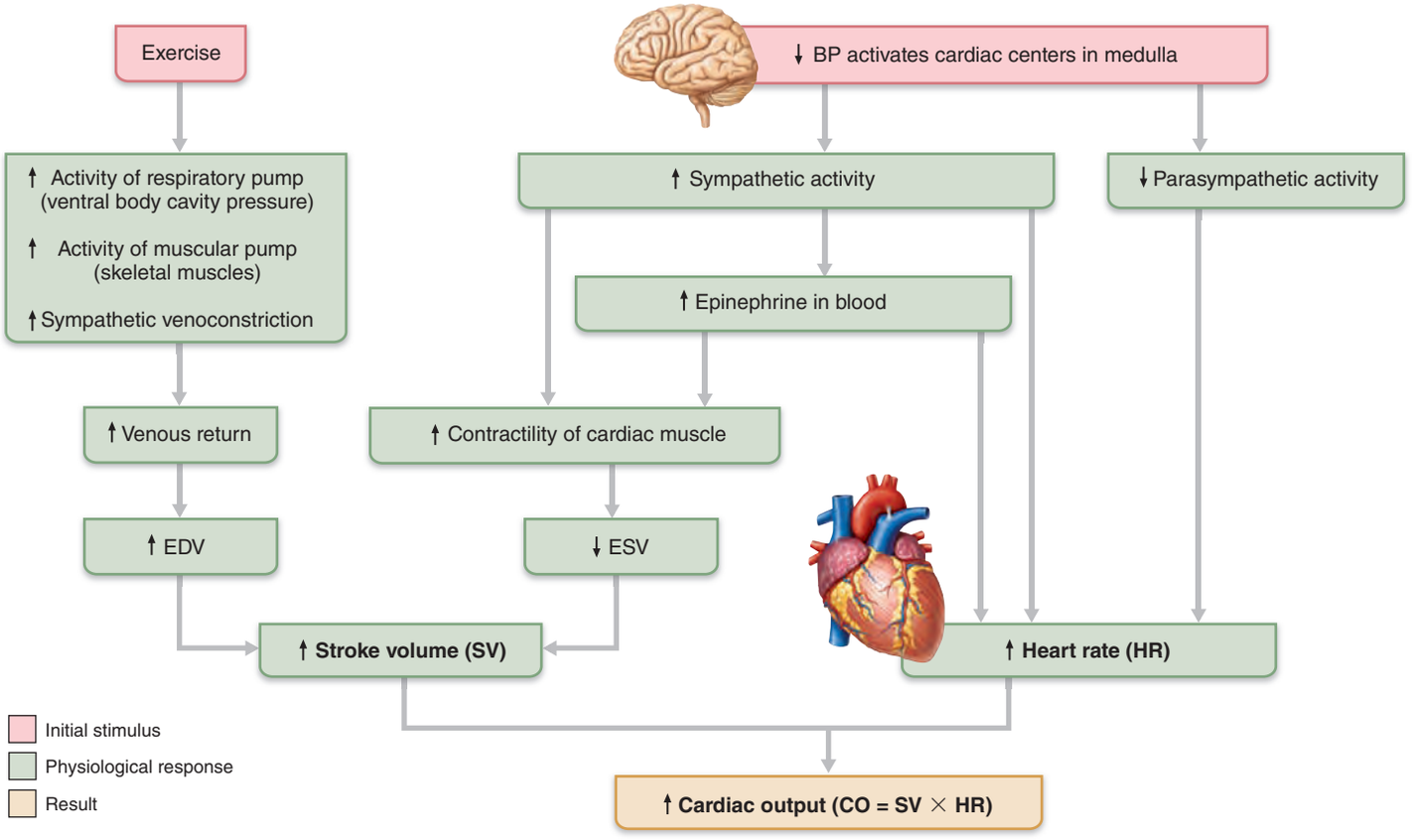


Figure 19.8 Major factors enhancing cardiac output. BP = blood pressure, EDV = end diastolic volume, ESV = end systolic volume.

Short-Term Regulation: Neural Controls

Neural controls alter both cardiac output and peripheral resistance. Neural controls of peripheral resistance are directed at two main goals:

- Maintaining adequate MAP by altering blood vessel diameter on a moment-to-moment basis. (Remember, very small changes in blood vessel diameter cause substantial changes in peripheral resistance, and hence in systemic blood pressure.) Under conditions of low blood volume, all vessels except those supplying the heart and brain are constricted to allow as much blood as possible to flow to those two vital organs.
- Altering blood distribution to respond to specific demands of various organs. For example, during exercise blood is shunted temporarily from the digestive organs to the skeletal muscles.

Most neural controls operate via reflex arcs involving *baroreceptors* and associated afferent fibers. These reflexes are integrated in the cardiovascular center of the medulla, and their output travels via autonomic fibers to the heart and vascular smooth muscle. Occasionally, inputs from *chemoreceptors* and higher brain centers also influence the neural control mechanism.

Role of the Cardiovascular Center

Several clusters of neurons in the medulla oblongata act together to integrate blood pressure control by altering cardiac output and blood vessel diameter. This **cardiovascular center** consists of the *cardiac centers* (the cardioacceleratory and cardioinhibitory centers discussed in Chapter 18), and the **vasomotor center** that controls the diameter of blood vessels.

The vasomotor center transmits impulses at a fairly steady rate along sympathetic efferents called **vasomotor fibers**. These fibers exit from the T_1 through L_2 levels of the spinal cord and innervate the smooth muscle of blood vessels, mainly arterioles. As a result, the arterioles are almost always in a state of moderate constriction, called **vasomotor tone**.

The degree of vasomotor tone varies from organ to organ. Generally, arterioles of the skin and digestive viscera receive vasomotor impulses more frequently and tend to be more strongly constricted than those of skeletal muscles. Any increase in sympathetic activity produces generalized vasoconstriction and raises blood pressure. Decreased sympathetic activity allows the vascular muscle to relax somewhat and lowers blood pressure to basal levels.

Cardiovascular center activity is modified by inputs from (1) baroreceptors (pressure-sensitive mechanoreceptors that respond to changes in arterial pressure and stretch), (2) chemoreceptors (receptors that respond to changes in blood levels of carbon dioxide, H^+, and oxygen), and (3) higher brain centers. Let's take a look.

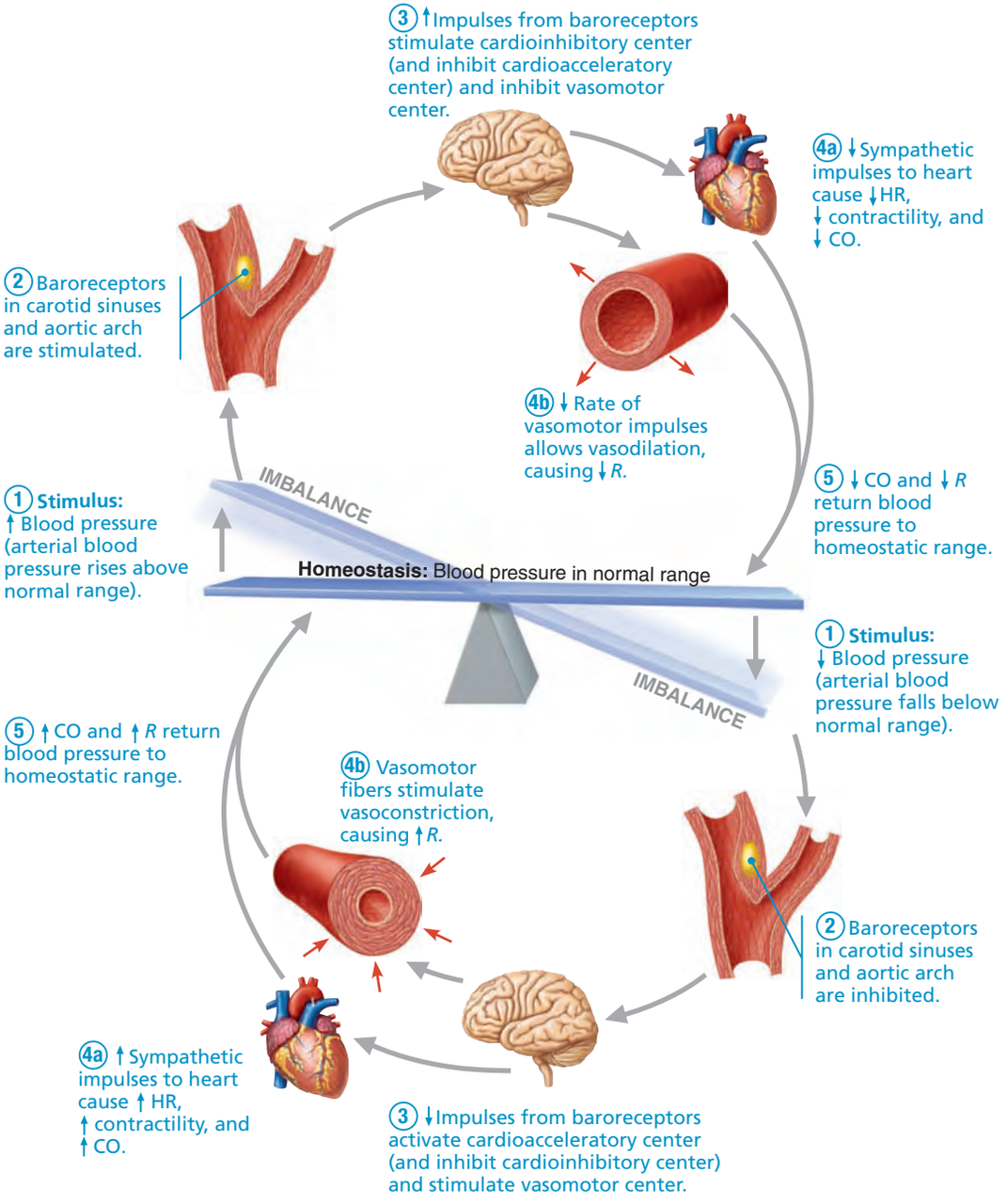


Figure 19.9 Baroreceptor reflexes that help maintain blood pressure homeostasis.
CO = cardiac output; *R* = peripheral resistance; HR = heart rate; BP = blood pressure.

Baroreceptor Reflexes

When arterial blood pressure rises, it activates **baroreceptors**. These stretch receptors are located in the *carotid sinuses* (dilations in the internal carotid arteries, which provide the major blood supply to the brain), in the *aortic arch*, and in the walls of nearly every large artery of the neck and thorax. When stretched, baroreceptors send a rapid stream of impulses to the cardiovascular center, inhibiting the vasomotor and cardioacceleratory centers and stimulating the cardioinhibitory center. The result is a decrease in blood pressure **(Figure 19.9)**.

Three mechanisms bring this about:

- **Arteriolar vasodilation.** Decreased output from the vasomotor center allows arterioles to dilate. As peripheral resistance falls, so does MAP.
- **Venodilation.** Decreased output from the vasomotor center also allows veins to dilate, which shifts blood to the venous reservoirs. This decreases venous return and CO.
- **Decreased cardiac output.** Impulses to the cardiac centers inhibit sympathetic activity and stimulate parasympathetic activity, reducing heart rate and contractile force. As CO falls, so does MAP.

Table 19.2 Effects of Selected Hormones on Blood Pressure

HORMONE	EFFECT ON BP	VARIABLE AFFECTED	SITE OF ACTION
Epinephrine and norepinephrine (NE)	↑	↑ CO (HR and contractility)	Heart (β_1 receptors)
		↑ Peripheral resistance (vasoconstriction)	Arterioles (α receptors)
Angiotensin II	↑	↑ Peripheral resistance (vasoconstriction)	Arterioles
Atrial natriuretic peptide (ANP)	↓	↓ Peripheral resistance (vasodilation)	Arterioles
Antidiuretic hormone (ADH)	↑	↑ Peripheral resistance (vasoconstriction)	Arterioles
		↑ Blood volume (↓ water loss)	Kidney tubule cells
Aldosterone	↑	↑ Blood volume (↓ water and salt loss)	Kidney tubule cells

In the opposite situation, a decline in MAP initiates reflex vasoconstriction and increases cardiac output, bringing blood pressure back up. In this way, peripheral resistance and cardiac output are regulated in tandem to minimize changes in blood pressure.

Rapidly responding baroreceptors protect the circulation against short-term (acute) changes in blood pressure. For example, blood pressure falls (particularly in the head) when you stand up after reclining. Baroreceptors taking part in the **carotid sinus reflex** protect the blood supply to your brain, whereas those activated in the **aortic reflex** help maintain adequate blood pressure in your systemic circuit as a whole.

Baroreceptors are relatively *ineffective* in protecting us against sustained pressure changes, as evidenced by the fact that many people develop chronic hypertension. In such cases, the baroreceptors are "reprogrammed" (adapt) to monitor pressure changes at a higher set point.

Chemoreceptor Reflexes

When the carbon dioxide levels rise, or the pH falls, or oxygen content of the blood drops sharply, **chemoreceptors** in the aortic arch and large arteries of the neck transmit impulses to the cardioacceleratory center, which then increases cardiac output, and to the vasomotor center, which causes reflex vasoconstriction. The rise in blood pressure that follows speeds the return of blood to the heart and lungs.

The most prominent chemoreceptors are the *carotid* and *aortic bodies* located close by the baroreceptors in the carotid sinuses and aortic arch. Chemoreceptors play a larger role in regulating respiratory rate than blood pressure, so we consider their function in Chapter 22.

Influence of Higher Brain Centers

Reflexes that regulate blood pressure are integrated in the medulla oblongata of the brain stem. Although the cerebral cortex and hypothalamus are not involved in routine controls of blood pressure, these higher brain centers can modify arterial pressure via relays to the medullary centers.

For example, the fight-or-flight response mediated by the hypothalamus has profound effects on blood pressure. (Even the simple act of speaking can make your blood pressure jump if the person you are talking to makes you anxious.) The hypothalamus also mediates the redistribution of blood flow and other cardiovascular responses that occur during exercise and changes in body temperature.

Short-Term Regulation: Hormonal Controls

Hormones also help regulate blood pressure, both in the short term via changes in peripheral resistance and in the long term via changes in blood volume (Table 19.2). Paracrines (local chemicals), on the other hand, primarily serve to match blood flow to the metabolic need of a particular tissue. In rare instances, massive release of paracrines can affect blood pressure. We will discuss these paracrines later—here we will examine the short-term effects of hormones.

- **Adrenal medulla hormones.** During periods of stress, the adrenal gland releases **epinephrine** and **norepinephrine (NE)** to the blood. Both hormones enhance the sympathetic response by increasing cardiac output and promoting generalized vasoconstriction.
- **Angiotensin II.** When blood pressure or blood volume are low, the kidneys release renin. Renin acts as an enzyme, ultimately generating **angiotensin II** (an″je-o-ten′sin), which stimulates intense vasoconstriction, promoting a rapid rise in systemic blood pressure. It also stimulates release of aldosterone and ADH, which act in long-term regulation of blood pressure by enhancing blood volume.
- **Atrial natriuretic peptide (ANP).** The atria of the heart produce the hormone **atrial natriuretic peptide (ANP)**, which leads to a reduction in blood volume and blood pressure. As noted in Chapter 16, ANP antagonizes aldosterone and prods the kidneys to excrete more sodium and water from the body, reducing blood volume. It also causes generalized vasodilation.
- **Antidiuretic hormone (ADH).** Produced by the hypothalamus, **antidiuretic hormone** (**ADH**, also called **vasopressin**) stimulates the kidneys to conserve water. It is not usually important in short-term blood pressure regulation. However, when blood pressure falls to dangerously low levels (as during severe hemorrhage), much more ADH is released and helps restore arterial pressure by causing intense vasoconstriction.

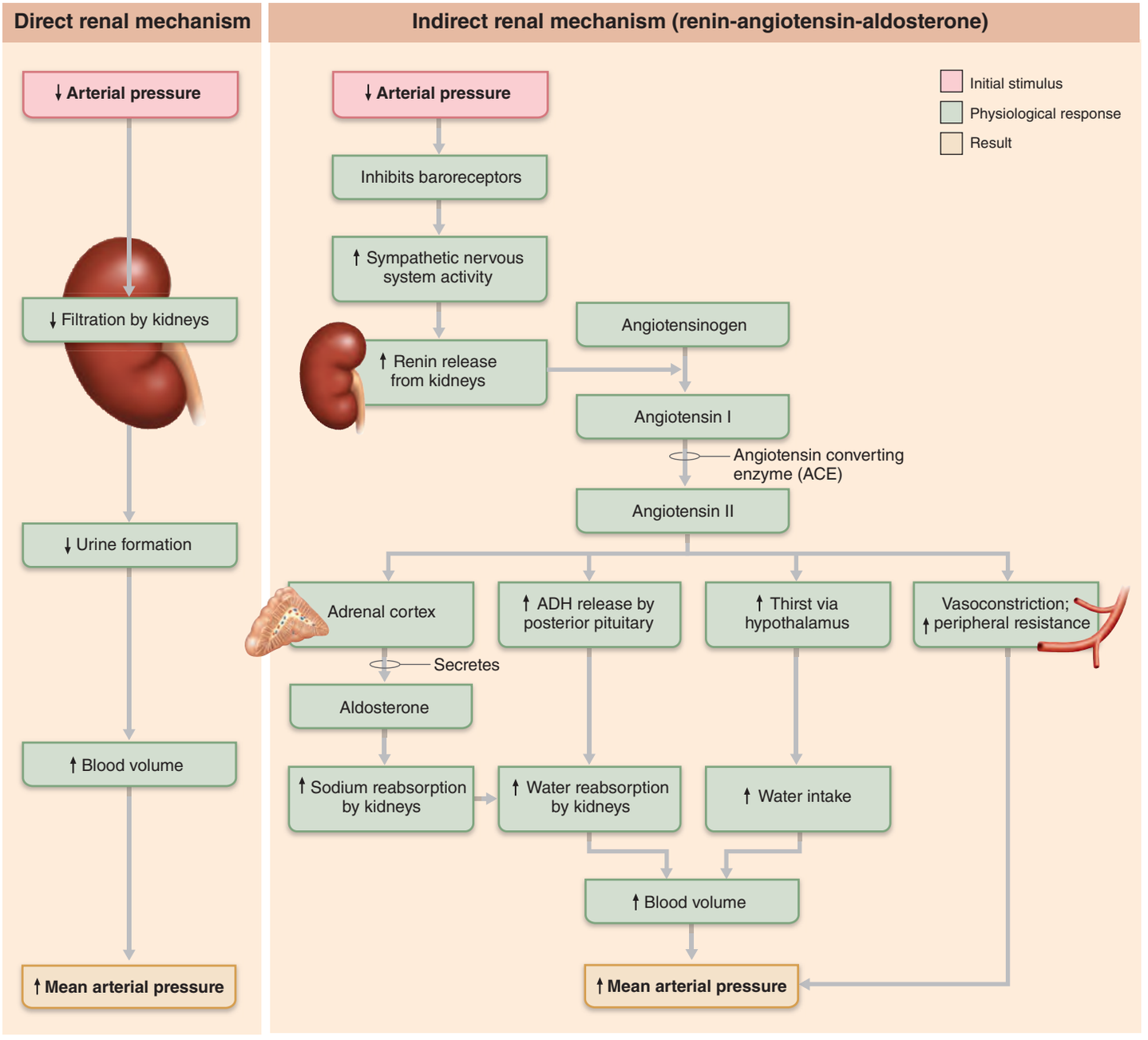


Figure 19.10 Direct and indirect (hormonal) mechanisms for renal control of blood pressure. Low blood pressure also triggers other actions not shown here that increase BP: additional mechanisms of renin release (described in Chapter 25) and short-term actions of the sympathetic nervous system.

Long-Term Regulation: Renal Mechanisms

Unlike short-term controls of blood pressure that alter peripheral resistance and cardiac output, long-term controls alter blood volume. Renal mechanisms mediate long-term regulation.

Although baroreceptors respond to short-term changes in blood pressure, they quickly adapt to prolonged or chronic episodes of high or low pressure. This is where the kidneys step in to restore and maintain blood pressure homeostasis by regulating blood volume. Although blood volume varies with age, body size, and sex, renal mechanisms usually keep it close to 5 L.

As we noted earlier, blood volume is a major determinant of cardiac output (via its influence on venous return, EDV, and stroke volume). An increase in blood volume is followed by a rise in blood pressure, and anything that increases blood volume—such as excessive salt intake, which promotes water retention—raises MAP because of the greater fluid load in the vascular tree.

By the same token, decreased blood volume translates to a fall in blood pressure. Blood loss and the garden-variety dehydration that occurs during vigorous exercise are common causes of reduced blood volume. A sudden drop in blood pressure often

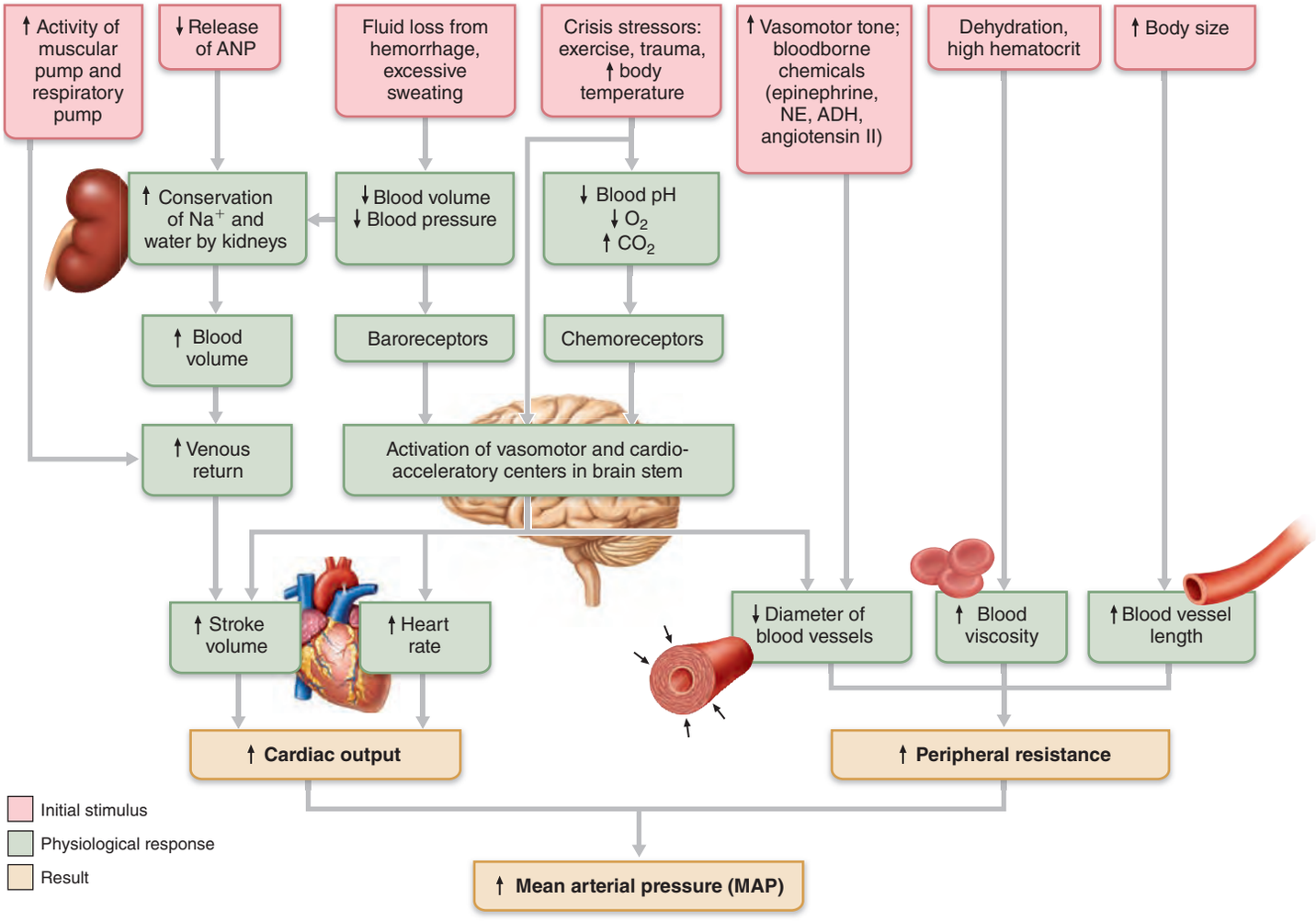


Figure 19.11 Factors that increase MAP.

signals internal bleeding and blood volume too low to support normal circulation.

However, these assertions—increased blood volume increases BP and decreased blood volume decreases BP—do not tell the whole story because we are dealing with a dynamic system. Increases in blood volume that raise blood pressure also stimulate the kidneys to eliminate water, which reduces blood volume and consequently blood pressure. Likewise, falling blood volume triggers renal mechanisms that increase blood volume and blood pressure. As you can see, blood pressure can be stabilized or maintained within normal limits only when blood volume is stable.

The kidneys act both directly and indirectly to regulate arterial pressure and provide the major long-term mechanisms of blood pressure control.

Direct Renal Mechanism

The *direct renal mechanism* alters blood volume independently of hormones. When either blood volume or blood pressure rises, the rate at which fluid filters from the bloodstream into the kidney tubules speeds up. In such situations, the kidneys cannot reabsorb the filtrate rapidly enough, and more of it leaves the body in urine. As a result, blood volume and blood pressure fall.

When blood pressure or blood volume is low, water is conserved and returned to the bloodstream, and blood pressure rises (**Figures 19.10** and **19.11**). As blood volume goes, so goes the arterial blood pressure.

Indirect Renal Mechanism

The kidneys can also regulate blood pressure *indirectly* via the **renin-angiotensin-aldosterone mechanism**. When arterial blood pressure declines, certain cells in the kidneys release the enzyme **renin** into the blood. Renin enzymatically cleaves **angiotensinogen**, a plasma protein made by the liver, converting it to **angiotensin I**. In turn, **angiotensin converting enzyme (ACE)** converts angiotensin I to **angiotensin II**. ACE activity is associated with the capillary endothelium in various body tissues, particularly the lungs.

Angiotensin II acts in four ways to stabilize arterial blood pressure and extracellular fluid volume (Figure 19.10).

- It stimulates the adrenal cortex to secrete **aldosterone**, a hormone that enhances renal reabsorption of sodium. As sodium moves into the bloodstream, water follows, which conserves blood volume. In addition, angiotensin II directly stimulates sodium reabsorption by the kidneys.

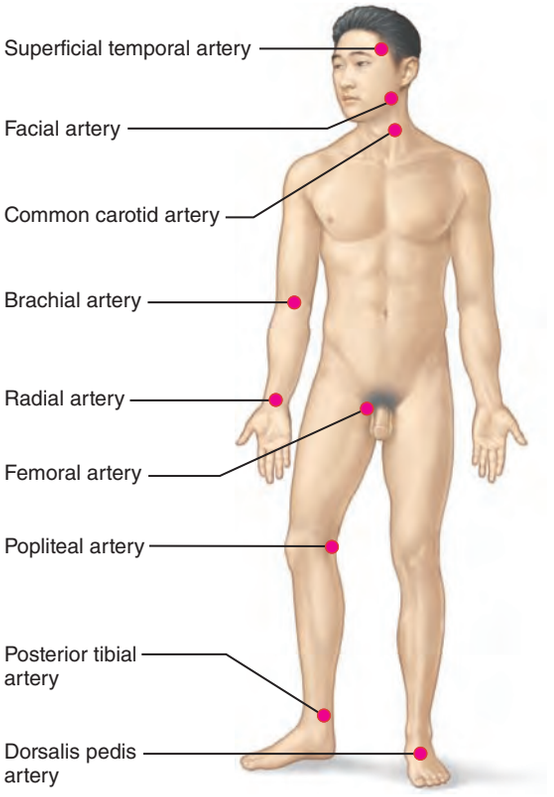


Figure 19.12 Body sites where the pulse is most easily palpated. (We discuss the specific arteries indicated on pp. 726–735.)

- It prods the posterior pituitary to release ADH, which promotes more water reabsorption by the kidneys.
- It triggers the sensation of thirst by activating the hypothalamic thirst center (see Chapter 26). This encourages water consumption, ultimately restoring blood volume and so blood pressure.
- It is a potent vasoconstrictor, increasing blood pressure by increasing peripheral resistance.

Clinical Monitoring of Circulatory Efficiency

Clinicians can assess the efficiency of a person's circulation by measuring pulse and blood pressure. These values, along with measurements of respiratory rate and body temperature, are referred to collectively as the body's **vital signs**. Let's examine how vital signs are determined or measured.

Taking a Pulse

The alternating expansion and recoil of arteries during each cardiac cycle allow us to feel a pressure wave—a **pulse**—that is transmitted through the arterial tree. You can feel a pulse in any artery that lies close to the body surface by compressing the artery against firm tissue, and this provides an easy way to count heart rate. Because it is so accessible, the point where the radial artery surfaces at the wrist, the *radial pulse*, is routinely used to take a pulse measurement, but there are several other clinically important arterial pulse points **(Figure 19.12)**.

These pulse points are also called **pressure points** because they are compressed to stop blood flow into distal tissues during hemorrhage. For example, if you seriously lacerate your hand, you can slow or stop the bleeding by compressing your radial or brachial artery.

Monitoring pulse rate is an easy way to assess the effects of activity, postural changes, and emotions on heart rate. For example, the pulse of a healthy man may be around 66 beats per minute when he is lying down, 70 when he sits up, and 80 if he suddenly stands. During vigorous exercise or emotional upset, pulse rates between 140 and 180 are not unusual because of sympathetic nervous system effects on the heart.

Measuring Blood Pressure

Most often, you measure systemic arterial blood pressure indirectly in the brachial artery of the arm by the **auscultatory method** (aw-skul′tah-to″re). The steps of this procedure are outlined next:

1. Wrap the *blood pressure cuff*, or *sphygmomanometer* (sfig″mo-mah-nom′ĕ-ter; *sphygmo* = pulse), snugly around the person's arm just superior to the elbow.
2. Inflate the cuff until the cuff pressure exceeds systolic pressure. At this point, blood flow into the arm stops and a brachial pulse cannot be felt or heard.
3. Reduce the cuff pressure gradually and listen (auscultate) with a stethoscope for sounds in the brachial artery.

The pressure read when the first soft tapping sounds are heard (the first point at which a small amount of blood is spurting through the constricted artery) is systolic pressure. As the cuff pressure is reduced further, these sounds, called the *sounds of Korotkoff*, become louder and more distinct. However, when the artery is no longer constricted and blood flows freely, the sounds can no longer be heard. The pressure at which the sounds disappear is the diastolic pressure.

Homeostatic Imbalances in Blood Pressure

Normal blood pressure for resting adults is a systolic pressure of less than 120 mm Hg and a diastolic pressure of less than 80 mm Hg. Transient elevations in blood pressure occur as normal adaptations during changes in posture, physical exertion, emotional upset, and fever. Age, sex, weight, and race also affect blood pressure. What is "normal" for you may not be normal for your grandfather or your neighbor.

Hypertension

Chronically elevated blood pressure is called **hypertension** and is characterized by a sustained increase in either systolic pressure (above 140 mm Hg) or diastolic pressure (above 90 mm Hg). The American Heart Association considers individuals to have *prehypertension* if their blood pressure values are elevated but not yet in the hypertension range. These individuals are at higher risk for developing full-blown hypertension and are often advised to change their lifestyles to reduce their risk of developing full-blown hypertension.

Chronic hypertension is a common and dangerous disease. An estimated 30% of people over age 50 are hypertensive. Although this "silent killer" is usually asymptomatic for the first 10 to 20 years, it slowly but surely strains the heart and damages the arteries. Prolonged hypertension is the major cause of heart failure, vascular disease, renal failure, and stroke. The higher the pressure, the greater the risk for these serious problems.

Because the heart is forced to pump against greater resistance, it must work harder, and over time the myocardium enlarges. When finally strained beyond its capacity, the heart weakens and its walls become flabby. Hypertension also ravages the blood vessels, accelerating the progress of atherosclerosis (see *A Closer Look* on pp. 700–701). As the vessels become increasingly blocked, blood flow to the tissues becomes inadequate and vascular complications appear in the brain, heart, kidneys, and retinas of the eyes.

Primary Hypertension Although hypertension and atherosclerosis are often linked, it is often difficult to blame hypertension on any distinct anatomical pathology. Indeed, about 90% of hypertensive people have **primary**, or **essential**, **hypertension**, for which no underlying cause has been identified. This is because primary hypertension is due to a rich interplay between your genes and a variety of environmental factors:

- **Heredity.** Hypertension runs in families. Children of hypertensive parents are twice as likely to develop hypertension as are children of normotensive parents, and more blacks than whites are hypertensive. Many of the factors listed here require a genetic predisposition, and the course of the disease varies in different population groups.
- **Diet.** Dietary factors that contribute to hypertension include high intakes of salt (NaCl), saturated fat, and cholesterol, and deficiencies in certain metal ions (K^+, Ca^{2+}, and Mg^{2+}).
- **Obesity.** Obesity causes hypertension in a number of ways that are not yet well understood. For example, adipocytes release hormones that appear to increase sympathetic tone and interfere with the ability of endothelial cells to induce vasodilation.
- **Age.** Hypertension usually appears after age 40.
- **Diabetes mellitus.**
- **Stress.** Particularly at risk are "hot reactors," people whose blood pressure zooms upward during every stressful event.
- **Smoking.** Nicotine, an important chemical in tobacco and one of the strongest toxins known, causes intense vasoconstriction not only by directly stimulating postganglionic sympathetic neurons but also by prompting release of large amounts of epinephrine and NE. Chemicals in cigarette smoke also damage the tunica intima, interfering with its ability to chemically regulate arteriolar diameter.

Primary hypertension cannot be cured, but most cases can be controlled. Restricting salt, fat, and cholesterol intake, increasing exercise and losing weight, stopping smoking, managing stress, and taking antihypertensive drugs can all help. Drugs commonly used are diuretics, beta-blockers, calcium channel blockers, angiotensin converting enzyme (ACE) inhibitors, and angiotensin II receptor blockers. Inhibiting ACE or blocking receptors for angiotensin II suppresses the renin-angiotensin-aldosterone mechanism.

Secondary Hypertension **Secondary hypertension**, which accounts for 10% of cases, is due to identifiable conditions, for example obstructed renal arteries, kidney disease, and endocrine disorders such as hyperthyroidism and Cushing's syndrome. Treatment for secondary hypertension focuses on correcting the problem that caused it.

Hypotension

In many cases, **hypotension**, or low blood pressure (below 90/60 mm Hg), simply reflects individual variations and is no cause for concern. In fact, low blood pressure is often associated with long life and an old age free of cardiovascular disease.

Hypotension is usually a concern only if it leads to inadequate blood flow to tissues. For example, hypotension may cause dizziness or fainting because of inadequate oxygen delivery to the brain. *Acute hypotension* is one of the most important signs of circulatory shock (p. 717) and a threat to patients undergoing surgery and those in intensive care units.

Orthostatic hypotension is a temporary drop in blood pressure resulting in dizziness when a person rises suddenly from a reclining or sitting position. Elderly people are prone to orthostatic hypotension because the aging sympathetic nervous system does not respond as quickly as it once did to postural changes. Blood pools briefly in the lower limbs, reducing blood pressure and consequently blood delivery to the brain. Changing position slowly gives the nervous system time to adjust and usually prevents this problem.

Occasionally, *chronic hypotension* is a sign of a serious underlying condition. Addison's disease (inadequate adrenal cortex function), hypothyroidism, or severe malnutrition can cause chronic hypotension.

☑ Check Your Understanding

9. Describe the baroreceptor reflex changes that occur to maintain blood pressure when you rise from a lying-down to a standing position.
10. The kidneys play an important role in maintaining MAP by influencing which variable? Explain how renal artery obstruction could cause secondary hypertension.

For answers, see Appendix H.

Blood Flow Through Body Tissues: Tissue Perfusion

✓ Explain how blood flow is regulated in the body in general and in specific organs.

Blood flow through body tissues, or **tissue perfusion**, is involved in (1) delivering oxygen and nutrients to tissue cells, and removing wastes from them, (2) exchanging gases in the lungs, (3) absorbing nutrients from the digestive tract, and (4) forming

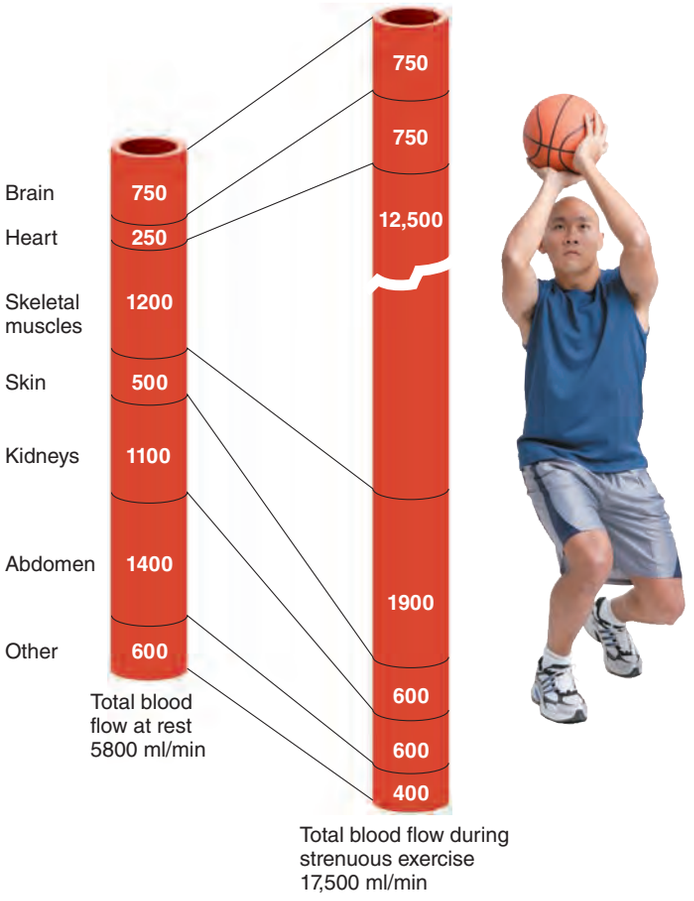


Figure 19.13 Distribution of blood flow at rest and during strenuous exercise.

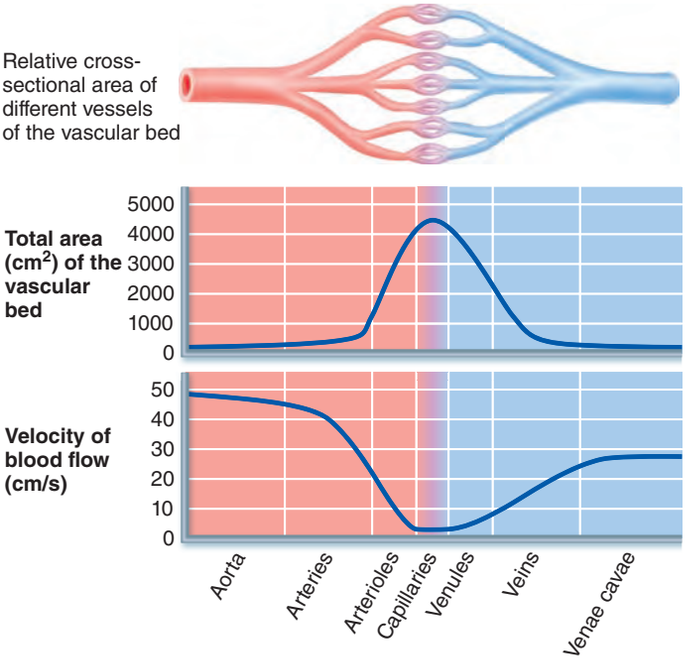


Figure 19.14 Blood flow velocity and total cross-sectional area of vessels. Various blood vessels of the systemic circulation differ in their total cross-sectional area (e.g., the cross section of all systemic capillaries combined versus the cross section of all systemic arteries combined), which affects the velocity of blood flow through them.

urine in the kidneys. The rate of blood flow to each tissue and organ is almost exactly the right amount to provide for proper function—no more, no less.

When the body is at rest, the brain receives about 13% of total blood flow, the heart 4%, kidneys 20%, and abdominal organs 24%. Skeletal muscles, which make up almost half of body mass, normally receive about 20% of total blood flow. During exercise, however, nearly all of the increased cardiac output flushes into the skeletal muscles and blood flow to the kidneys and digestive organs declines **(Figure 19.13)**.

Velocity of Blood Flow

Have you ever watched a swift river emptying into a large lake? The water's speed decreases as it enters the lake until its flow becomes almost imperceptible. This is because the total cross-sectional area of the lake is much larger than that of the river. Velocity in this case is *inversely* related to cross-sectional area. The same thing happens with blood flow inside our blood vessels.

As shown in **Figure 19.14**, the speed or velocity of blood flow changes as blood travels through the systemic circulation. It is fastest in the aorta and other large arteries (the river), slowest in the capillaries (whose large total cross-sectional area make them analogous to the lake), and then picks up speed again in the veins (the river again).

Just as in our analogy of the river and lake, blood flows fastest where the total cross-sectional area is least. As the arterial system branches, the total cross-sectional area of the vascular bed increases, and the velocity of blood flow declines proportionately. Even though the individual branches have smaller lumens, their *combined* cross-sectional areas and thus the volume of blood they can hold are much greater than that of the aorta.

For example, the cross-sectional area of the aorta is 2.5 cm^2 but the combined cross-sectional area of all the capillaries is 4500 cm^2. This difference results in fast blood flow in the aorta (40–50 cm/s) and slow blood flow in the capillaries (about 0.03 cm/s). Slow capillary flow is beneficial because it allows adequate time for exchanges between the blood and tissue cells.

As capillaries combine to form first venules and then veins, total cross-sectional area declines and velocity increases. The cross-sectional area of the venae cavae is 8 cm^2, and the velocity of blood flow varies from 10 to 30 cm/s in those vessels, depending on the activity of the skeletal muscle pump.

Autoregulation: Local Regulation of Blood Flow

As our activities change throughout the day, how does each organ or tissue manage to get the blood flow it needs? The answer is **autoregulation**, the automatic adjustment of blood flow to each tissue in proportion to the tissue's requirements at any instant. Local conditions regulate this process independent of control by nerves or hormones. MAP is the same everywhere in the body and homeostatic mechanisms adjust cardiac output

as needed to maintain that constant pressure. Changes in blood flow through individual organs are controlled *intrinsically* by modifying the diameter of local arterioles feeding the capillaries.

You can compare blood flow autoregulation to water use in your home. To get water in a sink or a garden hose, you have to turn on a faucet. Whether you have several taps open or none, the pressure in the main water pipe in the street remains relatively constant, as it does in the even larger water lines closer to the pumping station. Similarly, local conditions in the arterioles feeding the capillary beds of an organ have little effect on pressure in the muscular artery feeding that organ, or in the large elastic arteries. The pumping station is, of course, the heart. The beauty of this system is that as long as the water company (circulatory feedback mechanisms) maintains a relatively constant water pressure (MAP), local demand regulates the amount of fluid (blood) delivered to various areas.

In summary, organs regulate their own blood flows by varying the resistance of their arterioles. As we describe next, these intrinsic control mechanisms may be classed as *metabolic* (chemical) or *myogenic* (physical).

Metabolic Controls

When blood flow is too low to meet a tissue's metabolic needs, oxygen levels decline and metabolic products (which act as paracrines) accumulate. These changes serve as autoregulation stimuli that lead to automatic increases in tissue blood flow.

The metabolic factors that regulate blood flow are low oxygen levels, and increases in H^+ (from CO_2 and lactic acid), K^+, adenosine, and prostaglandins. The relative importance of these factors is not clear. Many of them act directly to relax vascular smooth muscle, but some may act by causing vascular endothelial cells to release nitric oxide.

Nitric oxide (NO) is a powerful vasodilator which acts via a cyclic GMP second-messenger system. NO is quickly destroyed and its potent vasodilator effects are very brief. Even so, NO is the major player in controlling local vasodilation, often overriding sympathetic vasoconstriction when tissues need more blood flow.

The endothelium also releases potent vasoconstrictors, including the family of peptides called **endothelins**, which are among the most potent vasoconstrictors known. Normally, NO and endothelin release from endothelial cells are in a dynamic balance, but this balance tips in favor of NO when blood flow is too low for metabolic needs.

The net result of metabolically controlled autoregulation is immediate vasodilation of the arterioles serving the capillary beds of the "needy" tissues and dilation of their precapillary sphincters. Blood flow to the area rises temporarily, allowing blood to surge through the true capillaries and become available to the tissue cells.

Inflammatory chemicals (such as histamine, kinins, and prostaglandins) released in injury, infection, or allergic reactions also cause local vasodilation. Inflammatory vasodilation helps the defense mechanisms clear microorganisms and toxins from the area, and promotes healing.

Myogenic Controls

Fluctuations in systemic blood pressure would cause problems for individual organs were it not for the **myogenic responses** (*myo* = muscle; *gen* = origin) of vascular smooth muscle. Inadequate blood perfusion through an organ is quickly followed by a decline in the organ's metabolic rate and, if prolonged, organ death. Likewise, excessively high arterial pressure and tissue perfusion can be dangerous because the combination may rupture more fragile blood vessels.

Fortunately, vascular smooth muscle prevents these problems by responding directly to passive stretch (caused by increased intravascular pressure) with increased tone, which resists the stretch and causes vasoconstriction. Reduced stretch promotes vasodilation and increases blood flow into the tissue. These myogenic responses keep tissue perfusion fairly constant despite most variations in systemic pressure.

Generally, both metabolic and myogenic factors determine the final autoregulatory response of a tissue. For example, **reactive hyperemia** (hi″per-e′me-ah) refers to the dramatically increased blood flow into a tissue that occurs after the blood supply to the area has been temporarily blocked. It results both from the myogenic response and from the metabolic wastes that accumulated in the area during occlusion. **Figure 19.15** summarizes the various intrinsic (local) and extrinsic controls of arteriolar diameter.

Long-Term Autoregulation

If a tissue needs more nutrients than short-term autoregulatory mechanisms can supply, a long-term autoregulatory mechanism may develop over weeks or months to enrich local blood flow still more. The number of blood vessels in the region increases, and existing vessels enlarge. This phenomenon, called *angiogenesis*, is particularly common in the heart when a coronary vessel is partially occluded. It occurs throughout the body in people who live in high-altitude areas, where the air contains less oxygen.

Blood Flow in Special Areas

Each organ has special requirements and functions that are revealed in its pattern of autoregulation. Autoregulation in the brain, heart, and kidneys is extraordinarily efficient, maintaining adequate perfusion even when MAP fluctuates.

Skeletal Muscles

Blood flow in skeletal muscle varies with fiber type and muscle activity. Generally speaking, capillary density and blood flow are greater in red (slow oxidative) fibers than in white (fast glycolytic) fibers. Resting skeletal muscles receive about 1 L of blood per minute, and only about 25% of their capillaries are open. During rest, myogenic and general neural mechanisms predominate.

When muscles become active, blood flow increases (*hyperemia*) in direct proportion to their greater *metabolic* activity, a phenomenon called **active** or **exercise hyperemia**. This form of autoregulation occurs almost entirely in response to the decreased oxygen concentration and accumulated metabolic factors that result from the "revved-up" metabolism of working muscles.

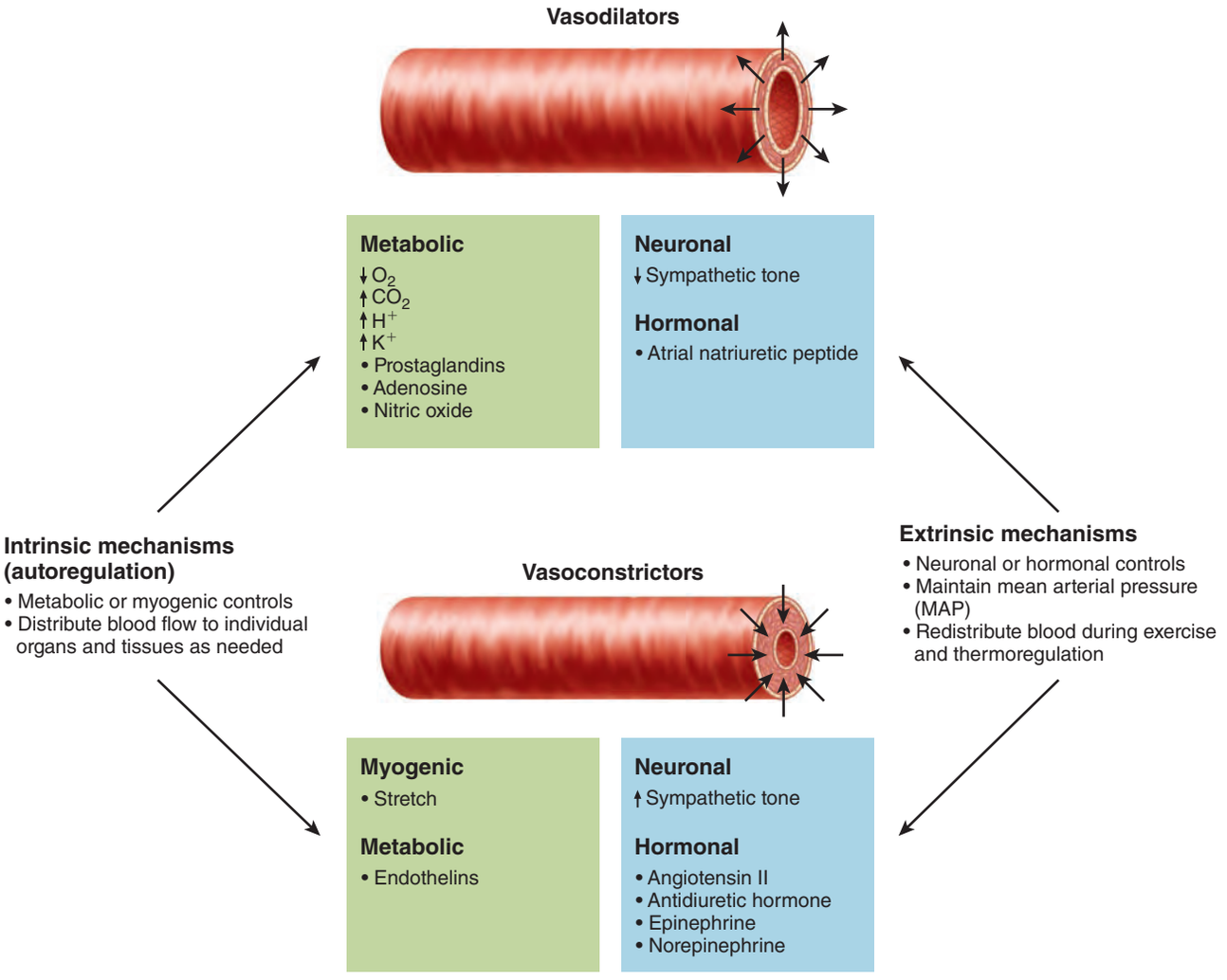


Figure 19.15 Intrinsic and extrinsic control of arteriolar smooth muscle in the systemic circulation. Epinephrine and norepinephrine constrict arteriolar smooth muscle by acting at α-adrenergic receptors. β-adrenergic receptors (causing vasodilation) are present in arterioles supplying skeletal and heart muscle, but their physiological relevance is minimal.

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However, systemic adjustments mediated by the vasomotor center must also occur to ensure that blood delivery to the muscles is both faster and more abundant. During exercise, sympathetic nervous system activity increases. Norepinephrine released from sympathetic nerve endings causes vasoconstriction of the vessels of blood reservoirs such as the digestive viscera and skin, diverting blood away from these regions temporarily and ensuring that more blood reaches the muscles.

In skeletal muscles, the sympathetic nervous system and local metabolic controls have opposing effects on arteriolar diameter. During exercise, local controls *override* sympathetic vasoconstriction. Consequently, blood flow to skeletal muscles can increase tenfold or more during physical activity, as you saw in Figure 19.13, and virtually all capillaries in the active muscles open to accommodate the increased flow.

Epinephrine acting at beta (β) adrenergic receptors and acetylcholine acting at cholinergic receptors were once thought to contribute to arteriolar dilation during exercise. However, these appear to have little physiological importance in controlling human skeletal muscle blood flow.

Without question, strenuous exercise is one of the most demanding conditions the cardiovascular system faces. Ultimately, the major factor determining how long muscles can contract vigorously is the ability of the cardiovascular system to deliver adequate oxygen and nutrients and remove waste products.

The Brain

Blood flow to the brain averages 750 ml/min and is maintained at a relatively constant level. Constant cerebral blood flow is necessary because neurons are totally intolerant of ischemia. Also, the brain is unable to store essential nutrients despite being the most metabolically active organ in the body.

Cerebral blood flow is regulated by one of the body's most precise autoregulatory systems and is tailored to local neuronal need. For example, when you make a fist with your right hand, the neurons in the left cerebral motor cortex controlling

that movement receive more blood than the adjoining neurons. Brain tissue is exceptionally sensitive to declining pH, and increased blood carbon dioxide levels (resulting in acidic conditions in brain tissue) cause marked vasodilation. Low blood levels of oxygen are a much less potent stimulus for autoregulation. However, very high carbon dioxide levels abolish autoregulatory mechanisms and severely depress brain activity.

Besides metabolic controls, the brain also has a myogenic mechanism that protects it from possibly damaging changes in blood pressure. When MAP declines, cerebral vessels dilate to ensure adequate brain perfusion. When MAP rises, cerebral vessels constrict, protecting the small, more fragile vessels farther along the pathway from excessive pressure. Under certain circumstances, such as brain ischemia caused by rising intracranial pressure (as with a brain tumor), the brain (via the medullary cardiovascular centers) regulates its own blood flow by triggering a rise in systemic blood pressure.

However, when systemic pressure changes are extreme, the brain becomes vulnerable. Fainting, or *syncope* (sin′cuh-pe; "cutting short"), occurs when MAP falls below 60 mm Hg. Cerebral edema is the usual result of pressures over 160 mm Hg, which dramatically increase brain capillary permeability.

The Skin

Blood flow through the skin (1) supplies nutrients to cells, (2) helps regulate body temperature, and (3) provides a blood reservoir. Autoregulation serves the first function in response to the need for oxygen, but the other two require neural intervention. The primary function of the cutaneous circulation is to help maintain body temperature, so we will concentrate on that function here.

Below the skin surface are extensive venous plexuses (networks of intertwining vessels). The blood flow through these plexuses can change from 50 ml/min to as much as 2500 ml/min, depending on body temperature. This capability reflects neural adjustments of blood flow through arterioles and through unique coiled arteriovenous anastomoses. These tiny arteriovenous shunts are located mainly in the fingertips, palms of the hands, toes, soles of the feet, ears, nose, and lips. Richly supplied with sympathetic nerve endings (unlike the shunts of most other capillary beds), they are controlled by reflexes initiated by temperature receptors or signals from higher CNS centers. The arterioles, in addition, respond to metabolic autoregulatory stimuli.

When the skin is exposed to heat, or body temperature rises for other reasons (such as vigorous exercise), the hypothalamic "thermostat" signals for reduced vasomotor stimulation of the skin vessels. As a result, warm blood flushes into the capillary beds and heat radiates from the skin surface. The arterioles dilate even more when we sweat, because an enzyme in perspiration acts on a protein in tissue fluid to produce *bradykinin*, which stimulates the vessel's endothelial cells to release the potent vasodilator NO.

When the ambient temperature is cold and body temperature drops, superficial skin vessels strongly constrict. Hence, blood almost entirely bypasses the capillaries associated with the arteriovenous anastomoses, diverting the warm blood to the deeper, more vital organs. Paradoxically, the skin may stay quite rosy because some blood gets "trapped" in the superficial capillary loops as the shunts swing into operation. The trapped blood remains red because the chilled skin cells take up less O_2.

The Lungs

Blood flow through the pulmonary circuit to and from the lungs is unusual in many ways. The pathway is relatively short, and pulmonary arteries and arterioles are structurally like veins and venules. That is, they have thin walls and large lumens. Because resistance to blood flow is low in the pulmonary arterial system, less pressure is needed to propel blood through those vessels. Consequently, arterial pressure in the pulmonary circulation is much lower than in the systemic circulation (24/10 versus 120/80 mm Hg).

In the pulmonary circulation, the autoregulatory mechanism is the *opposite* of what is seen in most tissues: Low pulmonary oxygen levels cause local vasoconstriction, and high levels promote vasodilation. While this may seem odd, it is perfectly consistent with the gas exchange role of this circulation. When the air sacs of the lungs are flooded with oxygen-rich air, the pulmonary capillaries become flushed with blood and ready to receive the oxygen load. If the air sacs are collapsed or blocked with mucus, the oxygen content in those areas is low, and blood largely bypasses those nonfunctional areas.

The Heart

Aortic pressure and the pumping activity of the ventricles influence the movement of blood through the smaller vessels of the coronary circulation. When the ventricles contract and compress the coronary vessels, blood flow through the myocardium stops. As the heart relaxes, the high aortic pressure forces blood through the coronary circulation.

Under normal circumstances, the myoglobin in cardiac cells stores sufficient oxygen to satisfy the cells' oxygen needs during systole. However, an abnormally rapid heartbeat seriously reduces the ability of the myocardium to receive adequate oxygen and nutrients during diastole.

Under resting conditions, blood flow through the heart is about 250 ml/min and is probably controlled by a myogenic mechanism. Consequently, blood flow remains fairly constant despite wide variations (50 to 140 mm Hg) in coronary perfusion pressure. During strenuous exercise, the coronary vessels dilate in response to local accumulation of vasodilators (particularly adenosine), and blood flow may increase three to four times (see Figure 19.13). Additionally, any event that decreases the oxygen content of the blood releases vasodilators that adjust the O_2 supply to the O_2 demand.

This enhanced blood flow during increased heart activity is important because under resting conditions, cardiac cells use as much as 65% of the oxygen carried to them in blood. (Most other tissue cells use about 25% of the delivered oxygen.) Consequently, increasing the blood flow is the only way to provide more oxygen to a vigorously working heart.

Check Your Understanding

11. Suppose you are in a bicycle race. What happens to the smooth muscle in the arterioles supplying your leg muscles? What is the key mechanism in this case?
12. If many arterioles in your body dilated at once, you would expect MAP to plummet. What prevents MAP from decreasing during your bicycle race?

For answers, see Appendix H.

Blood Flow Through Capillaries and Capillary Dynamics

✓ Outline factors involved in capillary dynamics, and explain the significance of each.

Blood flow through capillary networks is slow and intermittent. Intermittent flow is due to **vasomotion**, the on/off opening and closing of precapillary sphincters in response to local autoregulatory controls.

Capillary Exchange of Respiratory Gases and Nutrients

Oxygen, carbon dioxide, most nutrients, and metabolic wastes pass between the blood and interstitial fluid by diffusion. Recall that in **diffusion**, net movement always occurs along a concentration gradient—each substance moving from an area of its higher concentration to an area of its lower concentration. Hence, oxygen and nutrients pass from the blood, where their concentration is fairly high, through the interstitial fluid to the tissue cells. Carbon dioxide and metabolic wastes leave the cells, where their content is higher, and diffuse into the capillary blood.

There are four different routes across capillaries for different types of molecules, as **Figure 19.16** shows. ① Lipid-soluble molecules, such as respiratory gases, diffuse through the lipid bilayer of the endothelial cell plasma membranes. Small water-soluble solutes, such as amino acids and sugars, pass through ② fluid-filled intercellular capillary clefts or ③ fenestrations. ④ Some larger molecules, such as proteins, are actively transported in pinocytotic vesicles or caveolae.

As we mentioned earlier, capillaries differ in their "leakiness," or permeability. Liver capillaries, for instance, are sinusoids that allow even proteins to pass freely, whereas brain capillaries are impermeable to most substances.

Fluid Movements: Bulk Flow

While nutrient and gas exchanges are occurring across the capillary walls by diffusion, bulk fluid flows are also going on. Fluid is forced out of the capillaries through the clefts at the arterial end of the bed, but most of it returns to the bloodstream at the venous end. Though relatively unimportant to capillary exchange of nutrients and wastes, bulk flow is extremely important in determining the relative fluid volumes in the bloodstream and the interstitial space. (Approximately 20 L of fluid filter out of the capillaries each day before being returned to the blood—almost seven times the total plasma volume!)

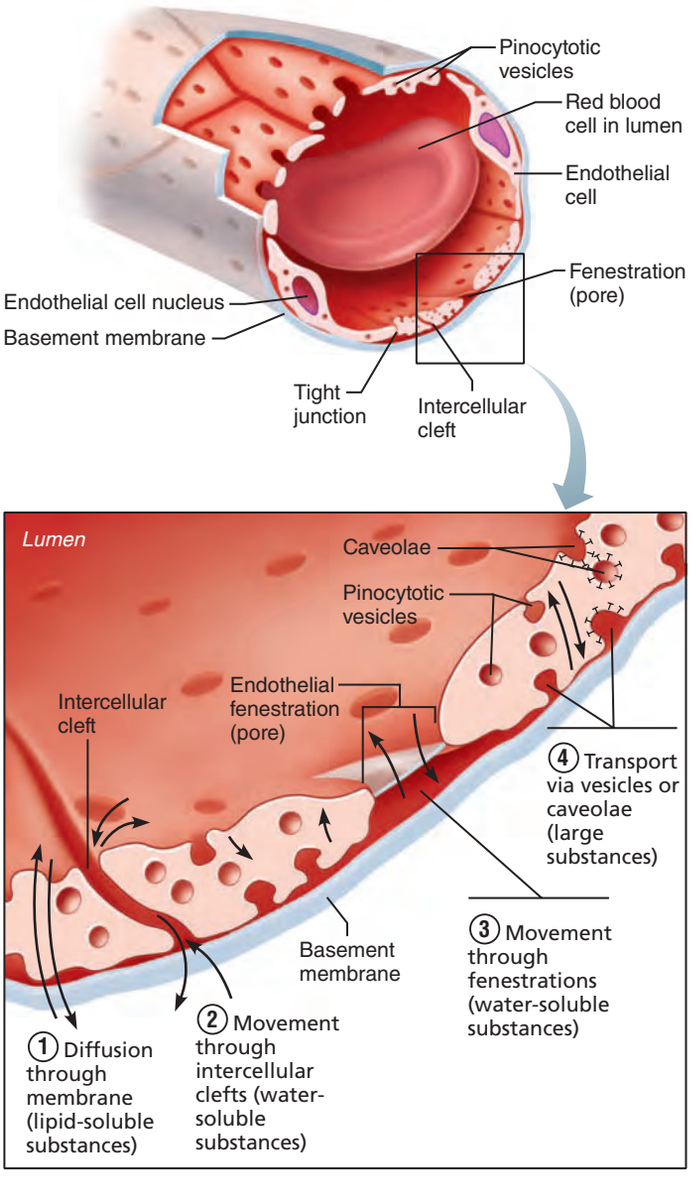


Figure 19.16 Capillary transport mechanisms. The four possible pathways or routes of transport across the endothelial cell wall of a fenestrated capillary.

As we describe next and as shown in *Focus on Bulk Flow Across Capillary Walls* **(Figure 19.17)**, the *direction and amount* of flow across capillary walls reflect the balance between two dynamic and opposing forces—hydrostatic and colloid osmotic pressures.

Hydrostatic Pressures **Hydrostatic pressure (HP)** is the force exerted by a fluid pressing against a wall. In capillaries, hydrostatic pressure is the same as *capillary blood pressure*—the pressure exerted by blood on capillary walls. **Capillary hydrostatic pressure (HP_c)** tends to force fluids through capillary walls (a process called *filtration*), leaving behind cells and most proteins. Blood pressure drops as blood flows along a capillary bed, so HP_c is higher at the arterial end of the bed (35 mm Hg) than at the venous end (17 mm Hg).

In theory, blood pressure—which forces fluid out of the capillaries—is opposed by the **interstitial fluid hydrostatic pressure (HP_{if})** acting outside the capillaries and pushing fluid in. However, there is usually very little fluid in the interstitial space, because the lymphatic vessels constantly withdraw it. HP_{if} may vary from slightly negative to slightly positive, but traditionally it is assumed to be zero.

Colloid Osmotic Pressures **Colloid osmotic pressure (OP)**, the force opposing hydrostatic pressure, is created by large nondiffusible molecules, such as plasma proteins, that are unable to cross the capillary wall. Such molecules draw water toward themselves. In other words, they encourage osmosis because the water concentration in their vicinity is lower than it is on the opposite side of the capillary wall. A quick and dirty way to remember this is "hydrostatic pressure pushes and osmotic pressure pulls (or sucks)."

The abundant plasma proteins in capillary blood (primarily albumin molecules) develop a **capillary colloid osmotic pressure (OP_c)**, also called *oncotic pressure*, of approximately 26 mm Hg. Interstitial fluid contains few proteins, so its colloid osmotic pressure (OP_{if}) is substantially lower—from 0.1 to 5 mm Hg. Unlike HP, OP does not vary significantly from one end of the capillary bed to the other.

Hydrostatic-Osmotic Pressure Interactions We are now ready to calculate the **net filtration pressure (NFP)**, which considers all the forces acting at the capillary bed. As you work your way through the right-hand page of Figure 19.17, notice that while net *filtration* is occurring at the arteriolar end of the capillary, a negative value for NFP at the venous end of the capillary indicates that fluid is moving *into* the capillary bed (a process called *reabsorption*). As a result, net fluid flow is *out* of the circulation at the arterial ends of capillary beds and *into* the circulation at the venous ends.

However, more fluid enters the tissue spaces than returns to the blood, resulting in a net loss of fluid from the circulation of about 1.5 ml/min. Lymphatic vessels pick up this fluid and any leaked proteins and return it to the vascular system, which accounts for the relatively low levels of both fluid and proteins in the interstitial space. Were this not so, this "insignificant" fluid loss would empty your blood vessels of plasma in about 24 hours!

☑ Check Your Understanding

13. Suppose OP_{if} rises dramatically—say because of a severe bacterial infection in the surrounding tissue. (a) Predict how fluid flow will change in this situation. (b) Now calculate the NFP at the venous end of the capillary in Figure 19.17 if OP_{if} increases to 10 mm Hg. (c) In which direction does fluid flow at the venous end of the capillary now—in or out?

For answers, see Appendix H.

Circulatory Shock

✓ Define circulatory shock. List several possible causes.

Circulatory shock is any condition in which blood vessels are inadequately filled and blood cannot circulate normally. Blood flow is inadequate to meet tissue needs. If circulatory shock persists, cells die and organ damage follows.

Hypovolemic Shock

The most common form of circulatory shock is **hypovolemic shock** (hi″po-vo-le′mik; *hypo* = low, deficient; *volemia* = blood volume), which results from large-scale blood or fluid loss, as might follow acute hemorrhage, severe vomiting or diarrhea, or extensive burns. If blood volume drops rapidly, heart rate increases in an attempt to correct the problem. Thus, a weak, "thready" pulse is often the first sign of hypovolemic shock. Intense vasoconstriction also occurs, which shifts blood from the various blood reservoirs into the major circulatory channels and enhances venous return.

Blood pressure is stable at first, but eventually drops if blood loss continues. A sharp drop in blood pressure is a serious, and late, sign of hypovolemic shock. The key to managing hypovolemic shock is to replace fluid volume as quickly as possible.

Although you have not yet explored all of the body systems that respond to hypovolemic shock, acute bleeding is such a threat to life that it seems important to have a summary of its signs and symptoms and the body's attempts to restore homeostasis. **Figure 19.18** provides such a resource. Study it in part now, and in more detail later once you have studied the remaining body systems.

Vascular Shock

In **vascular shock**, blood volume is normal, but circulation is poor as a result of extreme vasodilation. A huge drop in peripheral resistance follows, as revealed by rapidly falling blood pressure.

A common cause of vascular shock is loss of vasomotor tone due to anaphylaxis (anaphylactic shock), a systemic allergic reaction in which the massive release of histamine triggers body-wide vasodilation. Two other common causes are failure of autonomic nervous system regulation (*neurogenic shock*), and septicemia (*septic shock*), a severe systemic bacterial infection (bacterial toxins are notorious vasodilators).

Transient vascular shock may occur when you sunbathe for a prolonged time. The heat of the sun on your skin dilates cutaneous blood vessels. Then, if you stand up abruptly, blood pools briefly (because of gravity) in the dilated vessels of your lower limbs rather than returning promptly to the heart. Consequently, your blood pressure falls. The dizziness you feel is a signal that your brain is not receiving enough oxygen.

Cardiogenic Shock

Cardiogenic shock, or pump failure, occurs when the heart is so inefficient that it cannot sustain adequate circulation. Its usual cause is myocardial damage, as might follow numerous myocardial infarctions (heart attacks).

☑ Check Your Understanding

14. Your neighbor, Bob, calls you because he thinks he is having an allergic reaction to a medication. You find Bob on the verge of losing consciousness and having trouble breathing. When paramedics arrive, they note his blood pressure is 63/38 and he has a rapid, thready pulse. Explain Bob's low blood pressure and rapid heart rate.

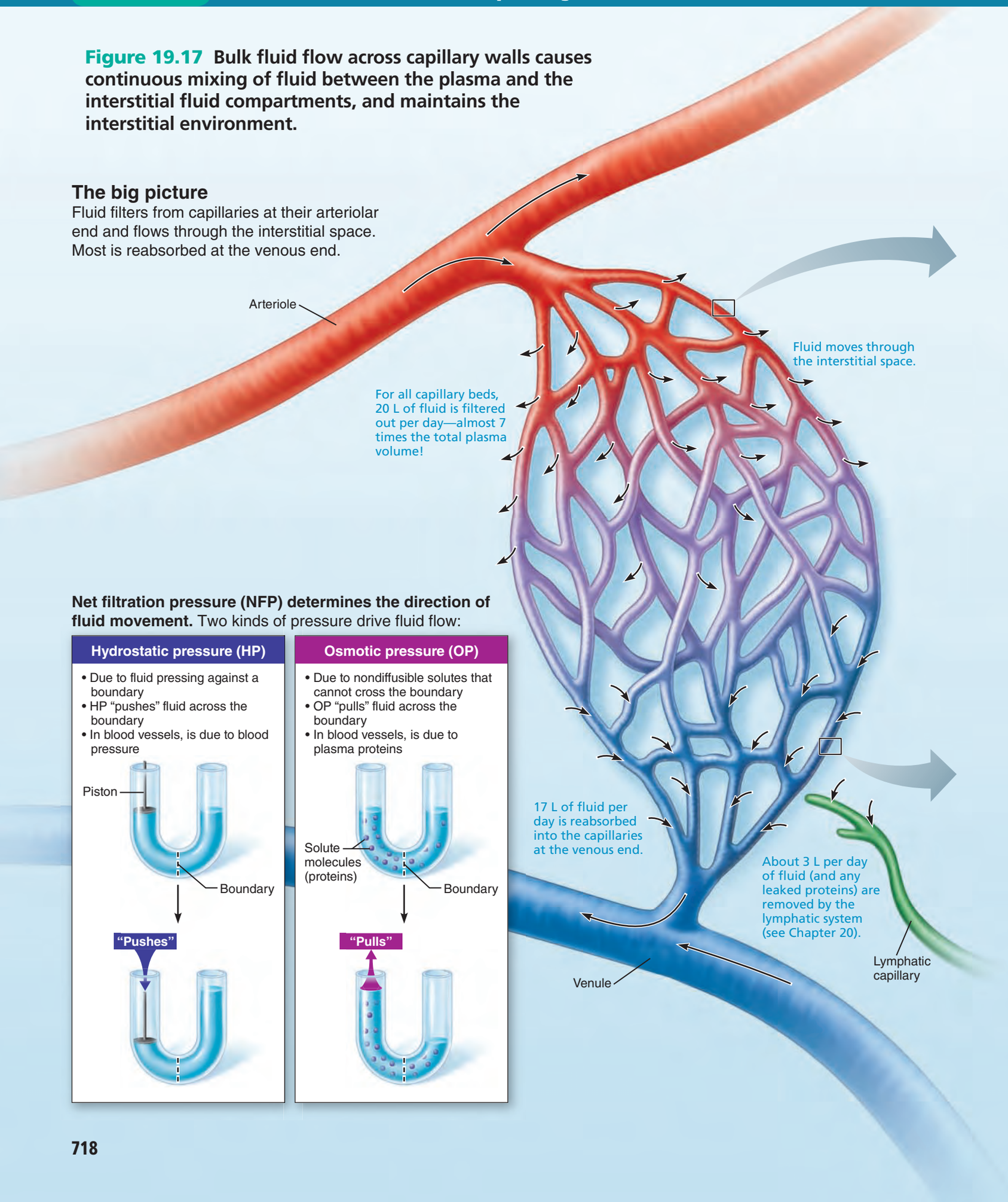
For answers, see Appendix H.

(Text continues on p. 721.)

Figure 19.17 Bulk fluid flow across capillary walls causes continuous mixing of fluid between the plasma and the interstitial fluid compartments, and maintains the interstitial environment.

The big picture

Fluid filters from capillaries at their arteriolar end and flows through the interstitial space. Most is reabsorbed at the venous end.



Net filtration pressure (NFP) determines the direction of fluid movement. Two kinds of pressure drive fluid flow:

Hydrostatic pressure (HP)

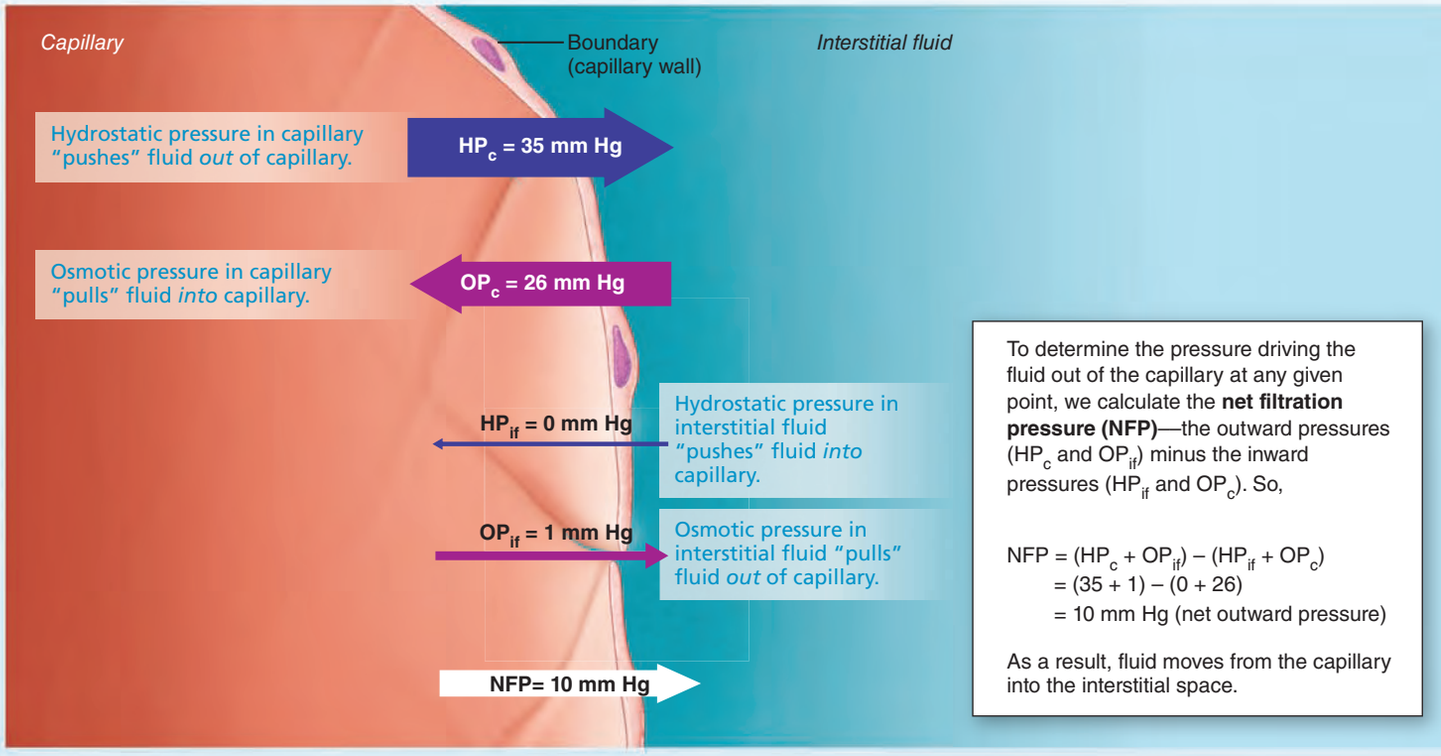
- Due to fluid pressing against a boundary
- HP "pushes" fluid across the boundary
- In blood vessels, is due to blood pressure

Osmotic pressure (OP)

- Due to nondiffusible solutes that cannot cross the boundary
- OP "pulls" fluid across the boundary
- In blood vessels, is due to plasma proteins

How do the pressures drive fluid flow across a capillary?

Net filtration occurs at the arteriolar end of a capillary.

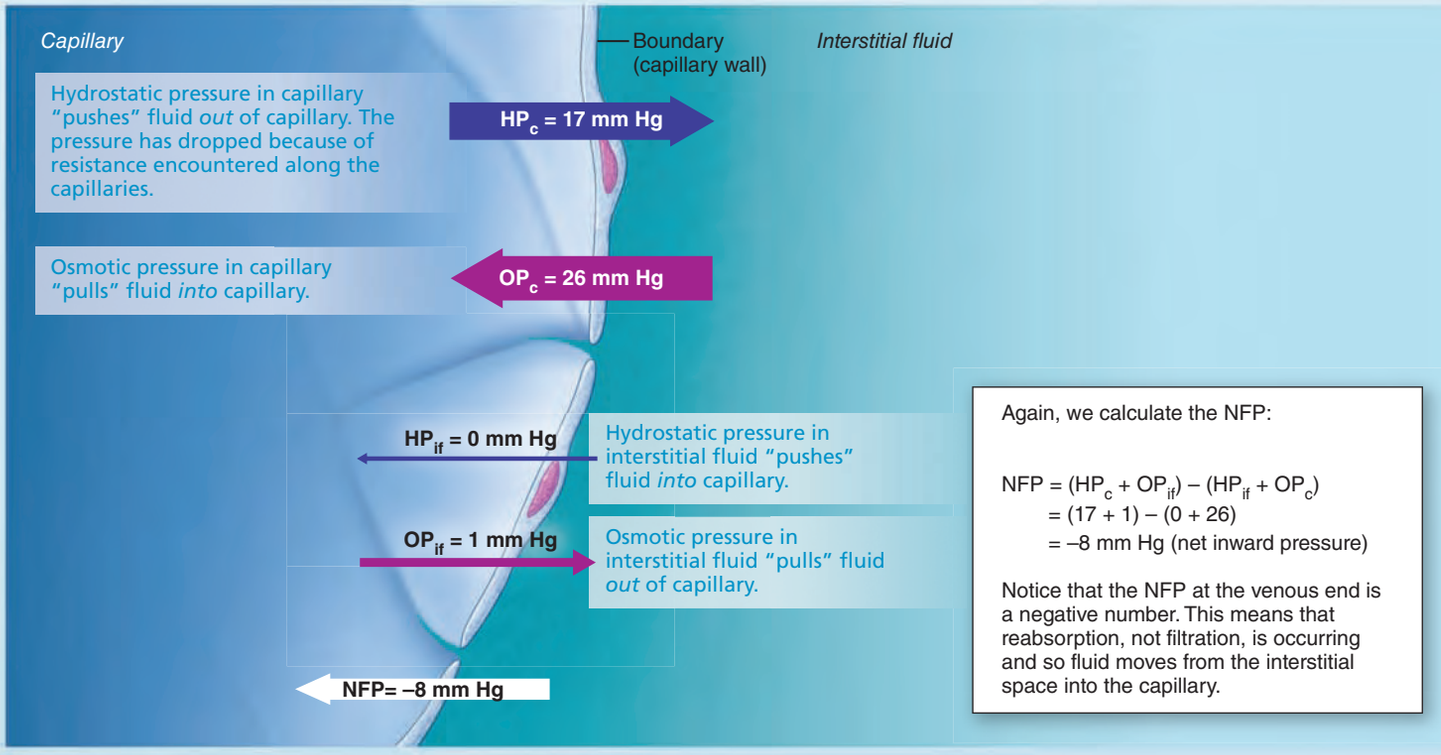


To determine the pressure driving the fluid out of the capillary at any given point, we calculate the **net filtration pressure (NFP)**—the outward pressures (HP_c and OP_{if}) minus the inward pressures (HP_{if} and OP_c). So,

$$NFP = (HP_c + OP_{if}) - (HP_{if} + OP_c)$$
$$= (35 + 1) - (0 + 26)$$
$$= 10 \text{ mm Hg (net outward pressure)}$$

As a result, fluid moves from the capillary into the interstitial space.

Net reabsorption occurs at the venous end of a capillary.



Again, we calculate the NFP:

$$NFP = (HP_c + OP_{if}) - (HP_{if} + OP_c)$$
$$= (17 + 1) - (0 + 26)$$
$$= -8 \text{ mm Hg (net inward pressure)}$$

Notice that the NFP at the venous end is a negative number. This means that reabsorption, not filtration, is occurring and so fluid moves from the interstitial space into the capillary.

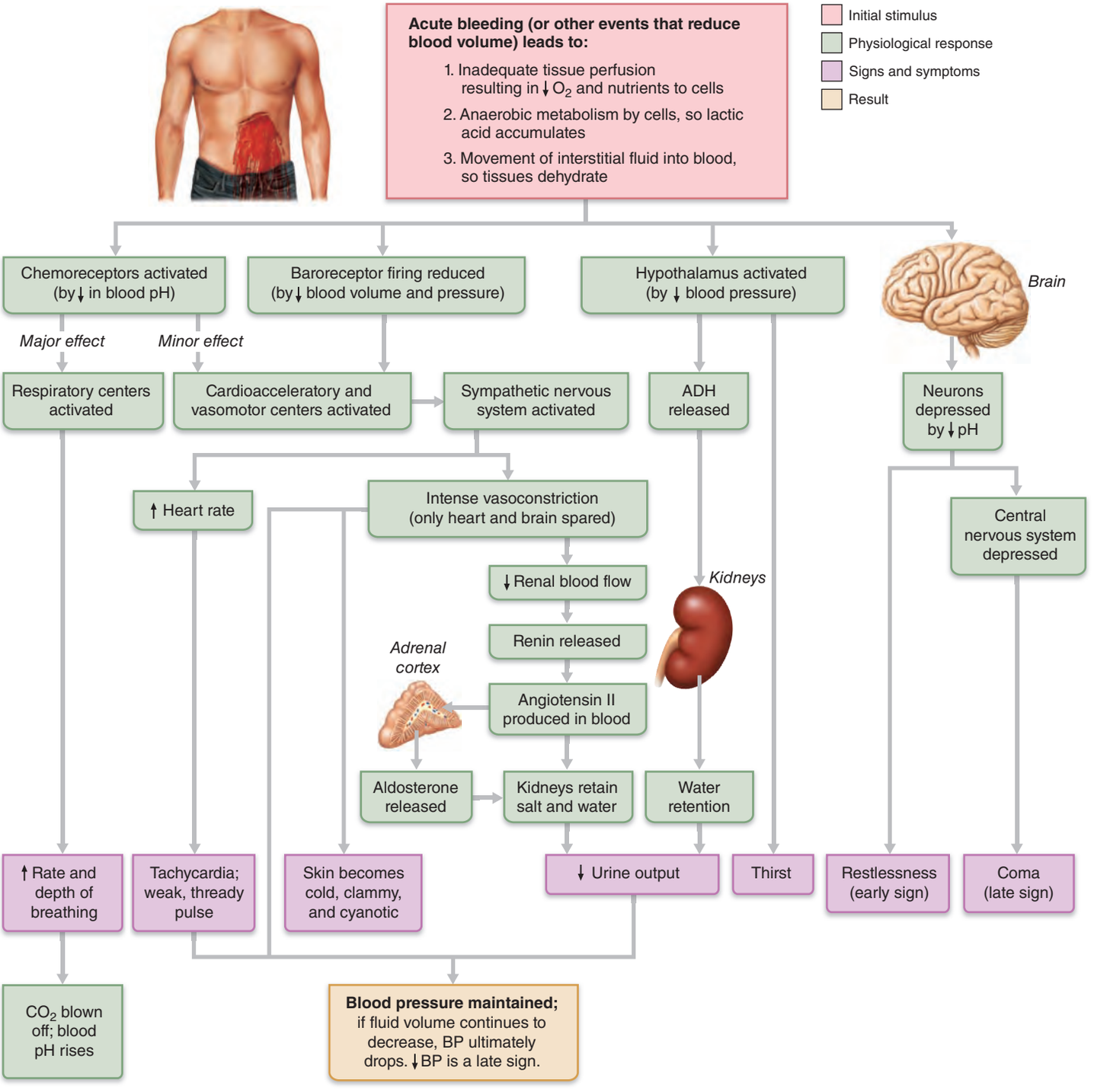


Figure 19.18 Events and signs of hypovolemic shock.

PART 3

Circulatory Pathways: Blood Vessels of the Body

The Two Main Circulations of the Body

✓ Trace the pathway of blood through the pulmonary circuit, and state the importance of this special circulation.

✓ Describe the general functions of the systemic circuit.

The term **vascular system** is often used to describe the body's complex network of blood vessels. However, the heart is actually a double pump that serves two distinct circulations, each with its own set of arteries, capillaries, and veins. The *pulmonary circulation* is the short loop that runs from the heart to the lungs and back to the heart. The *systemic circulation* routes blood through a long loop to all parts of the body before returning it to the heart. Table 19.3 on pp. 722–723 shows both circuits schematically.

Systemic Arteries and Veins: Differences in Pathways and Courses

As we saw in Chapter 18, the heart pumps all of its blood into a single systemic artery—the aorta. In contrast, blood returning to the heart is delivered largely by two terminal systemic veins, the superior and inferior venae cavae. The single exception to this is the blood draining from the myocardium of the heart, which is collected by the cardiac veins and reenters the right atrium via the coronary sinus.

In addition to these differences between arteries and veins connecting to the heart, there are three important differences between systemic arteries and veins:

- **Arteries run deep while veins are both deep and superficial.** Deep veins parallel the course of the systemic arteries and both are protected by body tissues along most of their course. With a few exceptions, these veins are named identically to their companion arteries. Superficial veins run just beneath the skin and are readily seen, especially in the limbs, face, and neck. Because there are no superficial arteries, the names of the superficial veins do not correspond to the names of any of the arteries.
- **Venous pathways are more interconnected.** Unlike the fairly distinct arterial pathways, venous pathways tend to have numerous interconnections, and many veins are represented by not one but two similarly named vessels. As a result, venous pathways are more difficult to follow.
- **The brain and digestive systems have unique venous drainage systems.** Most body regions have a similar pattern for their arterial supply and venous drainage. However, the venous drainage pattern in at least two important body areas is unique. First, venous blood draining from the brain enters large *dural venous sinuses* rather than typical veins. Second, blood draining from the digestive organs enters a special subcirculation, the *hepatic portal system*, and perfuses through the liver before it reenters the general systemic circulation (see Table 19.12).

Principal Vessels of the Systemic Circulation

✓ Name and give the location of the major arteries and veins in the systemic circulation.

✓ Describe the structure and special function of the hepatic portal system.

Except for special vessels and shunts of the fetal circulation (described in Chapter 28), the principal arteries and veins of the systemic circulation are described in Tables 19.4 through 19.13.

Notice that by convention, oxygen-rich blood is shown red, while blood that is relatively oxygen-poor is depicted blue, regardless of vessel type. The schematic flowcharts (pipe diagrams) that accompany each table show the vessels that would be closer to the viewer in brighter, more intense colors than vessels deeper or farther from the viewer. For example, darker blue veins would be closer to the viewer than lighter blue veins in the body region shown.

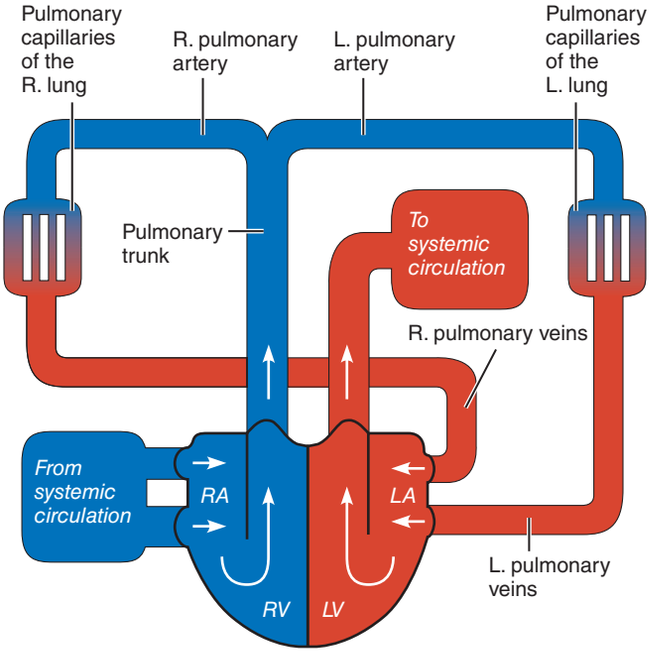
(Text continues on p. 745.)

Table 19.3 Pulmonary and Systemic Circulations

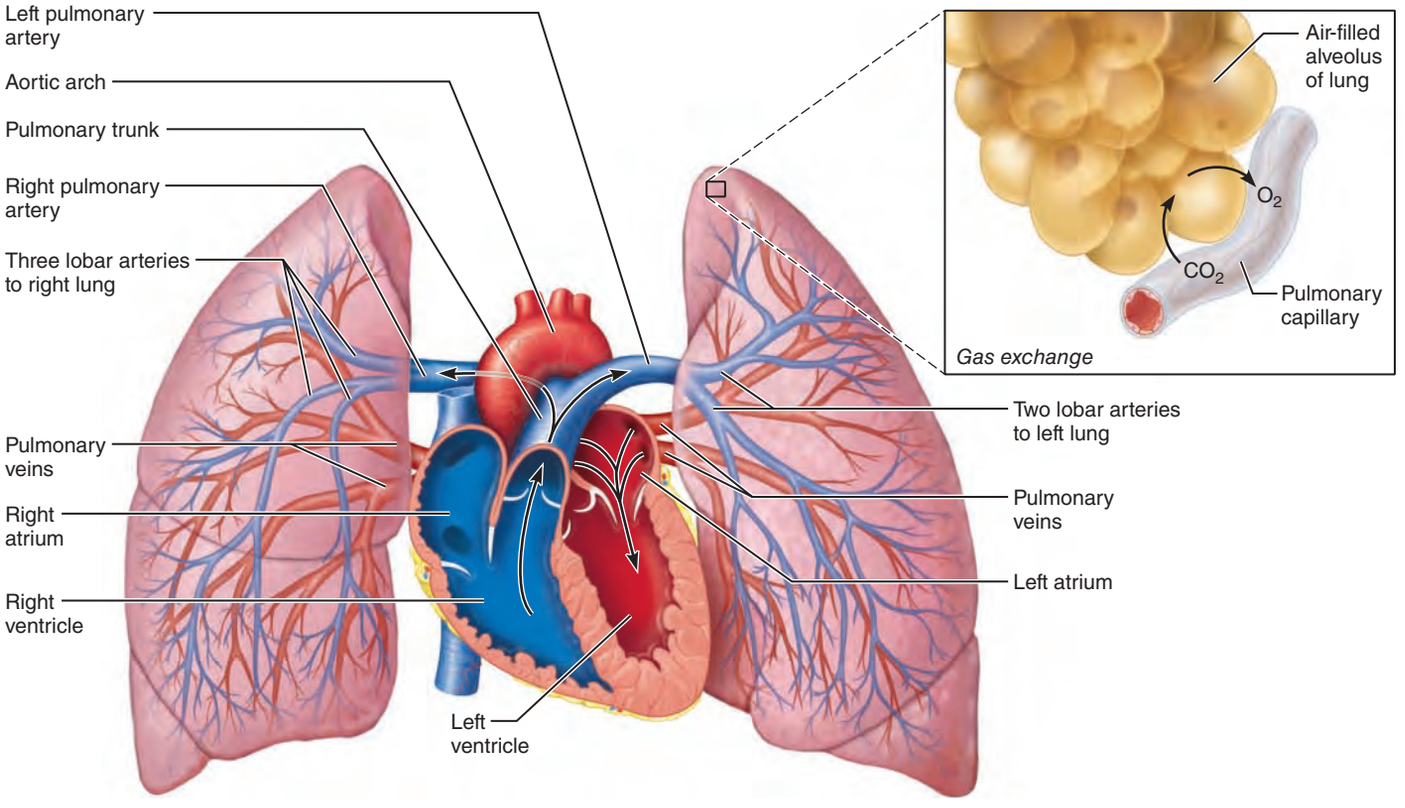
Pulmonary Circulation

The pulmonary circulation **(Figure 19.19a)** functions only to bring blood into close contact with the alveoli (air sacs) of the lungs so that gases can be exchanged. It does not directly serve the metabolic needs of body tissues.

Oxygen-poor, dark red blood enters the pulmonary circulation as it is pumped from the right ventricle into the large **pulmonary trunk** (Figure 19.19b), which runs diagonally upward for about 8 cm and then divides abruptly to form the **right** and **left pulmonary arteries**. In the lungs, the pulmonary arteries subdivide into the **lobar arteries** (lo′bar) (three in the right lung and two in the left lung), each of which serves one lung lobe. The lobar arteries accompany the main bronchi into the lungs and then branch profusely, forming first arterioles and then the dense networks of **pulmonary capillaries** that surround and cling to the delicate air sacs. It is here that oxygen moves from the alveolar air to the blood and carbon dioxide moves from the blood to the alveolar air. As gases are exchanged and the oxygen content of the blood rises, the blood becomes bright red. The pulmonary capillary beds drain into venules, which join to form the two **pulmonary veins** exiting from each lung. The four pulmonary veins complete the circuit by unloading their precious cargo into the left atrium of the heart.



(a) Schematic flowchart.



(b) Illustration. The pulmonary arterial system is shown in blue to indicate that the blood it carries is oxygen-poor. The pulmonary venous drainage is shown in red to indicate that the blood it transports is oxygen-rich.

Figure 19.19 Pulmonary circulation. RA = right atrium, RV = right ventricle, LA = left atrium, LV = left ventricle.

Table 19.3 *(continued)*

Note that any vessel with the term *pulmonary* or *lobar* in its name is part of the pulmonary circulation. All others are part of the systemic circulation.

Pulmonary arteries carry oxygen-poor, carbon dioxide–rich blood, and pulmonary veins carry oxygen-rich blood.* This is opposite to the systemic circulation, where arteries carry oxygen-rich blood and veins carry carbon dioxide–rich, relatively oxygen-poor blood.

Systemic Circulation

The systemic circulation provides the *functional blood supply* to all body tissues; that is, it delivers oxygen, nutrients, and other needed substances while carrying away carbon dioxide and other metabolic wastes. Freshly oxygenated blood* returning from the pulmonary circuit is pumped out of the left ventricle into the aorta **(Figure 19.20)**.

From the aorta, blood can take various routes, because essentially all systemic arteries branch from this single great vessel. The aorta arches upward from the heart and then curves and runs downward along the body midline to its terminus in the pelvis, where it splits to form the two large arteries serving the lower extremities. The branches of the aorta continue to subdivide to produce the arterioles and, finally, the capillaries that ramify through the organs. Venous blood draining from organs inferior to the diaphragm ultimately enters the inferior vena cava.† Except for some coronary and thoracic venous drainage (which enters the azygos system of veins), the superior vena cava drains body regions above the diaphragm. The venae cavae empty the carbon dioxide–laden blood into the right atrium of the heart.

Two important points concerning the two major circulations: (1) Blood passes from systemic veins to systemic arteries only after first moving through the pulmonary circuit (Figure 19.19a), and (2) although the entire cardiac output of the right ventricle passes through the pulmonary circulation, only a small fraction of the output of the left ventricle flows through any single organ (Figure 19.20). The systemic circulation can be viewed as multiple circulatory channels functioning in parallel to distribute blood to all body organs.

As you examine the tables that follow and locate the various systemic arteries and veins in the illustrations, be aware of cues that make your memorization task easier. In many cases, the name of a vessel reflects the body region traversed (axillary, brachial, femoral, etc.), the organ served (renal, hepatic, gonadal), or the bone followed (vertebral, radial, tibial). Also, notice that arteries and veins tend to run side by side and, in many places, they also run with nerves. Finally, be alert to the fact that the systemic vessels do not always match on the right and left sides of the body. Thus, while almost all vessels in the head and limbs are bilaterally symmetrical, some of the large, deep vessels of the trunk region are asymmetrical or unpaired.

*By convention, oxygen-rich blood is shown red and oxygen-poor blood is shown blue.
†Venous blood from the digestive viscera passes through the hepatic portal circulation (liver and associated veins) before entering the inferior vena cava.

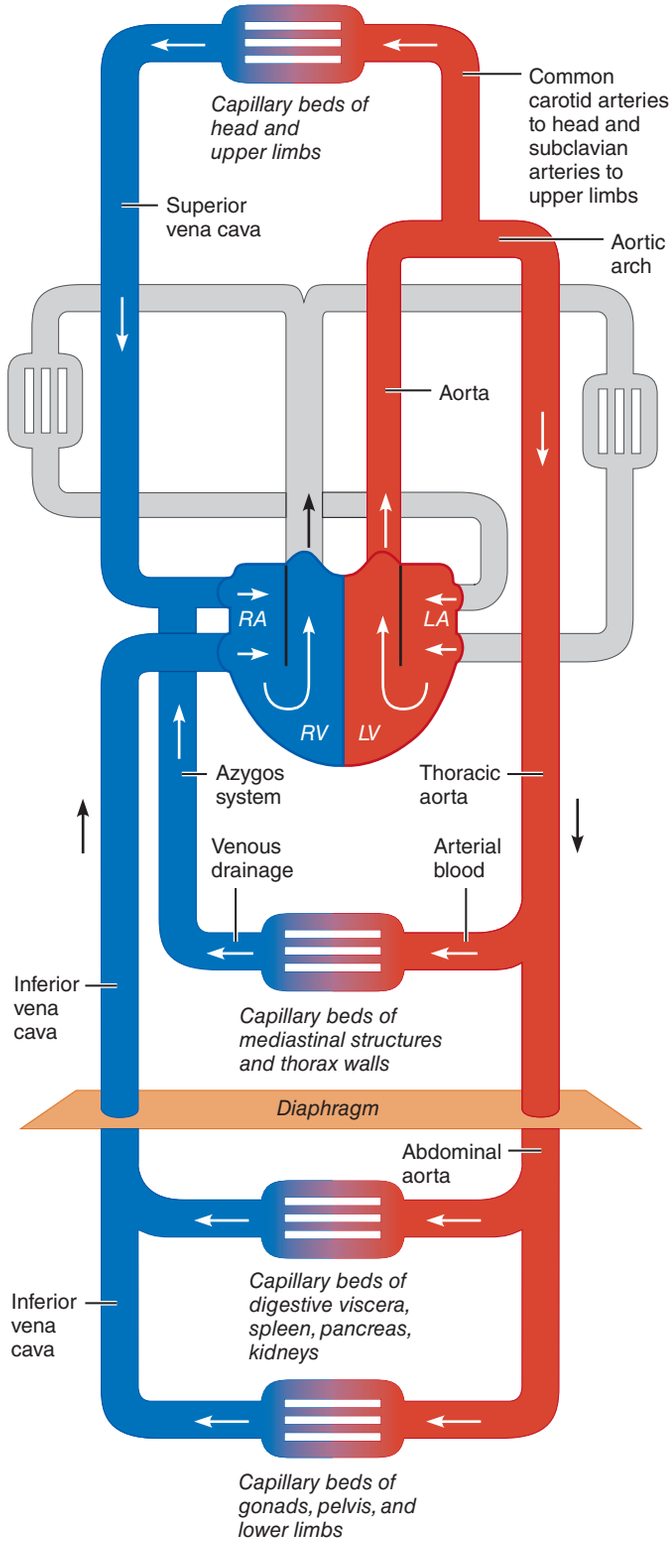


Figure 19.20 Schematic flowchart showing an overview of the systemic circulation. The pulmonary circulation is shown in gray for comparison. RA = right atrium, RV = right ventricle, LA = left atrium, LV = left ventricle.

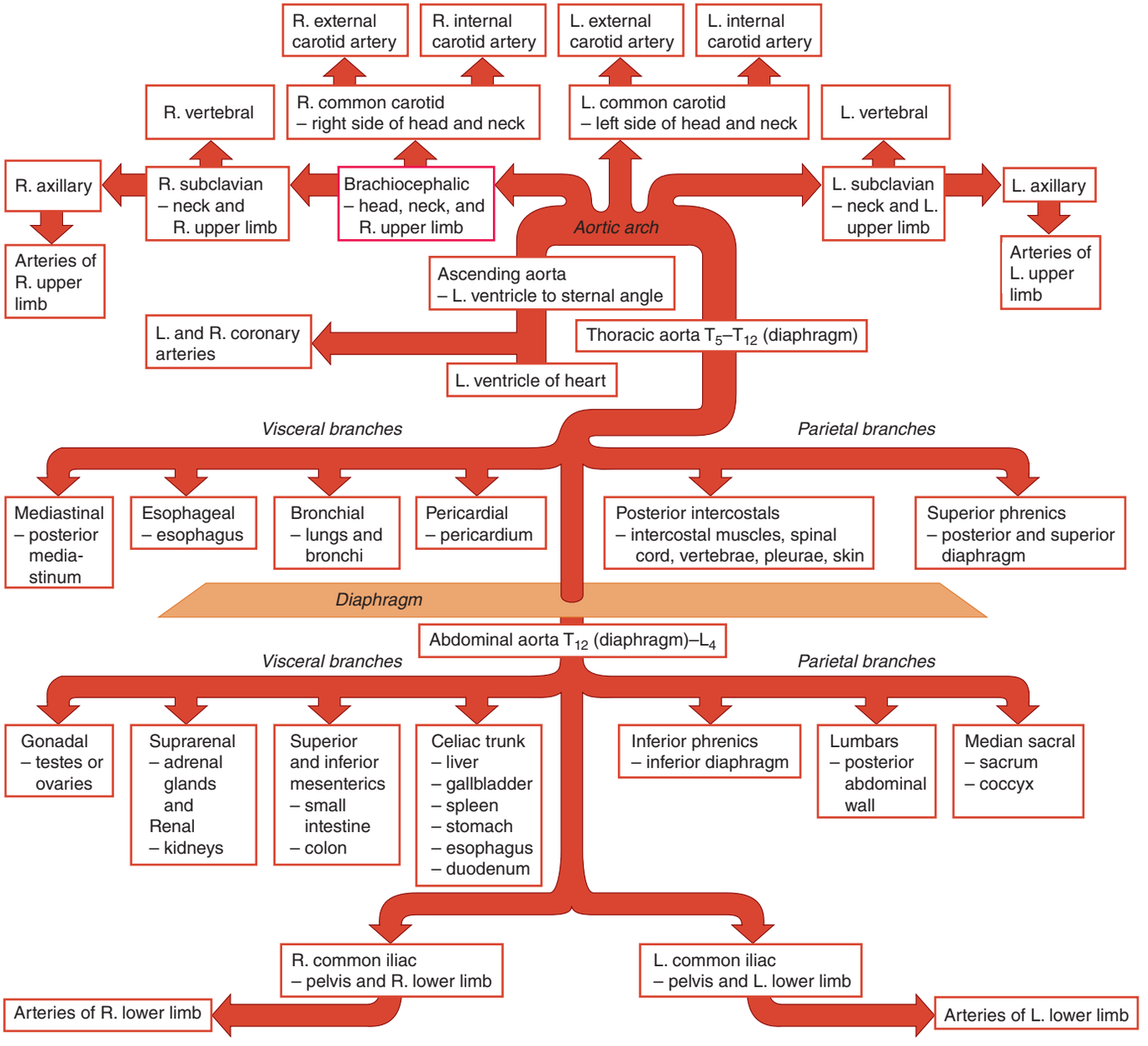
Table 19.4 The Aorta and Major Arteries of the Systemic Circulation

Figure 19.21a diagrams the distribution of the aorta and major arteries of the systemic circulation in flowchart form, and Figure 19.21b illustrates them. See Tables 19.5 through 19.8 for fine points about the vessels arising from the aorta.

The **aorta** is the largest artery in the body. In adults, the aorta (a-or′tah) is approximately the size of a garden hose where it issues from the left ventricle of the heart. Its internal diameter is 2.5 cm, and its wall is about 2 mm thick. It decreases in size slightly as it runs to its terminus. The aortic valve guards the base of the aorta and prevents backflow of blood during diastole. Opposite each aortic valve cusp is an *aortic sinus*, which contains baroreceptors important in reflex regulation of blood pressure.

Different portions of the aorta are named according to shape or location. The first portion, the **ascending aorta**, runs posteriorly and to the right of the pulmonary trunk. It persists for only about 5 cm before curving to the left as the aortic arch. The only branches of the ascending aorta are the **right** and **left coronary arteries**, which supply the myocardium. The **aortic arch**, deep to the sternum, begins and ends at the sternal angle (T_4 level). Its three major branches (R to L) are: (1) the **brachiocephalic trunk** (bra′ke-o-sĕ-fal″ik; "armhead"), which passes superiorly under the right sternoclavicular joint and branches into the **right common carotid artery** (kah-rot′id) and the **right subclavian artery**, (2) the **left common carotid artery**, and (3) the **left subclavian artery**. These three vessels provide the arterial supply of the head, neck, upper limbs, and part of the thorax wall.

The **descending aorta** runs along the anterior spine. Called the **thoracic aorta** from T_5 to T_{12}, it sends off numerous small arteries to the thorax wall and viscera before piercing the diaphragm. As it enters the abdominal cavity, it becomes the **abdominal aorta**. This portion supplies the abdominal walls and viscera and ends at the L_4 level, where it splits into the **right** and **left common iliac arteries**, which supply the pelvis and lower limbs.



(a) Schematic flowchart

Table 19.4 *(continued)*

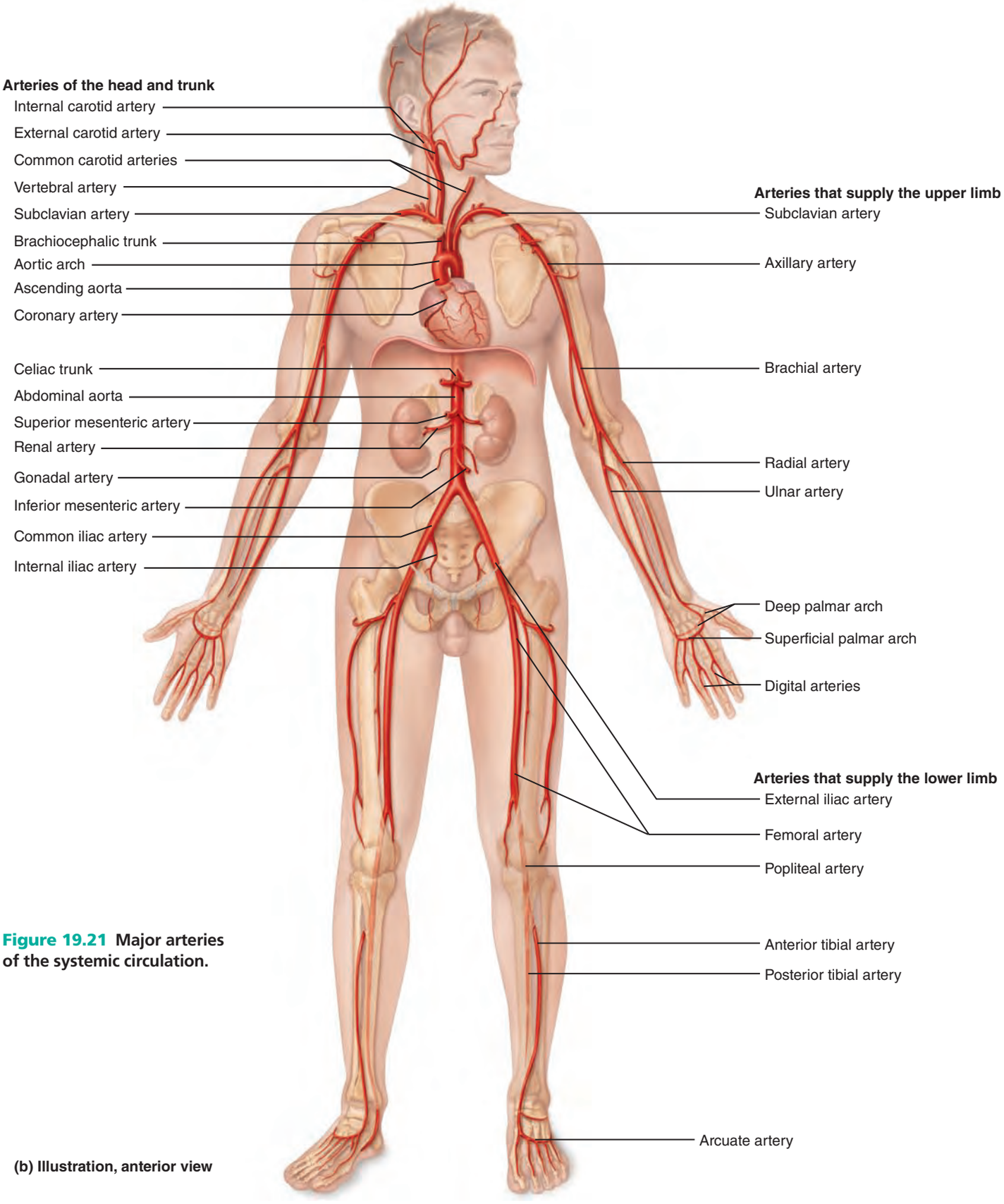


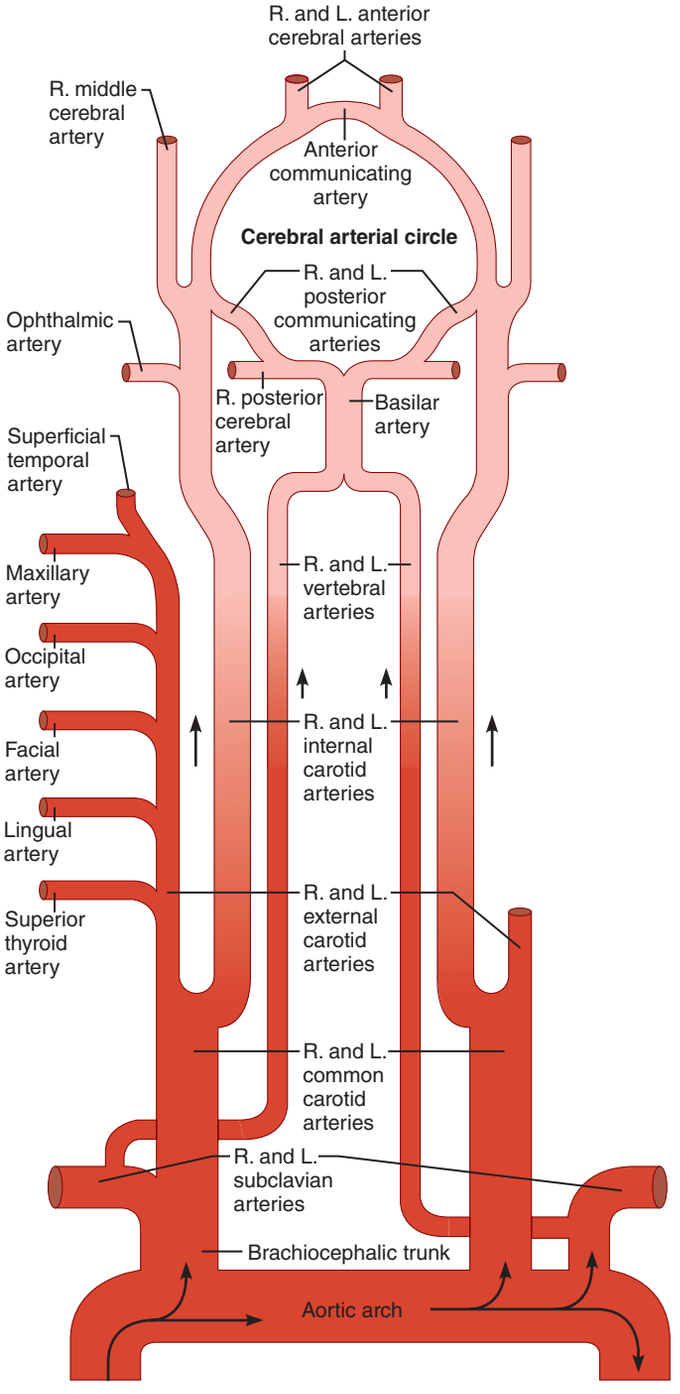
Figure 19.21 **Major arteries of the systemic circulation.**

(b) Illustration, anterior view

19

Table 19.5 Arteries of the Head and Neck

Four paired arteries supply the head and neck. These are the common carotid arteries, plus three branches from each subclavian artery: the vertebral arteries, the thyrocervical trunks, and the costocervical trunks **(Figure 19.22b)**. Of these, the common carotid arteries have the broadest distribution (Figure 19.22a).



(a) Schematic flowchart

Figure 19.22 Arteries of the head, neck, and brain.

Each common carotid divides into two major branches (the internal and external carotid arteries). At the division point, each internal carotid artery has a slight dilation, the **carotid sinus**, that contains baroreceptors that assist in reflex blood pressure control. The **carotid bodies**, chemoreceptors involved in controlling respiratory rate, are located close by. Pressing on the neck in the area of the carotid sinuses can cause unconsciousness (*carot* = stupor) because the pressure created mimics high blood pressure, eliciting vasodilation, which interferes with blood delivery to the brain.

Description and Distribution

Common carotid arteries. The origins of these two arteries differ: The right common carotid artery arises from the brachiocephalic trunk; the left is the second branch of the aortic arch. The common carotid arteries ascend through the lateral neck, and at the superior border of the larynx (the level of the "Adam's apple"), each divides into its two major branches, the *external* and *internal carotid arteries*.

The **external carotid arteries** supply most tissues of the head except for the brain and orbit. As each artery runs superiorly, it sends branches to the thyroid gland and larynx **(superior thyroid artery)**, the tongue **(lingual artery)**, the skin and muscles of the anterior face **(facial artery)**, and the posterior scalp **(occipital artery)**. Each external carotid artery terminates by splitting into a **superficial temporal artery**, which supplies the parotid salivary gland and most of the scalp, and a **maxillary artery**, which supplies the upper and lower jaws and chewing muscles, the teeth, and the nasal cavity. A clinically important branch of the maxillary artery is the *middle meningeal artery* (not illustrated). It enters the skull through the foramen spinosum and supplies the inner surface of the parietal bone, squamous part of the temporal bone, and the underlying dura mater.

The larger **internal carotid arteries** supply the orbits and more than 80% of the cerebrum. They assume a deep course and enter the skull through the carotid canals of the temporal bones. Once inside the cranium, each artery gives off one main branch, the ophthalmic artery, and then divides into the anterior and middle cerebral arteries. The **ophthalmic arteries** (of-thal′mik) supply the eyes, orbits, forehead, and nose. Each **anterior cerebral artery** supplies the medial surface of the frontal and parietal lobes of the cerebral hemisphere on its side and also anastomoses with its partner on the opposite side via a short arterial shunt called the **anterior communicating artery** (Figure 19.22d). The **middle cerebral arteries** run in the lateral sulci of their respective cerebral hemispheres and supply the lateral parts of the temporal, parietal, and frontal lobes.

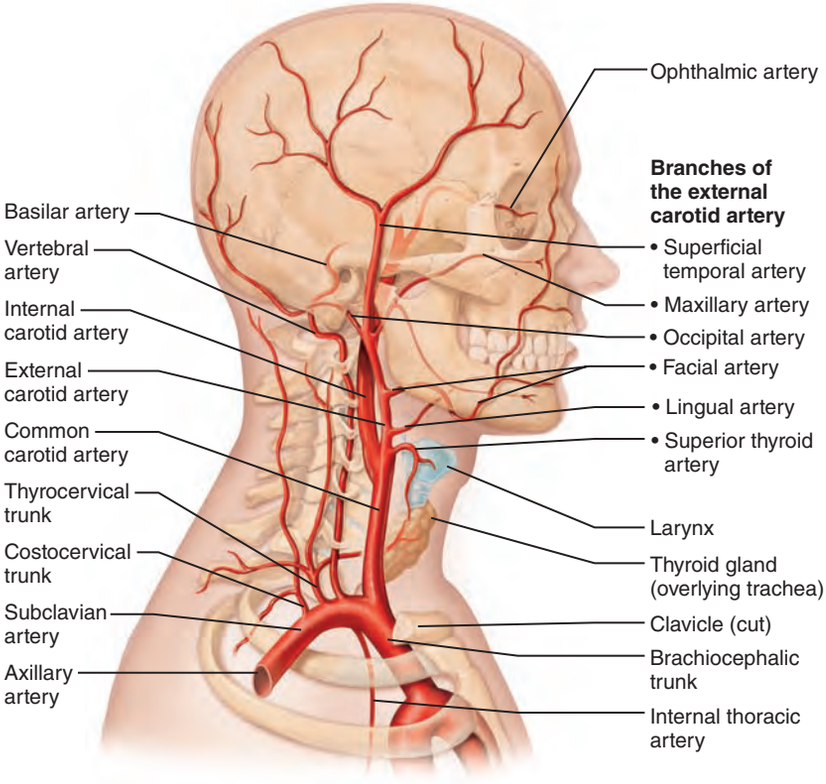
Vertebral arteries. The vertebral arteries spring from the subclavian arteries at the root of the neck and ascend through foramina in the transverse processes of the cervical vertebrae to enter the skull through the foramen magnum. En route, they send branches

Table 19.5 *(continued)*

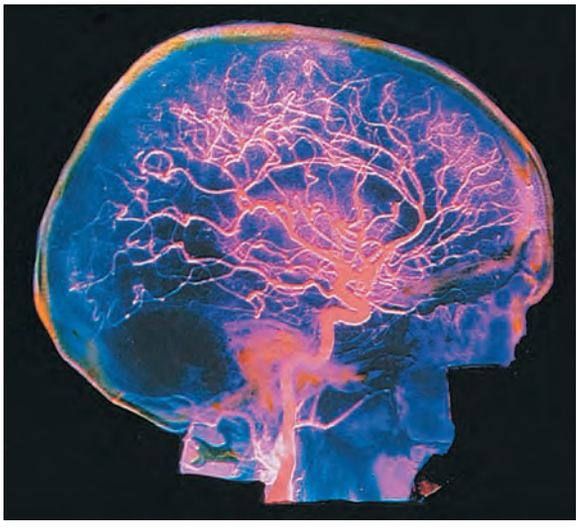
to the vertebrae and cervical spinal cord and to some deep structures of the neck. Within the cranium, the right and left vertebral arteries join to form the **basilar artery** (bas′ĭ-lar), which ascends along the anterior aspect of the brain stem, giving off branches to the cerebellum, pons, and inner ear (Figure 19.22b and d). At the pons-midbrain border, the basilar artery divides into a pair of **posterior cerebral arteries**, which supply the occipital lobes and the inferior parts of the temporal lobes.

Arterial shunts called **posterior communicating arteries** connect the posterior cerebral arteries to the middle cerebral arteries anteriorly. The two posterior and single anterior communicating arteries complete the formation of an arterial anastomosis called the **cerebral arterial circle** (*circle of Willis*). This structure encircles the pituitary gland and optic chiasma and unites the brain's anterior and posterior blood supplies. It also equalizes blood pressure in the two brain areas and provides alternate routes for blood to reach the brain tissue if a carotid or vertebral artery becomes occluded.

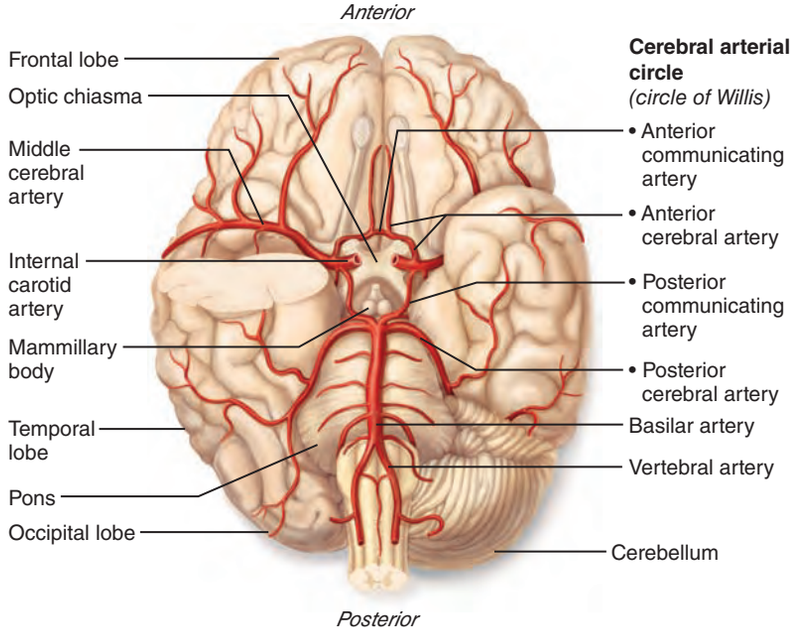
Thyrocervical and costocervical trunks. These short vessels arise from the subclavian artery just lateral to the vertebral arteries on each side (Figures 19.22b and Figure 19.23). The thyrocervical trunk mainly supplies the thyroid gland, portions of the cervical vertebrae and spinal cord, and some scapular muscles. The costocervical trunk serves deep neck and superior intercostal muscles.



(b) Arteries of the head and neck, right aspect



(c) Colorized arteriograph of the arterial supply of the brain



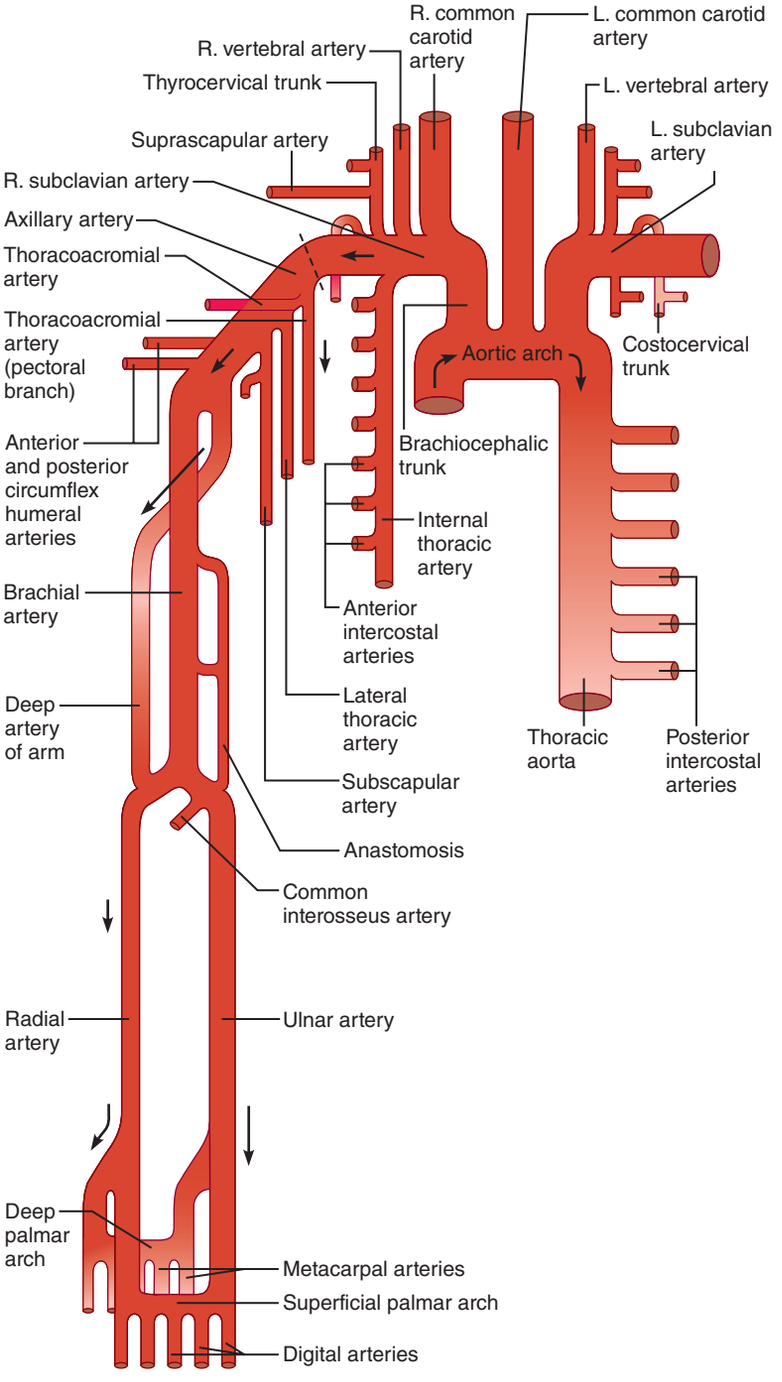
(d) Major arteries serving the brain (inferior view, right side of cerebellum and part of right temporal lobe removed)

Figure 19.22 *(continued)*

19

Table 19.6 Arteries of the Upper Limbs and Thorax

The upper limbs are supplied entirely by arteries arising from the **subclavian arteries** (Figure 19.23a). After giving off branches to the neck, each subclavian artery courses laterally between the clavicle and first rib to enter the axilla, where its name changes to axillary artery. The thorax wall is supplied by an array of vessels that arise either directly from the thoracic aorta or from branches of the subclavian arteries. Most visceral organs of the thorax receive their functional blood supply from small branches issuing from the thoracic aorta. Because these vessels are so small and tend to vary in number (except for the bronchial arteries), Figures 19.23a and b do not illustrate them, but several are listed at the end of this table.



(a) Schematic flowchart

Figure 19.23 Arteries of the right upper limb and thorax.

Description and Distribution

Arteries of the Upper Limb

Axillary artery. As it runs through the axilla accompanied by cords of the brachial plexus, each axillary artery gives off branches to the axilla, chest wall, and shoulder girdle. These branches include the **thoracoacromial artery** (tho″rah-ko-ah-kro′me-al), which supplies the deltoid muscle and pectoral region; the **lateral thoracic artery**, which serves the lateral chest wall and breast; the **subscapular artery** to the scapula, dorsal thorax wall, and part of the latissimus dorsi muscle; and the **anterior** and **posterior circumflex humeral arteries**, which wrap around the humeral neck and help supply the shoulder joint and the deltoid muscle. As the axillary artery emerges from the axilla, it becomes the brachial artery.

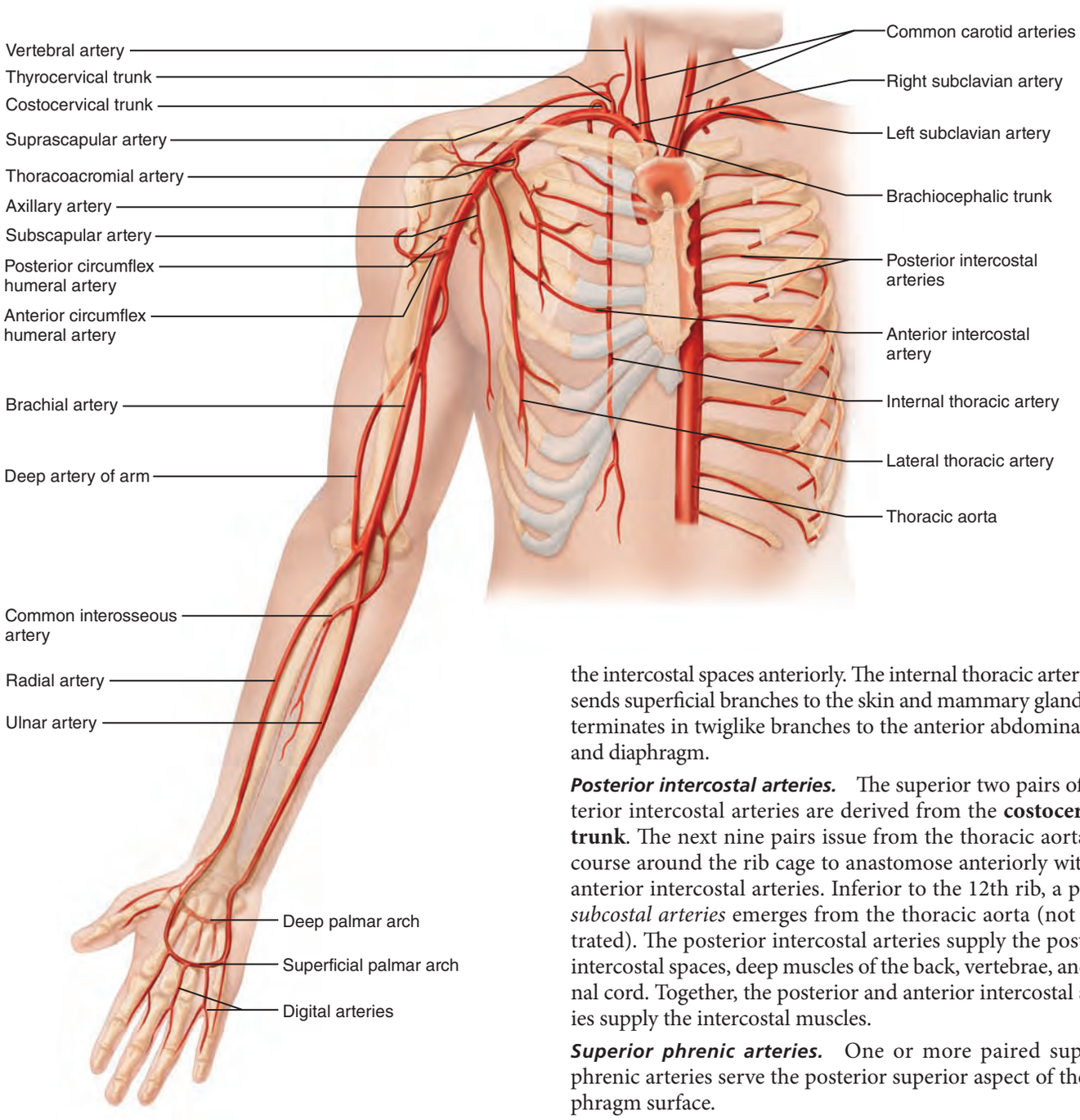
Brachial artery. The brachial artery runs down the medial aspect of the humerus and supplies the anterior flexor muscles of the arm. One major branch, the **deep artery of the arm**, serves the posterior triceps brachii muscle. As it nears the elbow, the brachial artery gives off several small branches that contribute to an anastomosis serving the elbow joint and connecting it to the arteries of the forearm. As the brachial artery crosses the anterior midline aspect of the elbow, it provides an easily palpated pulse point (brachial pulse) (see Figure 19.12). Immediately beyond the elbow, the brachial artery splits to form the radial and ulnar arteries, which more or less follow the course of similarly named bones down the anterior forearm.

Radial artery. The radial artery runs from the median line of the cubital fossa to the styloid process of the radius. It supplies the lateral muscles of the forearm, the wrist, and the thumb and index finger. At the root of the thumb, the radial artery provides a convenient site for taking the radial pulse.

Ulnar artery. The ulnar artery supplies the medial aspect of the forearm, fingers 3–5, and the medial aspect of the index finger. Proximally, the ulnar artery gives off a short branch, the **common interosseous artery** (in″ter-os′e-us), which runs between the radius and ulna to serve the deep flexors and extensors of the forearm.

Palmar arches. In the palm, branches of the radial and ulnar arteries anastomose to form the **superficial** and **deep palmar arches**. The **metacarpal arteries** and **digital arteries** that supply the fingers arise from these palmar arches.

Table 19.6 *(continued)*



(b) Illustration, anterior view

Figure 19.23 *(continued)*

Arteries of the Thorax Wall

Internal thoracic arteries. The internal thoracic arteries (formerly called the internal mammary arteries) arise from the subclavian arteries and supply blood to most of the anterior thorax wall. Each of these arteries descends lateral to the sternum and gives off **anterior intercostal arteries**, which supply the intercostal spaces anteriorly. The internal thoracic artery also sends superficial branches to the skin and mammary glands and terminates in twiglike branches to the anterior abdominal wall and diaphragm.

Posterior intercostal arteries. The superior two pairs of posterior intercostal arteries are derived from the **costocervical trunk**. The next nine pairs issue from the thoracic aorta and course around the rib cage to anastomose anteriorly with the anterior intercostal arteries. Inferior to the 12th rib, a pair of *subcostal arteries* emerges from the thoracic aorta (not illustrated). The posterior intercostal arteries supply the posterior intercostal spaces, deep muscles of the back, vertebrae, and spinal cord. Together, the posterior and anterior intercostal arteries supply the intercostal muscles.

Superior phrenic arteries. One or more paired superior phrenic arteries serve the posterior superior aspect of the diaphragm surface.

Arteries of the Thoracic Viscera

Pericardial arteries. Several tiny branches supply the posterior pericardium.

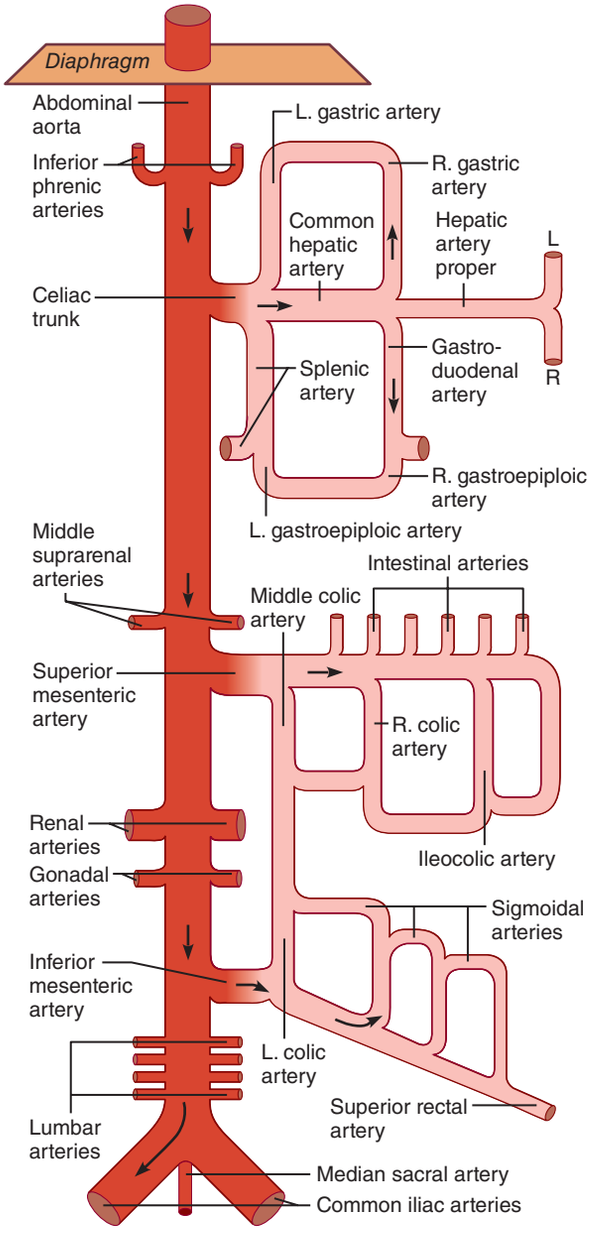
Bronchial arteries. Two left and one right bronchial arteries supply systemic (oxygen-rich) blood to the lungs, bronchi, and pleurae.

Esophageal arteries. Four to five esophageal arteries supply the esophagus.

Mediastinal arteries. Many small mediastinal arteries serve the posterior mediastinum.

Table 19.7 Arteries of the Abdomen

The arterial supply to the abdominal organs arises from the abdominal aorta **(Figure 19.24a)**. Under resting conditions, about half of the entire arterial flow moves through these vessels. Except for the celiac trunk, the superior and inferior mesenteric arteries, and the median sacral artery, all are paired vessels. These arteries supply the abdominal wall, diaphragm, and visceral organs of the abdominopelvic cavity. We discuss the branches in the order of their issue.



(a) Schematic flowchart.

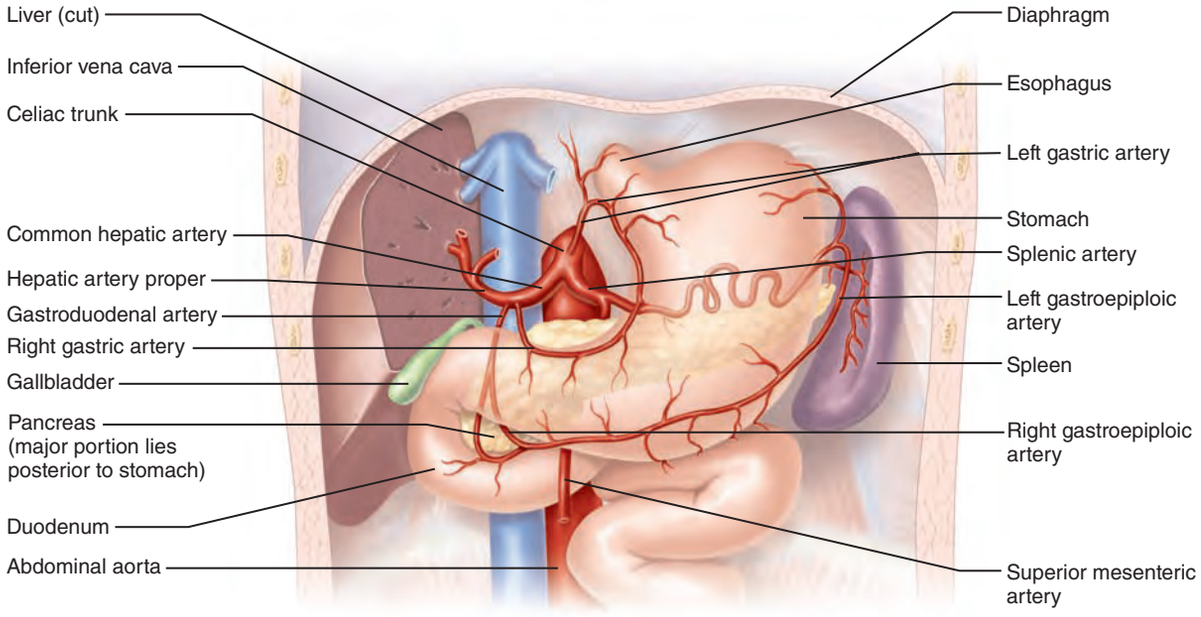
Figure 19.24 Arteries of the abdomen.

Table 19.7 *(continued)*

Description and Distribution

Inferior phrenic arteries. The inferior phrenics emerge from the aorta at T_{12}, just inferior to the diaphragm (Figure 19.24c). They serve the inferior diaphragm surface.

Celiac trunk. This very large unpaired branch of the abdominal aorta divides almost immediately into three branches: the common hepatic, splenic, and left gastric arteries (Figure 19.24b). The **common hepatic artery** (hĕ-pat′ik) gives off branches to the stomach, duodenum, and pancreas. Where the **gastroduodenal artery** branches off, the common hepatic becomes the **hepatic artery proper**, which splits into right and left branches that serve the liver. As the **splenic artery** (splen′ik) passes deep to the stomach, it sends branches to the pancreas and stomach and terminates in branches to the spleen. The **left gastric artery** (*gaster* = stomach) supplies part of the stomach and the inferior esophagus. The **right** and **left gastroepiploic arteries** (gas″tro-ep″ĭ-plo′ik)—branches of the gastroduodenal and splenic arteries, respectively—serve the greater curvature of the stomach. A **right gastric artery**, which supplies the stomach's lesser curvature, may arise from the common hepatic artery or from the hepatic artery proper.



(b) The celiac trunk and its major branches. The left half of the liver has been removed.

Figure 19.24 *(continued)*

Table 19.7 Arteries of the Abdomen *(continued)*

Superior mesenteric artery (mes-en-ter′ik). This large, unpaired artery arises from the abdominal aorta at the L_1 level immediately below the celiac trunk (Figure 19.24d). It runs deep to the pancreas and then enters the mesentery (a drapelike membrane that supports the small intestine), where its numerous anastomosing branches serve virtually all of the small intestine via the **intestinal arteries**, and most of the large intestine—the appendix, cecum, ascending colon (via the **ileocolic** and **right colic arteries**), and part of the transverse colon (via the **middle colic artery**).

Suprarenal arteries (soo″prah-re′nal). The **middle suprarenal arteries** flank the origin of the superior mesenteric artery as they emerge from the abdominal aorta (Figure 19.24c). They supply blood to the adrenal (suprarenal) glands overlying the kidneys. The adrenal glands also receive two sets of branches not illustrated: *superior suprarenal* branches from the nearby inferior phrenic arteries, and *inferior suprarenal* branches from the nearby renal arteries.

Renal arteries. The short but wide renal arteries, right and left, issue from the lateral surfaces of the aorta slightly below the superior mesenteric artery (between L_1 and L_2). Each serves the kidney on its side.

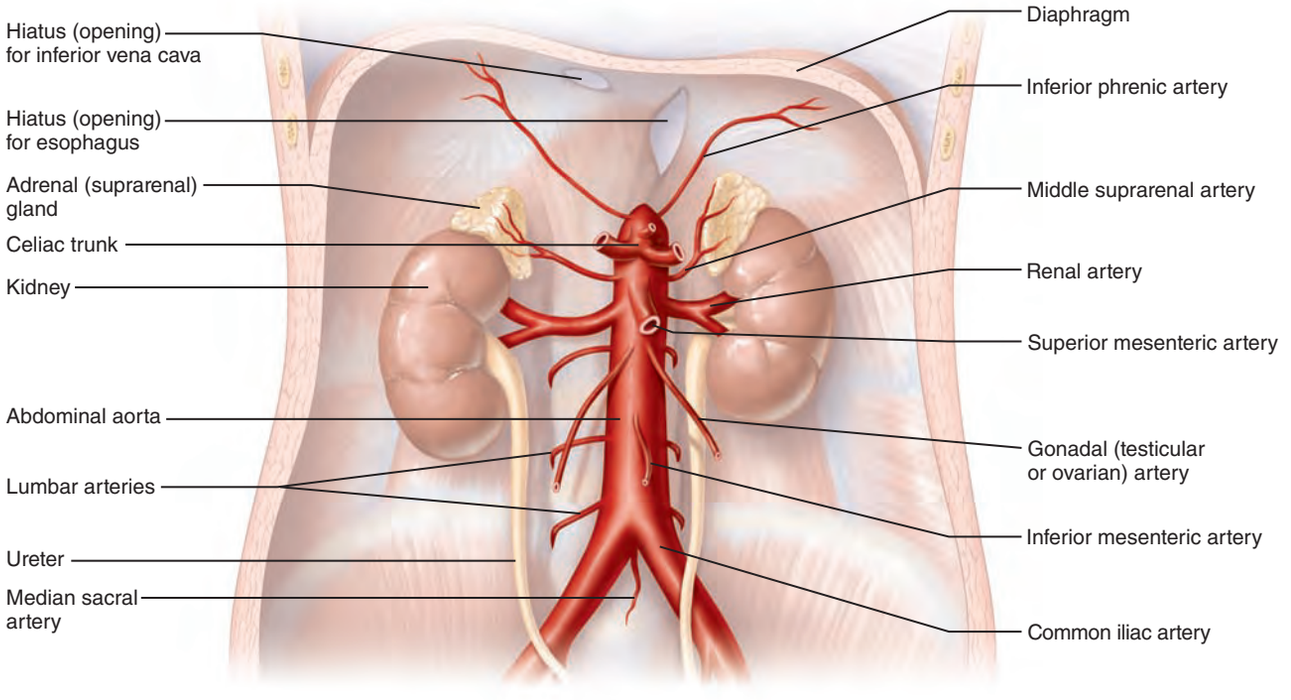
Gonadal arteries (go-nă′dul). The paired gonadal arteries are called the **ovarian arteries** in females and the **testicular arteries** in males. The ovarian arteries extend into the pelvis to serve the ovaries and part of the uterine tubes. The much longer testicular arteries descend through the pelvis and inguinal canals to enter the scrotum, where they serve the testes.

Inferior mesenteric artery. This final major branch of the abdominal aorta is unpaired and arises from the anterior aortic surface at the L_3 level. It serves the distal part of the large intestine—from the midpart of the transverse colon to the midrectum—via its **left colic**, **sigmoidal**, and **superior rectal branches** (Figure 19.24d). Looping anastomoses between the superior and inferior mesenteric arteries help ensure that blood will continue to reach the digestive viscera in cases of trauma to one of these abdominal arteries.

Lumbar arteries. Four pairs of lumbar arteries arise from the posterolateral surface of the aorta in the lumbar region. These segmental arteries supply the posterior abdominal wall.

Median sacral artery. The unpaired median sacral artery issues from the posterior surface of the abdominal aorta at its terminus. This tiny artery supplies the sacrum and coccyx.

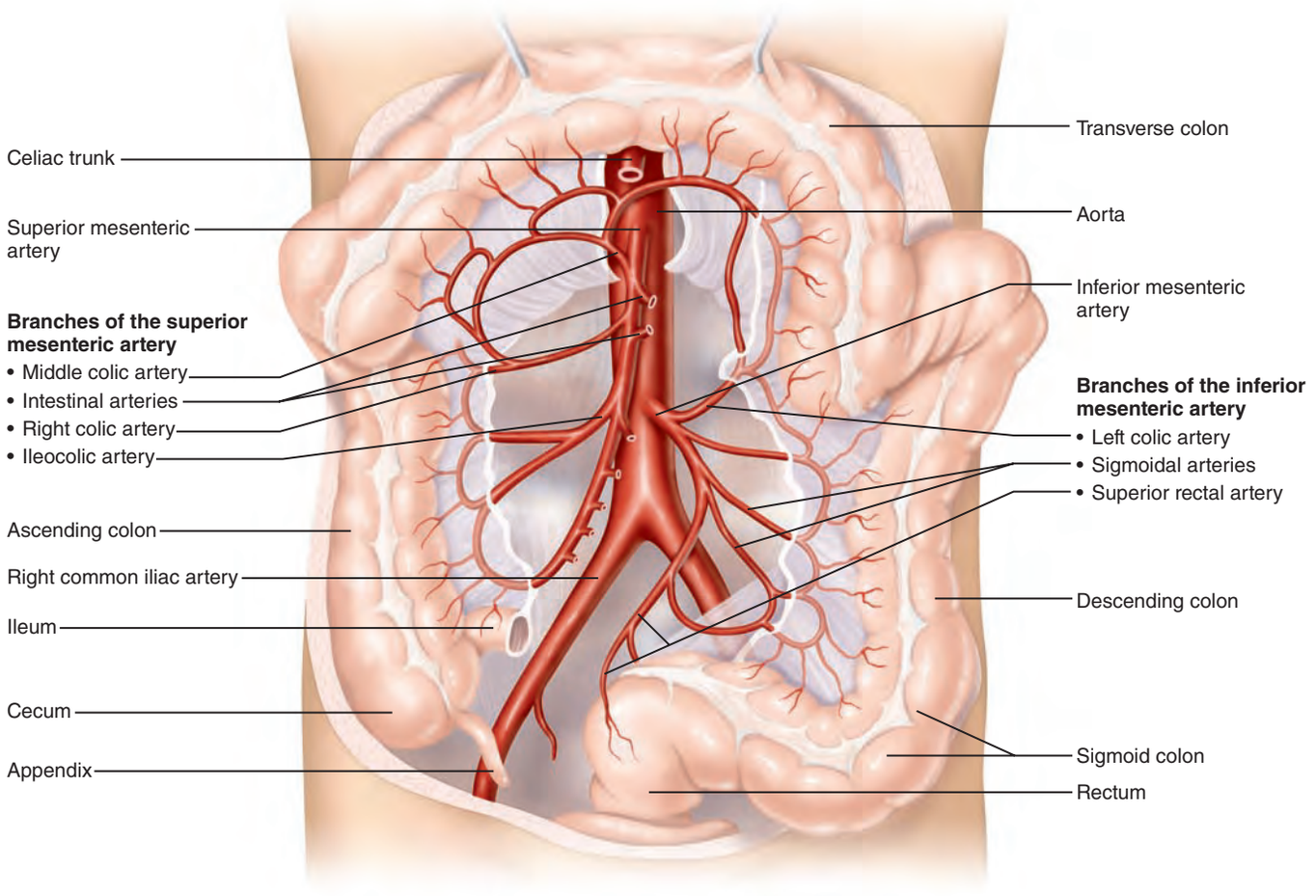
Common iliac arteries. At the L_4 level, the aorta splits into the right and left common iliac arteries, which supply blood to the lower abdominal wall, pelvic organs, and lower limbs (Figure 19.24c).



(c) Major branches of the abdominal aorta.

Figure 19.24 *(continued)* **Arteries of the abdomen.**

Table 19.7 *(continued)*



(d) Distribution of the superior and inferior mesenteric arteries. The transverse colon has been pulled superiorly.

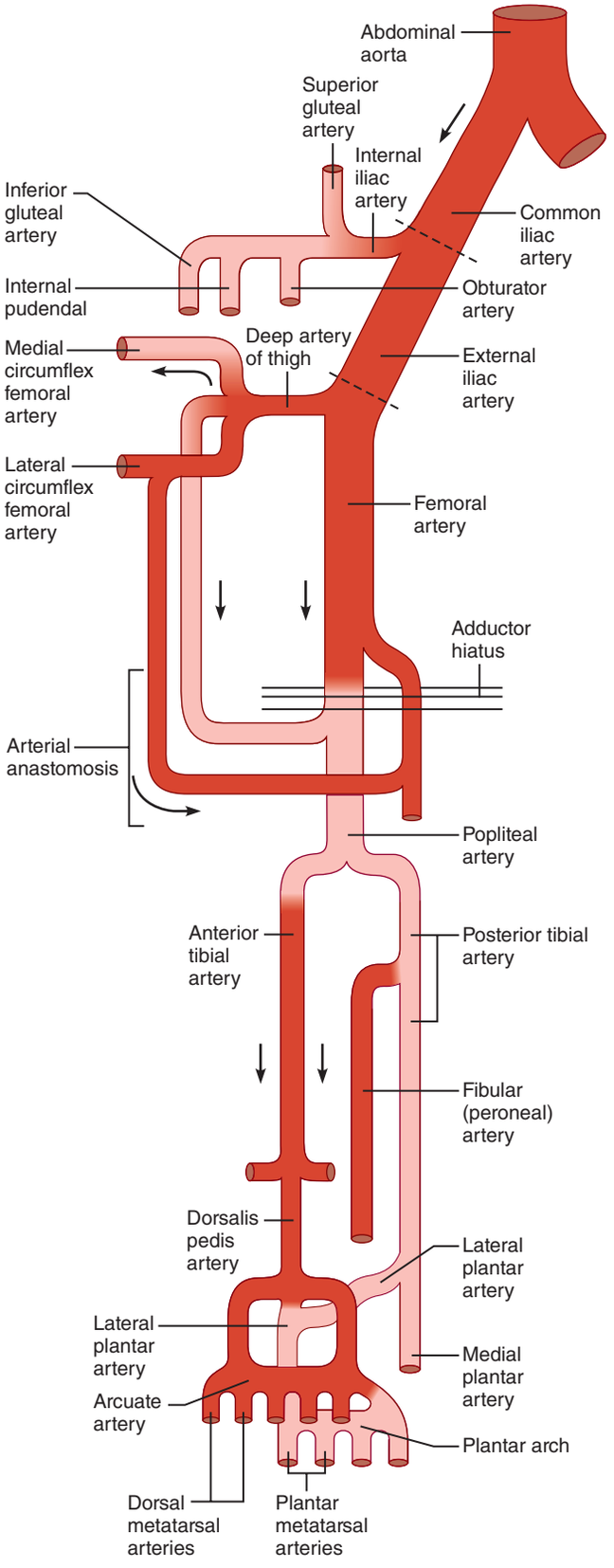
Figure 19.24 *(continued)*

Check Your Understanding

15. Which paired artery supplies most of the tissues of the head except for the brain and orbits?
16. Name the arterial anastomosis at the base of the cerebrum.
17. Name the four unpaired arteries that emerge from the abdominal aorta.

For answers, see Appendix H.

Table 19.8 Arteries of the Pelvis and Lower Limbs



(a) Schematic flowchart

At the level of the sacroiliac joints, the **common iliac arteries** divide into two major branches, the internal and external iliac arteries **(Figure 19.25a)**. The internal iliacs distribute blood mainly to the pelvic region. The external iliacs primarily serve the lower limbs but also send branches to the abdominal wall.

Description and Distribution

Internal iliac arteries. These paired arteries run into the pelvis and distribute blood to the pelvic walls and viscera (bladder and rectum, plus the uterus and vagina in the female and the prostate and ductus deferens in the male). Additionally they serve the gluteal muscles via the **superior** and **inferior gluteal arteries**, adductor muscles of the medial thigh via the **obturator artery**, and external genitalia and perineum via the **internal pudendal artery** (not illustrated).

External iliac arteries. These arteries supply the lower limbs (Figure 19.25b). As they course through the pelvis, they give off branches to the anterior abdominal wall. After passing under the inguinal ligaments to enter the thigh, they become the femoral arteries.

Femoral arteries. As each of these arteries passes down the anteromedial thigh, it gives off several branches to the thigh muscles. The largest of the deep branches is the **deep artery of the thigh** (also called the *deep femoral artery*), which is the main supply to the thigh muscles (hamstrings, quadriceps, and adductors). Proximal branches of the deep femoral artery, the **lateral** and **medial circumflex femoral arteries**, encircle the neck of the femur. The medial circumflex artery is the major vessel to the head of the femur. If it is torn in a hip fracture, the bone tissue of the head of the femur dies. A long descending branch of the lateral circumflex artery supplies the vastus lateralis muscle. Near the knee the femoral artery passes posteriorly and through a gap in the adductor magnus muscle, the *adductor hiatus*, to enter the popliteal fossa, where its name changes to popliteal artery.

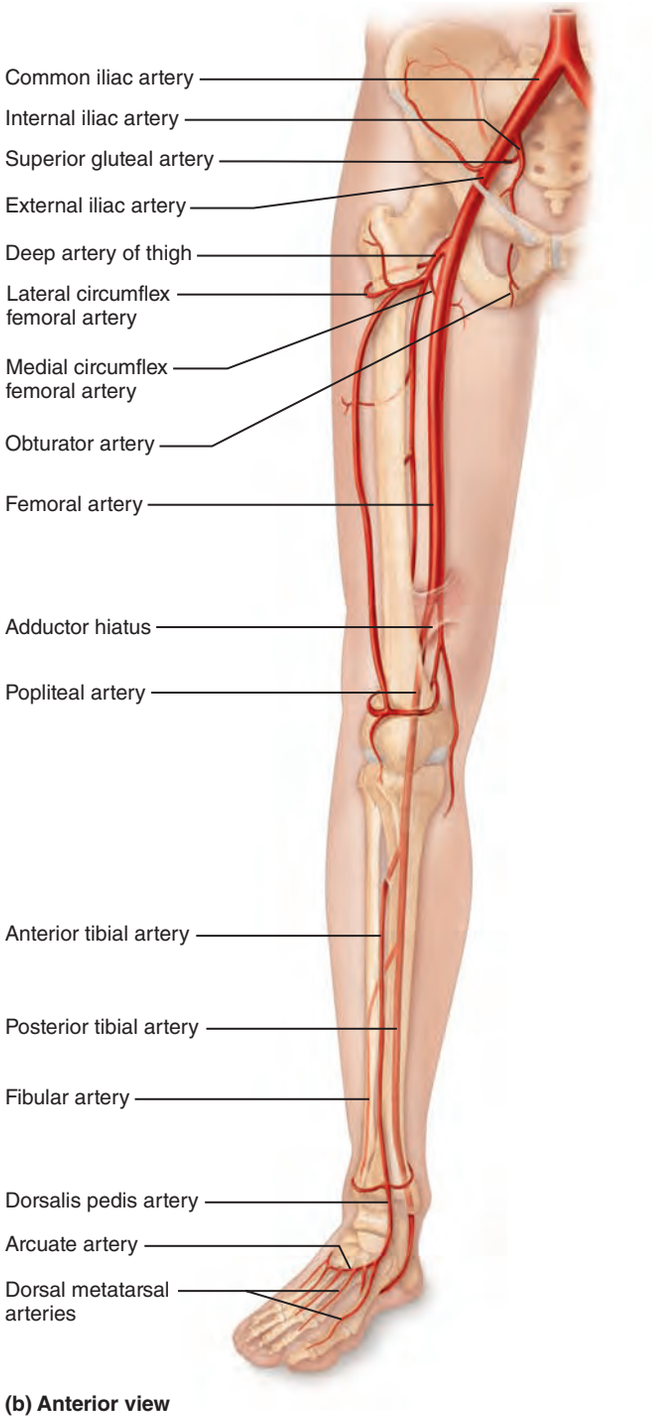
Popliteal artery. This posterior vessel contributes to an arterial anastomosis that supplies the knee region and then splits into the anterior and posterior tibial arteries of the leg.

Anterior tibial artery. The anterior tibial artery runs through the anterior compartment of the leg, supplying the extensor muscles along the way. At the ankle, it becomes the **dorsalis pedis artery**, which supplies the ankle and dorsum of the foot, and gives off a branch, the **arcuate artery**, which issues the **dorsal metatarsal arteries** to the metatarsus of the foot. The superficial dorsalis pedis ends by penetrating into the sole where it forms the medial part of the **plantar arch**. The dorsalis pedis artery provides a clinically important pulse point, the pedal pulse. If the pedal pulse is easily felt, it is fairly certain that the blood supply to the leg is good.

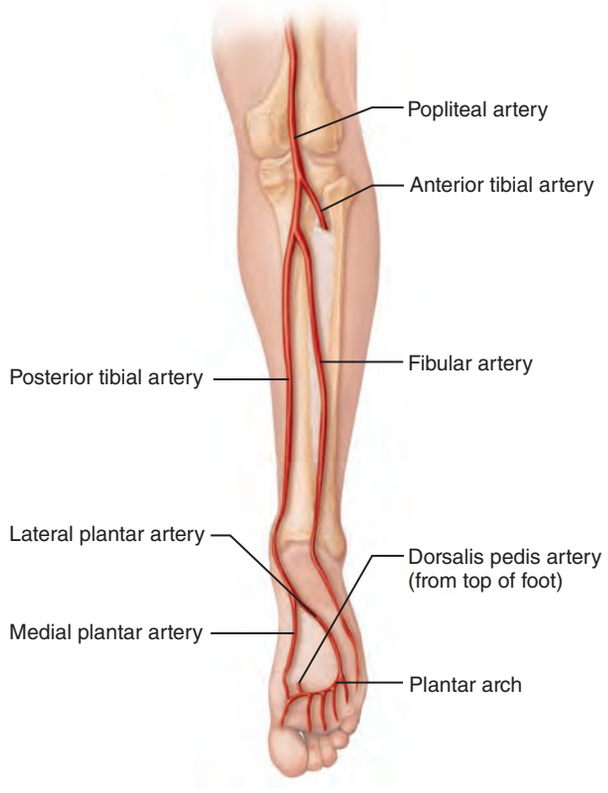
Figure 19.25 Arteries of the right pelvis and lower limb.

Table 19.8 *(continued)*

Posterior tibial artery. This large artery courses through the posteromedial part of the leg and supplies the flexor muscles. Proximally, it gives off a large branch, the **fibular (peroneal) artery**, which supplies the lateral fibularis muscles of the leg. On the medial side of the foot, the posterior tibial artery divides into **lateral** and **medial plantar arteries** that serve the plantar surface of the foot. The lateral plantar artery forms the lateral end of the plantar arch. **Plantar metatarsal arteries** and digital arteries to the toes arise from the plantar arch.



(b) Anterior view



(c) Posterior view

Figure 19.25 *(continued)*

Check Your Understanding

18. You are assessing the circulation in the leg of a diabetic patient at the clinic. Name the artery you palpate in each of these three locations: behind the knee, behind the medial malleolus of the tibia, on the dorsum of the foot.

For answers, see Appendix H.

19

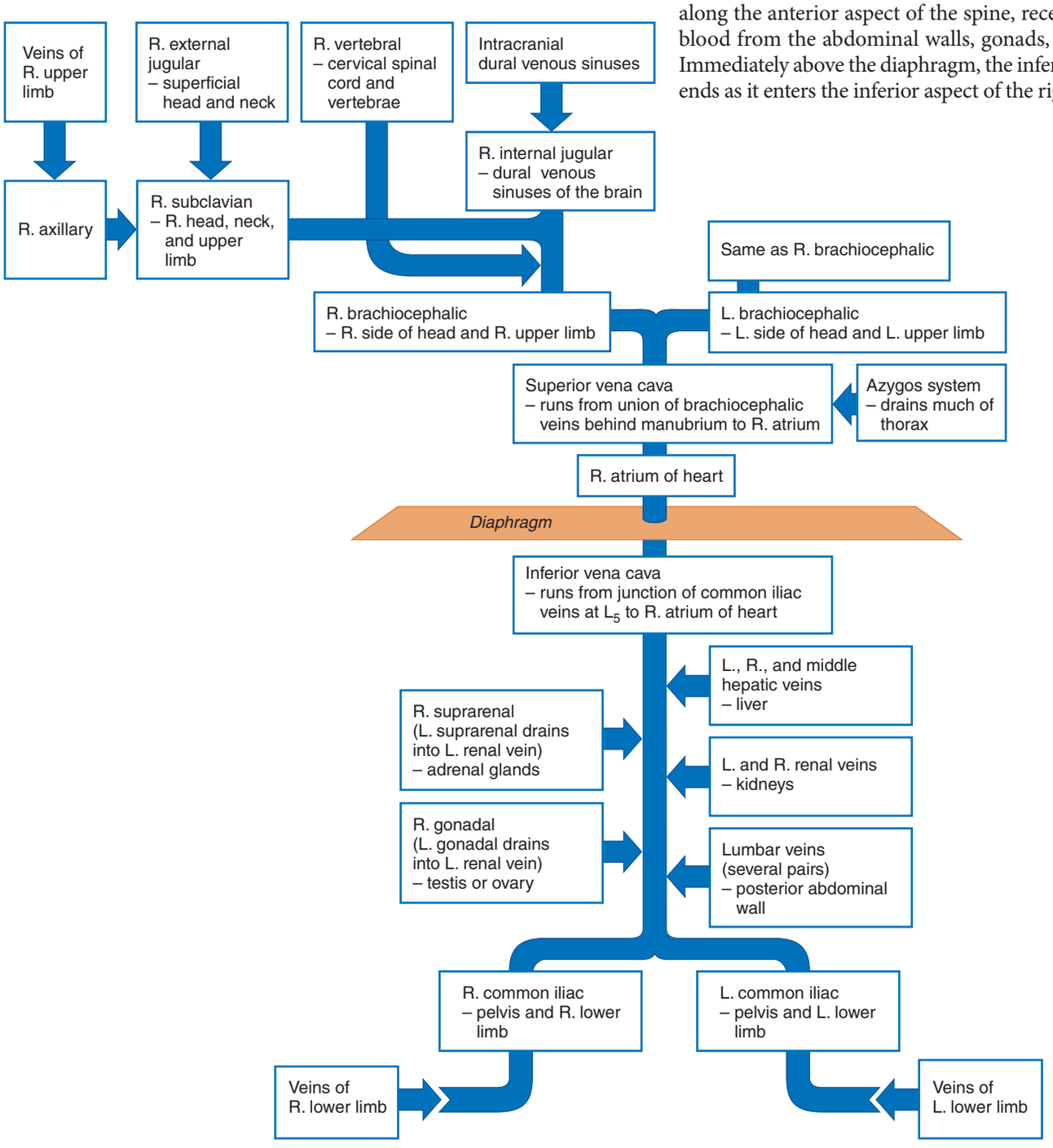
Table 19.9 The Venae Cavae and the Major Veins of the Systemic Circulation

In our survey of the systemic veins, the major tributaries (branches) of the venae cavae are noted first in **Figure 19.26**, followed by a description in Tables 19.10 through 19.13 of the venous pattern of the various body regions. Because veins run toward the heart, the most distal veins are named first and those closest to the heart last. Deep veins generally drain the same areas served by their companion arteries, so they are not described in detail.

Description and Areas Drained

Superior vena cava. This great vein receives systemic blood draining from all areas superior to the diaphragm, except the heart wall. It is formed by the union of the **right** and **left brachiocephalic veins** and empties into the right atrium (Figure 19.26b). Notice that there are two brachiocephalic veins, but only one brachiocephalic artery (trunk). Each brachiocephalic vein is formed by the joining of the **internal jugular** and **subclavian veins** on its side. In most of the flowcharts that follow, only the vessels draining blood from the right side of the body are shown (except for the azygos circulation of the thorax).

Inferior vena cava. The widest blood vessel in the body, this vein returns blood to the heart from all body regions below the diaphragm. The abdominal aorta lies directly to its left. The paired **common iliac veins** join at L_5 to form the distal end of the inferior vena cava. From this point, it courses superiorly along the anterior aspect of the spine, receiving venous blood from the abdominal walls, gonads, and kidneys. Immediately above the diaphragm, the inferior vena cava ends as it enters the inferior aspect of the right atrium.



(a) Schematic flowchart

Table 19.9 *(continued)*

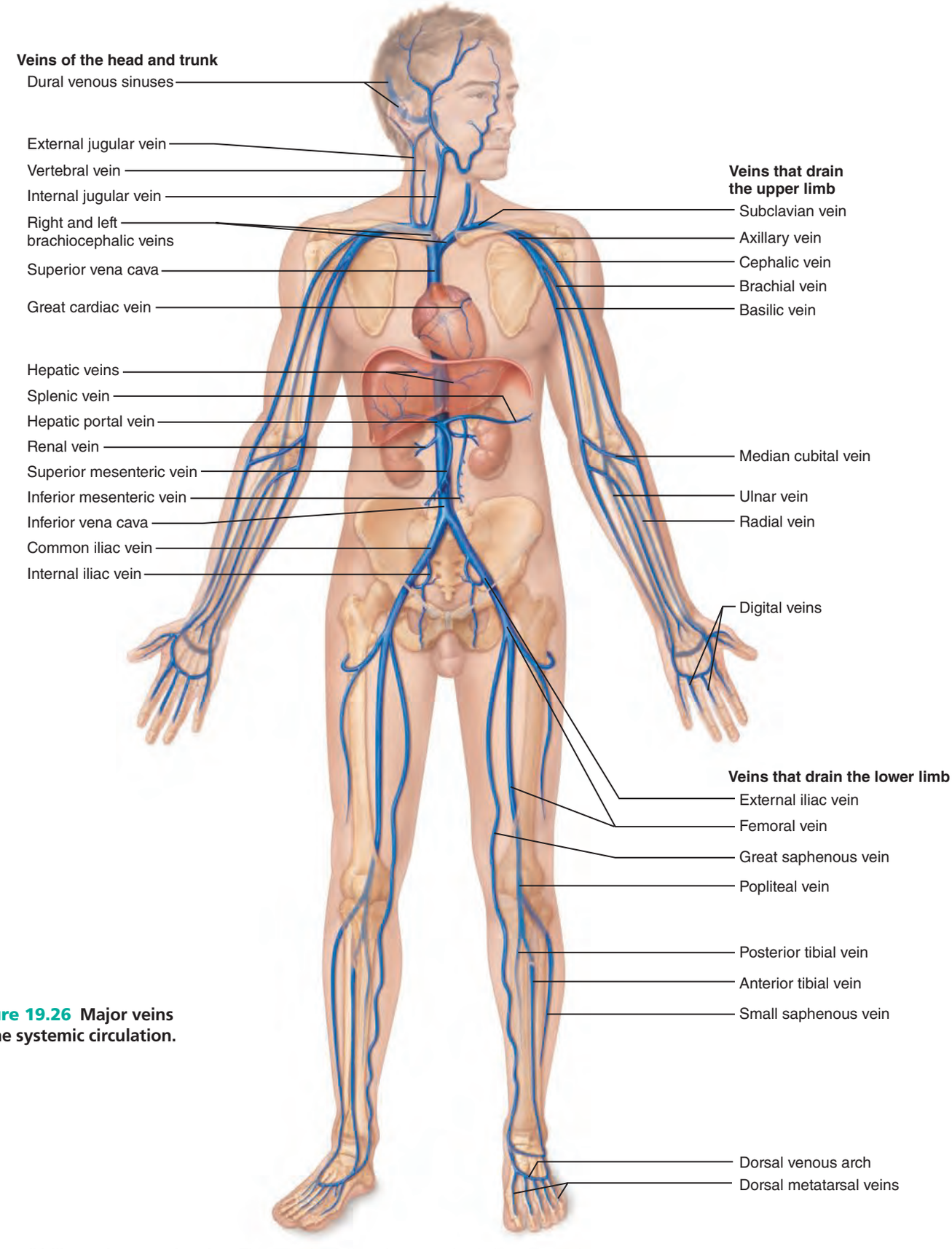


Figure 19.26 Major veins of the systemic circulation.

(b) Illustration, anterior view. The vessels of the pulmonary circulation are not shown.

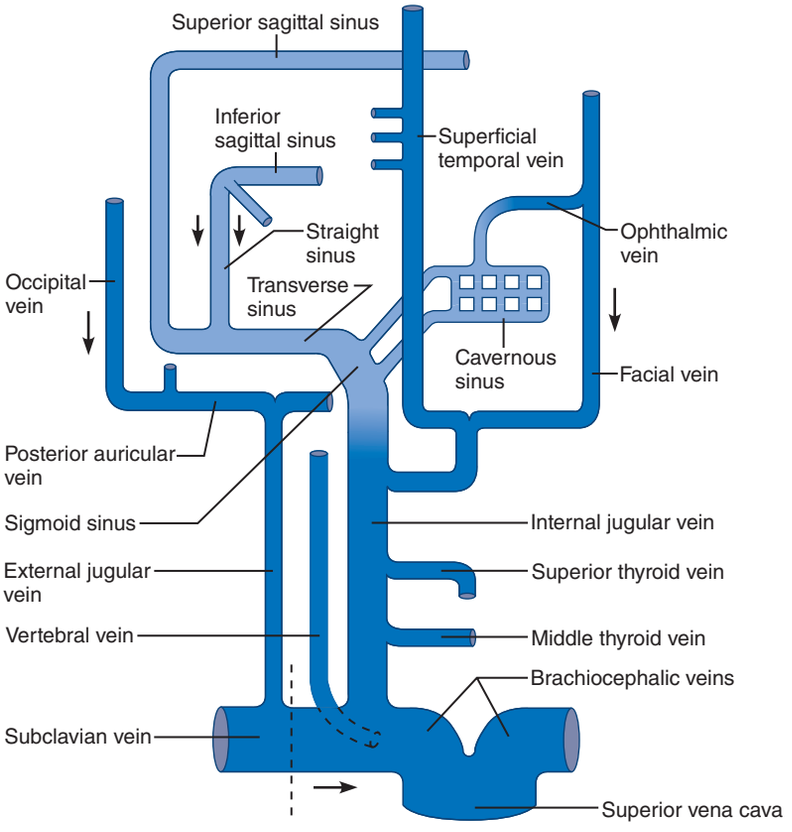
Table 19.10 Veins of the Head and Neck

Three pairs of veins collect most of the blood draining from the head and neck **(Figure 19.27a)**:

- The external jugular veins, which empty into the subclavians
- The internal jugular veins
- The vertebral veins, which drain into the brachiocephalic vein

Although most extracranial veins have the same names as the extracranial arteries, their courses and interconnections differ substantially.

Most veins of the brain drain into the **dural venous sinuses**, an interconnected series of enlarged chambers located between the dura mater layers. The **superior** and **inferior sagittal sinuses** are in the falx cerebri, which dips down between the cerebral hemispheres. The inferior sagittal sinus drains into the **straight sinus** posteriorly (Figure 19.27a and c). The superior sagittal and straight sinuses then empty into the **transverse sinuses**, which run in shallow grooves on the internal surface of the occipital bone. These drain into the S-shaped **sigmoid sinuses**, which become the *internal jugular veins* as they leave the skull through the jugular foramen. The **cavernous sinuses**, which flank the sphenoid body, receive venous blood from the **ophthalmic veins** of the orbits and the facial veins, which drain the nose and upper lip area. The internal carotid artery and cranial nerves III, IV, VI, and part of V, all run *through* the cavernous sinus on their way to the orbit and face.



(a) Schematic flowchart

Figure 19.27 Venous drainage of the head, neck, and brain.

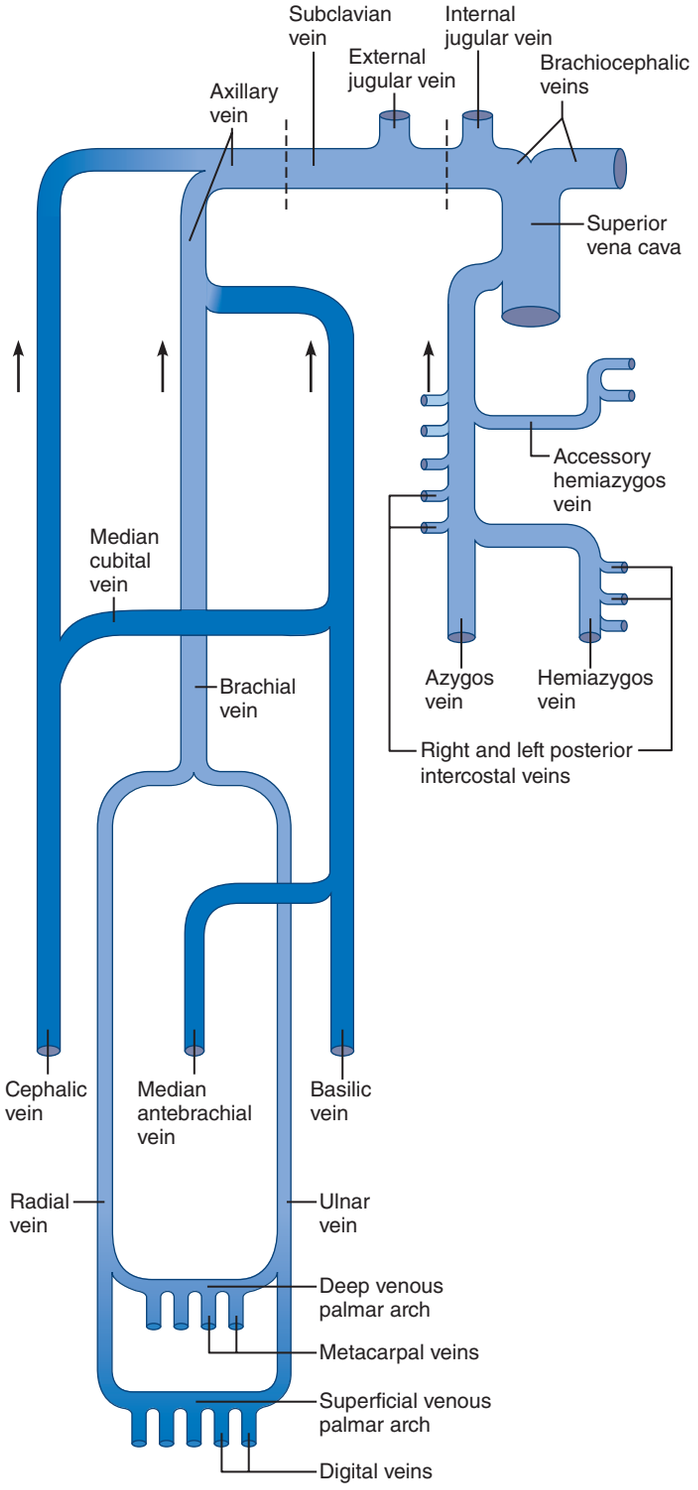
Description and Area Drained

External jugular veins. The right and left external jugular veins drain superficial scalp and face structures served by the external carotid arteries. However, their tributaries anastomose frequently, and some of the superficial drainage from these regions enters the internal jugular veins as well. As the external jugular veins descend through the lateral neck, they pass obliquely over the sternocleidomastoid muscles and then empty into the subclavian veins.

Vertebral veins. Unlike the vertebral arteries, the vertebral veins do not serve much of the brain. Instead they drain the cervical vertebrae, the spinal cord, and some small neck muscles. They run inferiorly through the transverse foramina of the cervical vertebrae and join the brachiocephalic veins at the root of the neck.

Internal jugular veins. The paired internal jugular veins, which receive the bulk of blood draining from the brain, are the largest of the paired veins draining the head and neck. They arise from the dural venous sinuses, exit the skull via the *jugular foramina*, and then descend through the neck alongside the internal carotid arteries. As they move inferiorly, they receive blood from some of the deep veins of the face and neck—branches of the **facial** and **superficial temporal veins** (Figure 19.27b). At the base of the neck, each internal jugular vein joins the subclavian vein on its own side to form a brachiocephalic vein. As already noted, the two brachiocephalic veins unite to form the **superior vena cava**.

Table 19.11 Veins of the Upper Limbs and Thorax



(a) Schematic flowchart

Figure 19.28 Veins of the thorax and right upper limb. For clarity, the abundant branching and anastomoses of the superficial veins are not shown.

The deep veins of the upper limbs follow the paths of their companion arteries and have the same names **(Figure 19.28a)**. However, except for the largest, most are paired veins that flank their artery. The superficial veins of the upper limbs are larger than the deep veins and are easily seen just beneath the skin. The median cubital vein, crossing the anterior aspect of the elbow, is commonly used to obtain blood samples or administer intravenous medications.

Blood draining from the mammary glands and the first two to three intercostal spaces enters the **brachiocephalic veins**. However, the vast majority of thoracic tissues and the thorax wall are drained by a complex network of veins called the **azygos system** (az′ĭ-gos). The branching nature of the azygos system provides a collateral circulation for draining the abdominal wall and other areas served by the inferior vena cava, and there are numerous anastomoses between the azygos system and the inferior vena cava.

Description and Areas Drained

Deep Veins of the Upper Limbs

The most distal deep veins of the upper limb are the radial and ulnar veins. The **deep** and **superficial venous palmar arches** of the hand empty into the **radial** and **ulnar veins** of the forearm, which then unite to form the **brachial vein** of the arm. As the brachial vein enters the axilla, it becomes the **axillary vein**, which becomes the **subclavian vein** at the level of the first rib.

Superficial Veins of the Upper Limbs

The superficial venous system begins with the *dorsal venous network* (not illustrated), a plexus of superficial veins in the dorsum of the hand. In the distal forearm, this plexus drains into two major superficial veins—the cephalic and basilic veins—which anastomose frequently as they course upward (Figure 19.28b). The **cephalic vein** bends around the radius as it travels superiorly and then continues up the lateral superficial aspect of the arm to the shoulder, where it runs in the groove between the deltoid and pectoralis muscles to join the axillary vein. The **basilic vein** courses along the posteromedial aspect of the forearm, crosses the elbow, and then joins the brachial vein in the axilla, forming the axillary vein. At the anterior aspect of the elbow, the **median cubital vein** connects the basilic and cephalic veins. The **median antebrachial vein** lies between the radial and ulnar veins in the forearm and terminates (variably) at the elbow by entering either the basilic or the cephalic vein.

The Azygos System

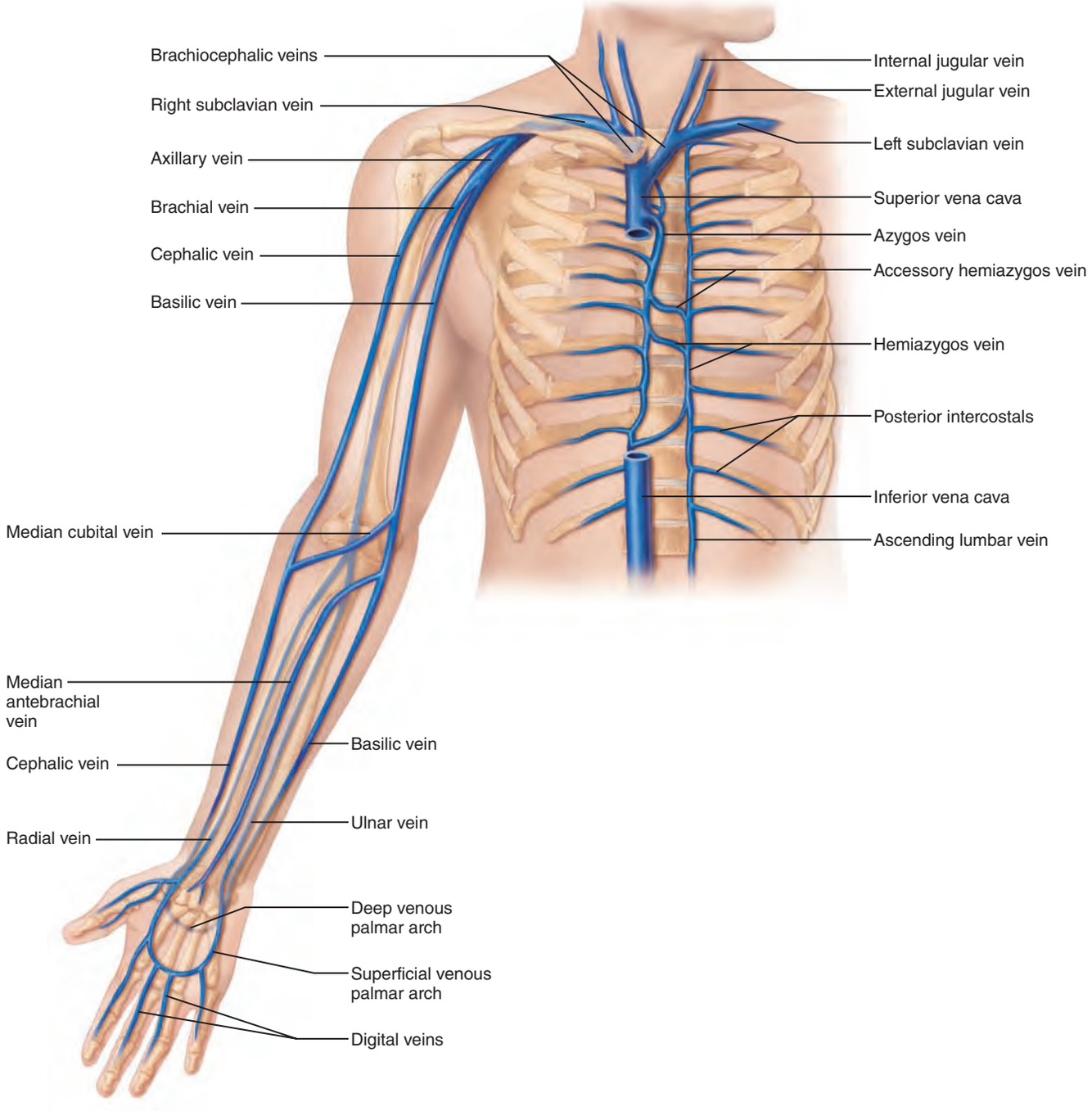
The azygos system consists of the following vessels, which flank the vertebral column laterally.

Azygos vein. Located against the right side of the vertebral column, the **azygos vein** (*azygos* = unpaired) originates in the abdomen, from the **right ascending lumbar vein** that drains most of the right abdominal cavity wall and from the **right posterior intercostal veins** (except the first) that drain the chest muscles. At the T_4 level, it arches over the great vessels that run to the right lung and empties into the superior vena cava.

Table 19.11 *(continued)*

Hemiazygos vein (hĕ″me-a-zi′gus; "half the azygos"). This vessel ascends on the left side of the vertebral column. Its origin, from the **left ascending lumbar vein** and the lower (9th–11th) **posterior intercostal veins**, mirrors that of the inferior portion of the azygos vein on the right. About midthorax, the hemiazygos vein passes in front of the vertebral column and joins the azygos vein.

Accessory hemiazygos vein. The accessory hemiazygos completes the venous drainage of the left (middle) thorax and can be thought of as a superior continuation of the hemiazygos vein. It receives blood from the 4th–8th posterior intercostal veins and then crosses to the right to empty into the azygos vein. Like the azygos, it receives oxygen-poor systemic blood from the bronchi of the lungs (*bronchial veins*).



(b) Anterior view

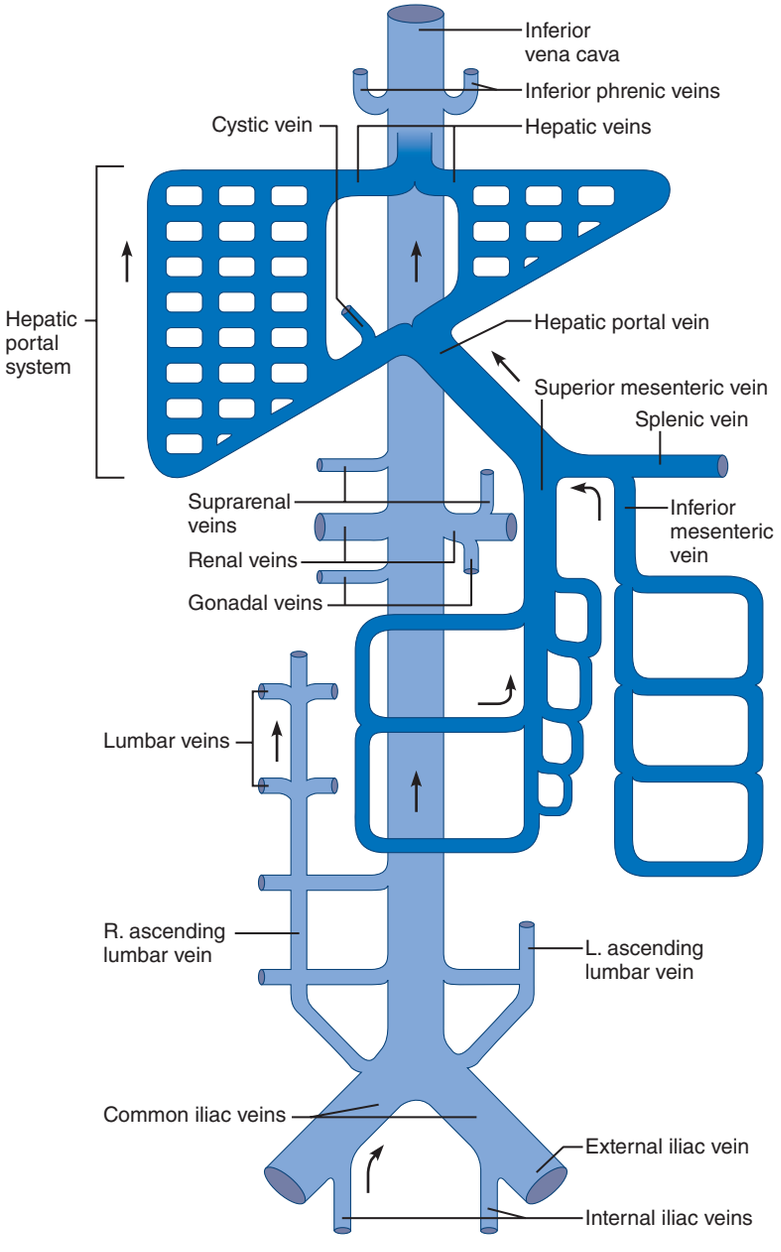
Figure 19.28 *(continued)*

19

Table 19.12 Veins of the Abdomen

The **inferior vena cava** returns blood from the abdominopelvic viscera and abdominal walls to the heart **(Figure 19.29a)**. Most of its venous tributaries have names that correspond to the arteries serving the abdominal organs.

Veins draining the digestive viscera empty into a common vessel, the *hepatic portal vein*, which transports this venous blood into the liver before it is allowed to enter the major systemic circulation via the hepatic veins (Figure 19.29c). Such a venous system—veins connecting two capillary beds together—is called a *portal system* and always serves very specific needs. The **hepatic portal system** carries nutrient-rich blood (which may also contain toxins and microorganisms) from the digestive organs to the liver, where it can be "treated" before it reaches the rest of the body. As the blood percolates slowly through the liver sinusoid capillaries, hepatocytes process nutrients and toxins, and phagocytic cells rid the blood of bacteria and other foreign matter. The veins of the abdomen are listed in inferior to superior order.



(a) Schematic flowchart.

Figure 19.29 Veins of the abdomen.

Description and Areas Drained

Lumbar veins. Several pairs of lumbar veins drain the posterior abdominal wall. They empty both directly into the inferior vena cava and into the ascending lumbar veins of the azygos system of the thorax.

Gonadal (testicular or ovarian) veins. The right gonadal vein drains the ovary or testis on the right side of the body and empties into the inferior vena cava. The left gonadal vein drains into the left renal vein superiorly.

Renal veins. The right and left renal veins drain the kidneys.

Suprarenal veins. The right suprarenal vein drains the adrenal gland on the right and empties into the inferior vena cava. The left suprarenal vein drains into the left renal vein.

Hepatic portal system. Like all portal systems, the hepatic portal system is a series of vessels in which two separate capillary beds lie between the arterial supply and the final venous drainage. In this case, the first capillary beds are in the stomach and intestines and drain into tributaries of the hepatic portal vein, which brings them to the second capillary bed in the liver. The short **hepatic portal vein** begins at the L_2 level. Numerous tributaries from the stomach and pancreas contribute to the hepatic portal system (Figure 19.29c), but the major vessels are as follows:

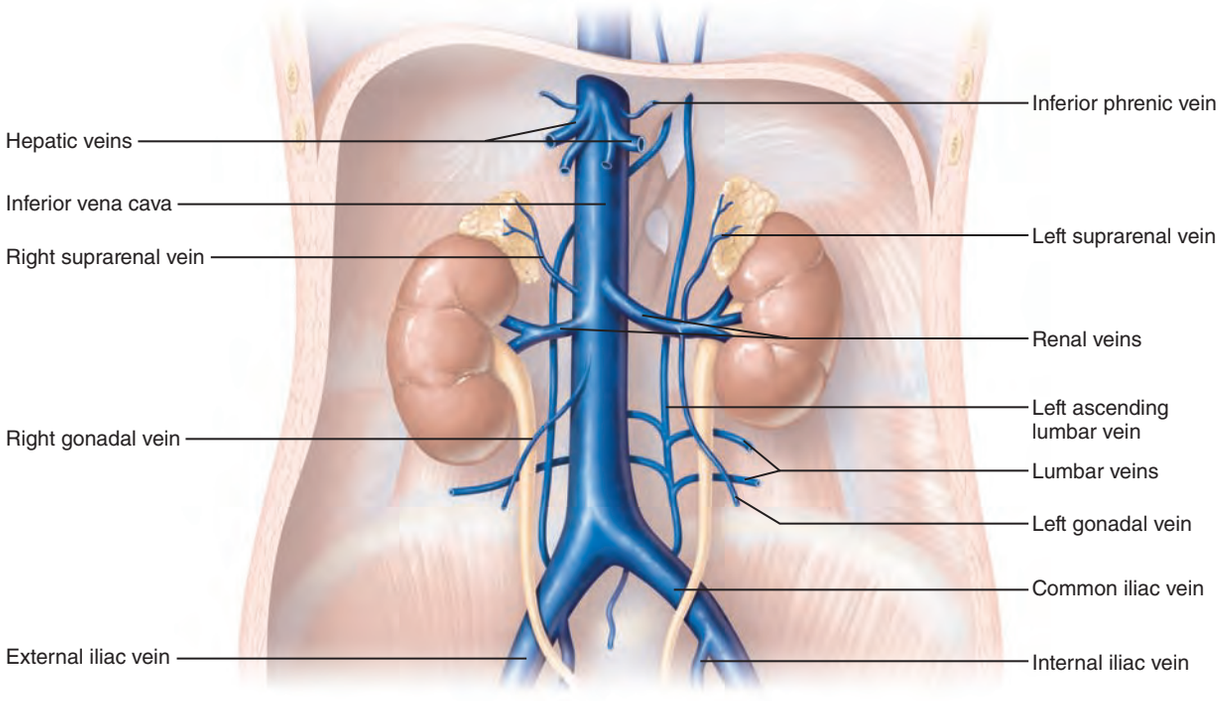
- **Superior mesenteric vein:** Drains the entire small intestine, part of the large intestine (ascending and transverse regions), and stomach.
- **Splenic vein:** Collects blood from the spleen, parts of the stomach and pancreas, and then joins the superior mesenteric vein to form the hepatic portal vein.
- **Inferior mesenteric vein:** Drains the distal portions of the large intestine and rectum and joins the splenic vein just before that vessel unites with the superior mesenteric vein to form the hepatic portal vein.

Hepatic veins. The right, left, and middle hepatic veins carry venous blood from the liver to the inferior vena cava.

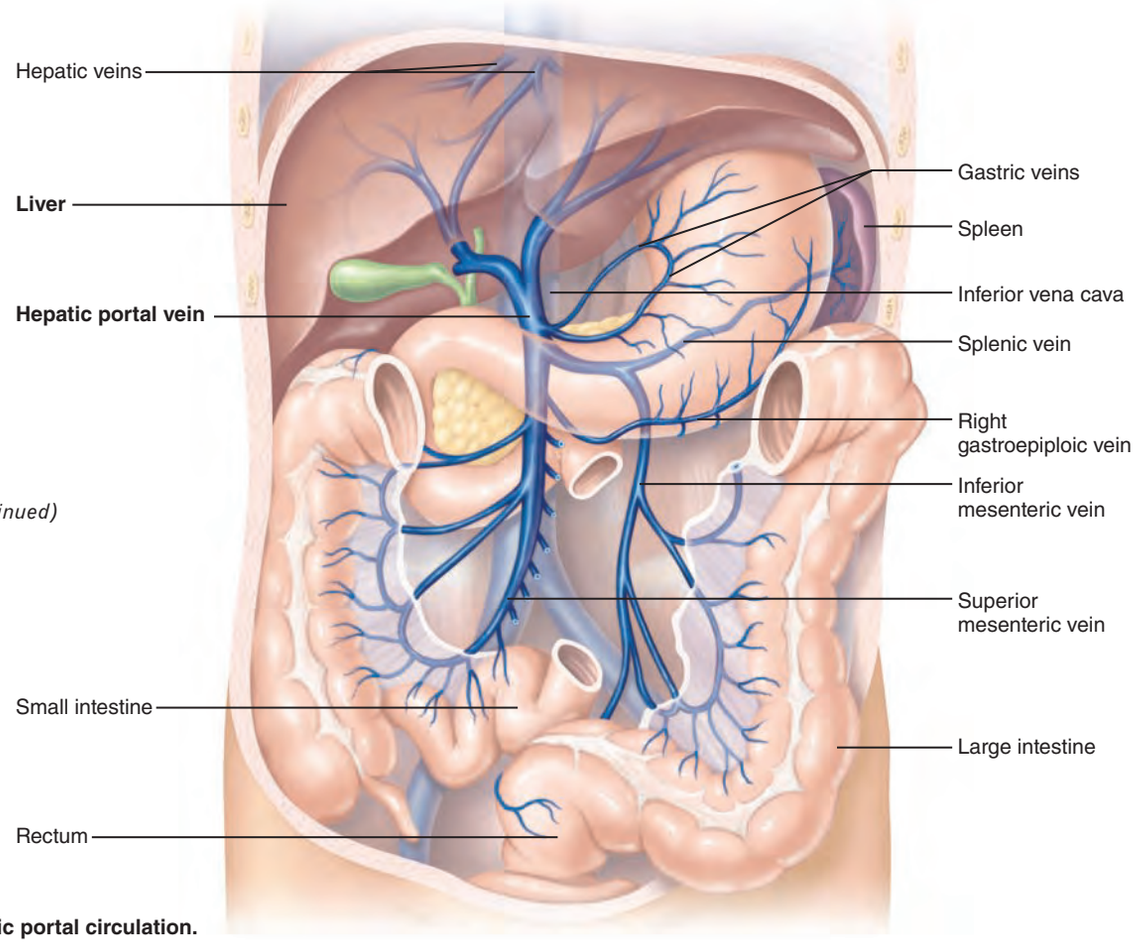
Cystic veins. The cystic veins drain the gallbladder and join the portal veins in the liver.

Inferior phrenic veins. The inferior phrenic veins drain the inferior surface of the diaphragm.

Table 19.12 *(continued)*



(b) Tributaries of the inferior vena cava. Venous drainage of abdominal organs not drained by the hepatic portal vein.



(c) The hepatic portal circulation.

Figure 19.29 *(continued)*

19

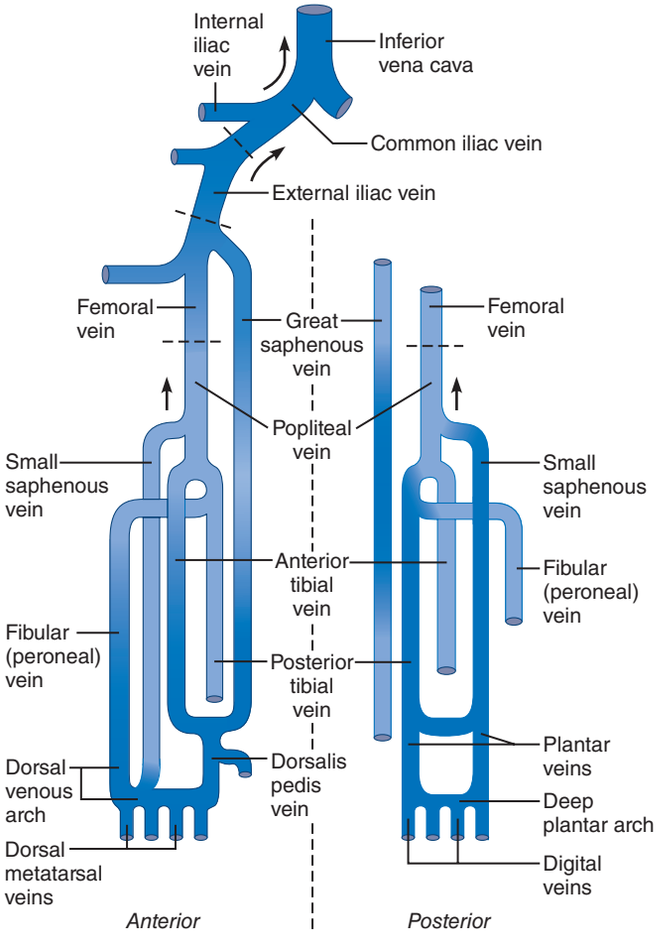
Table 19.13 Veins of the Pelvis and Lower Limbs

As in the upper limbs, most deep veins of the lower limbs have the same names as the arteries they accompany and many are double. Poorly supported by surrounding tissues, the two superficial saphenous veins (great and small) are common sites of varicosities. The great saphenous (*saphenous* = obvious) vein is frequently excised and used as a coronary bypass vessel.

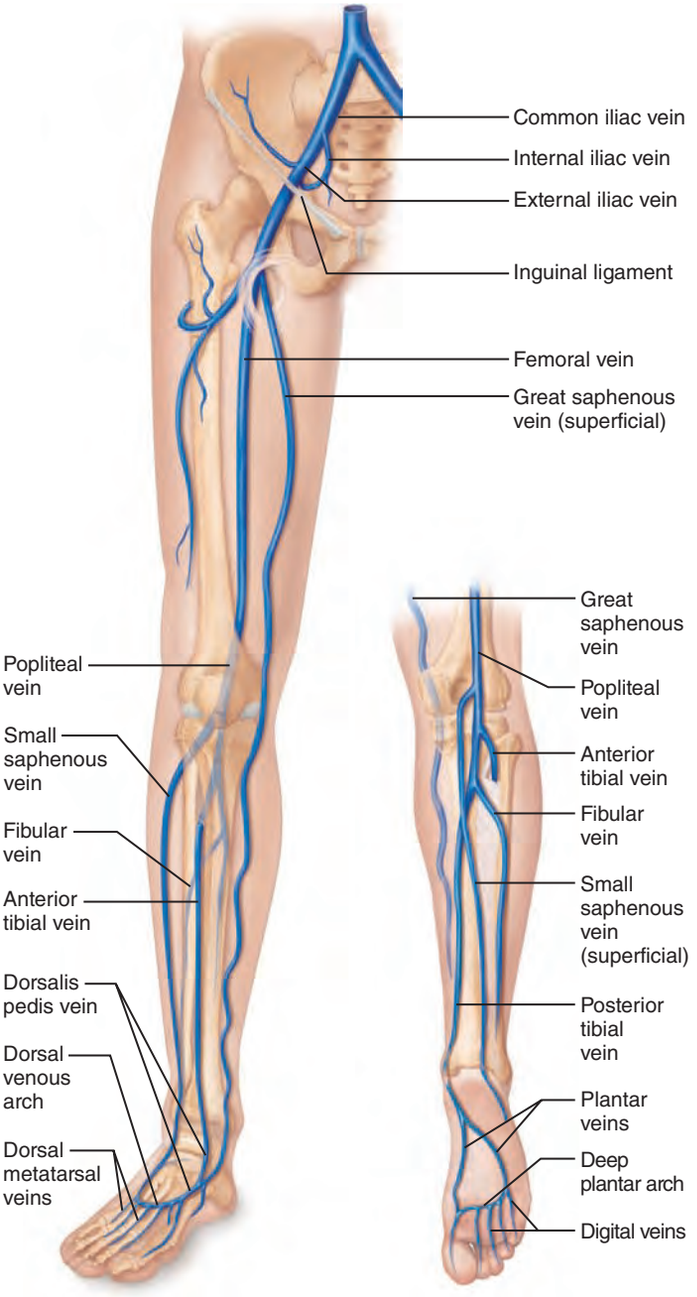
Description and Areas Drained

Deep veins. After being formed by the union of the **medial** and **lateral plantar veins**, the **posterior tibial vein** ascends deep in the calf muscle and receives the **fibular (peroneal) vein** (Figure 19.30). The **anterior tibial vein**, which is the superior continuation of the **dorsalis pedis vein** of the foot, unites at the knee with the posterior tibial vein to form the **popliteal vein**, which crosses the back of the knee. As the popliteal vein emerges from the knee, it becomes the **femoral vein**, which drains the deep structures of the thigh. The femoral vein becomes the **external iliac vein** as it enters the pelvis. In the pelvis, the external iliac vein unites with the **internal iliac vein** to form the **common iliac vein**. The distribution of the internal iliac veins parallels that of the internal iliac arteries.

Superficial veins. The **great** and **small saphenous veins** (sah-fe′nus) issue from the **dorsal venous arch** of the foot (Figure 19.30b and c). These veins anastomose frequently with each other and with the deep veins along their course. The great saphenous vein is the longest vein in the body. It travels superiorly along the medial aspect of the leg to the thigh, where it empties into the femoral vein just distal to the inguinal ligament. The small saphenous vein runs along the lateral aspect of the foot and then through the deep fascia of the calf muscles, which it drains. At the knee, it empties into the popliteal vein.



(a) Schematic flowchart of the anterior and posterior veins



(b) Anterior view (c) Posterior view

Figure 19.30 Veins of the right lower limb.

Check Your Understanding

21. What is a portal system? What is the function of the hepatic portal system?
22. Name the leg veins that often become varicosed.

For answers, see Appendix H.

Developmental Aspects of Blood Vessels

- Explain how blood vessels develop.
- Provide examples of changes that often occur in blood vessels as a person ages.

The endothelial lining of blood vessels is formed by mesodermal cells, which collect in little masses called **blood islands** throughout the microscopic embryo. These blood islands form fragile sprouting extensions that reach toward one another and toward the forming heart to lay down the rudimentary vascular tubes. Meanwhile, adjacent mesenchymal cells, stimulated by platelet-derived growth factor, surround the endothelial tubes, forming the stabilizing muscular and fibrous coats of the vessel walls.

How do blood vessels "know" where to grow? Many blood vessels simply follow the same guidance cues that nerves follow, which is why forming vessels often snuggle closely to nerves. Whether a vessel becomes an artery or a vein depends upon the local concentration of a differentiation factor called *vascular endothelial growth factor*. As noted in Chapter 18, the heart pumps blood through the rudimentary vascular system by the fourth week of development.

In addition to the fetal shunts that bypass the nonfunctional lungs (the *foramen ovale* and *ductus arteriosus*), other vascular modifications are found in the fetus. A special vessel, the *ductus venosus*, largely bypasses the liver. Also important are the *umbilical vein* and *arteries*, large vessels that circulate blood between the fetal circulation and the placenta where gas and nutrient exchanges occur with the mother's blood (see Chapter 28). Once the fetal circulatory pattern is laid down, few vascular changes occur until birth, when the umbilical vessels and shunts are occluded.

Unlike congenital heart diseases, congenital vascular problems are rare, and blood vessels are remarkably trouble-free during youth. Vessels form as needed to support body growth and wound healing, and to rebuild vessels lost each month during a woman's menstrual cycle. As we age, signs of vascular disease begin to appear. In some, the venous valves weaken, and purple, snakelike varicose veins appear. In others, more insidious signs of inefficient circulation appear: tingling fingers and toes and cramping muscles.

Although the degenerative process of atherosclerosis begins in youth, its consequences are rarely apparent until middle to old age, when it may precipitate a myocardial infarction or stroke. Until puberty, the blood vessels of boys and girls look alike, but from puberty to about age 45, women have strikingly less atherosclerosis than men because of the protective effects of estrogen. By enhancing nitric oxide production, inhibiting endothelin release, and blocking voltage-gated Ca^{2+} channels, estrogen reduces resistance to blood flow. Estrogen also stimulates the liver to produce enzymes that speed up catabolism of LDLs and increase the production of HDLs, thus reducing the risk of atherosclerosis (see *A Closer Look*).

Between the ages of 45 and 65, when estrogen production wanes in women, this "gap" between the sexes closes, and males and females above age 65 are equally at risk for cardiovascular disease. You might expect that giving postmenopausal women supplementary estrogen would maintain this protective effect. Surprisingly, clinical trials have shown that this is not the case.

Blood pressure changes with age. In a newborn baby, arterial pressure is about 90/55. Blood pressure rises steadily during childhood to finally reach the adult value (120/80). After age 40, the incidence of hypertension increases dramatically, as do associated illnesses such as heart attacks, strokes, vascular disease, and renal failure.

At least some vascular disease is a product of our modern technological culture. "Blessed" with high-protein and lipid-rich diets, empty-calorie snacks, energy-saving devices, and high-stress jobs, many of us are struck down prematurely. Lifestyle modifications—a healthy diet, regular aerobic exercise, and eliminating cigarette smoking—can help prevent cardiovascular disease. Poor diet, lack of exercise, and smoking are probably more detrimental to your blood vessels than aging itself could ever be!

Check Your Understanding

23. List three differences between systemic arteries and veins with respect to their general pathways and courses.
24. Name three fetal shunts that are occluded shortly after birth. Which structure does each shunt bypass?
25. List three common age-related vascular problems.

For answers, see Appendix H.

Now that we have described the structure and function of blood vessels, our survey of the cardiovascular system is complete. The pump, the plumbing, and the circulating fluid form a dynamic organ system that ceaselessly services every other organ system of the body, as summarized in *System Connections* on p. 746. However, our study of the circulatory system is still unfinished because we have yet to examine the lymphatic system, which acts with the cardiovascular system to ensure continuous circulation and to provide sites from which lymphocytes can police the body and provide immunity. These are the topics of Chapter 20.

Homeostatic Interrelationships Between the Cardiovascular System and Other Body Systems

Integumentary System Chapter 5

- The cardiovascular system delivers oxygen and nutrients; carries away wastes
- The skin vasculature is an important blood reservoir and provides a site for heat loss from the body

Skeletal System Chapters 6–8

- The cardiovascular system delivers oxygen and nutrients; carries away wastes
- Bones are the sites of hematopoiesis; protect cardiovascular organs by enclosure; and provide a calcium depot

Muscular System Chapters 9–10

- The cardiovascular system delivers oxygen and nutrients; carries away wastes
- The muscle "pump" aids venous return; aerobic exercise enhances cardiovascular efficiency and helps prevent atherosclerosis

Nervous System Chapters 11–15

- The cardiovascular system delivers oxygen and nutrients; carries away wastes
- The ANS regulates cardiac rate and force; sympathetic division maintains blood pressure and controls blood flow to skin for thermoregulation

Endocrine System Chapter 16

- The cardiovascular system delivers oxygen and nutrients; carries away wastes; blood serves as a transport vehicle for hormones
- Various hormones influence blood pressure (epinephrine, ANP, angiotensin II, thyroxine, ADH); estrogen maintains vascular health in premenopausal women

Lymphatic System/Immunity Chapters 20–21

- The cardiovascular system delivers oxygen and nutrients to lymphatic organs, which house immune cells; provides transport medium for lymphocytes and antibodies; carries away wastes
- The lymphatic system picks up leaked fluid and plasma proteins and returns them to the cardiovascular system; immune cells protect cardiovascular organs from specific pathogens

Respiratory System Chapter 22

- The cardiovascular system delivers oxygen and nutrients; carries away wastes
- The respiratory system carries out gas exchange: loads oxygen and unloads carbon dioxide from the blood; respiratory "pump" aids venous return

Digestive System Chapter 23

- The cardiovascular system delivers oxygen and nutrients; carries away wastes
- The digestive system provides nutrients to the blood including iron and B vitamins essential for RBC (and hemoglobin) formation

Urinary System Chapters 25–26

- The cardiovascular system delivers oxygen and nutrients; carries away wastes; blood pressure drives filtration in the kidneys
- The urinary system helps regulate blood volume and pressure by altering urine volume and releasing renin

Reproductive System Chapter 27

- The cardiovascular system delivers oxygen and nutrients; carries away wastes
- Estrogen maintains vascular and osseous health in women

Chapter Summary

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PART 1 Blood Vessel Structure and Function

1. Blood is transported throughout the body via a continuous system of blood vessels. Arteries transport blood away from the heart; veins carry blood back to the heart. Capillaries carry blood to tissue cells and are exchange sites.

Structure of Blood Vessel Walls (p. 693)

1. All blood vessels except capillaries have three layers: tunica intima, tunica media, and tunica externa. Capillary walls are composed of the tunica intima only.

Arterial System (pp. 693–696)

1. Elastic (conducting) arteries are the large arteries close to the heart that expand during systole, acting as pressure reservoirs, and then recoil during diastole to keep blood moving. Muscular (distributing) arteries carry blood to specific organs; they are less stretchy and more active in vasoconstriction. Arterioles regulate blood flow into capillary beds.
2. Atherosclerosis is a degenerative vascular disease that decreases the elasticity of arteries.

Capillaries (pp. 696–698)

1. Capillaries are microscopic vessels with very thin walls. Most exhibit intercellular clefts, which aid in the exchange between blood and interstitial fluid.
2. The most permeable capillaries are sinusoid capillaries (wide, tortuous channels). Fenestrated capillaries with pores are next most permeable. Least permeable are continuous capillaries, which lack pores.
3. Vascular shunts (metarteriole–thoroughfare channels) connect the terminal arteriole and postcapillary venule at opposite ends of a capillary bed. Most true capillaries arise from and rejoin the shunt channels. Precapillary sphincters regulate the amount of blood flowing into the true capillaries.

Venous System (pp. 698–699)

1. Veins have comparatively larger lumens than arteries, and a system of valves prevents backflow of blood.
2. Normally most veins are only partially filled; for this reason, they can serve as blood reservoirs.

Vascular Anastomoses (pp. 699–701)

1. The joining together of blood vessels to provide alternate channels in the same organ is called an anastomosis. Vascular anastomoses form between arteries, between veins, and between arterioles and venules.

Cardiovascular System; Topic: Anatomy Review: Blood Vessel Structure and Function, pp. 1–27.

PART 2 Physiology of Circulation

Introduction to Blood Flow, Blood Pressure, and Resistance (pp. 701–702)

1. Blood flow is the amount of blood flowing through a vessel, an organ, or the entire circulation in a given period of time. Blood pressure (BP) is the force per unit area exerted on a vessel wall by the contained blood. Resistance is opposition to blood flow; blood viscosity and blood vessel length and diameter contribute to resistance.
2. Blood flow is directly proportional to blood pressure and inversely proportional to resistance.

Cardiovascular System; Topic: Factors that Affect Blood Pressure, pp. 1–15.

Systemic Blood Pressure (pp. 702–704)

1. Systemic blood pressure is highest in the aorta and lowest in the venae cavae. The steepest drop in BP occurs in the arterioles, where resistance is greatest.
2. Arterial BP depends on compliance of the elastic arteries and on how much blood is forced into them. Arterial blood pressure is pulsatile, and peaks during systole; this is measured as systolic pressure. During diastole, as blood is forced distally in the circulation by the rebound of elastic arteries, arterial BP drops to its lowest value, called the diastolic pressure.
3. Pulse pressure is systolic pressure minus diastolic pressure. The mean arterial pressure (MAP) = diastolic pressure plus one-third of pulse pressure and is the pressure that keeps blood moving throughout the cardiac cycle.
4. Low capillary pressure (35 to 17 mm Hg) protects the delicate capillaries from rupture while still allowing adequate exchange across the capillary walls.
5. Venous pressure is nonpulsatile and low (declining to zero) because of the cumulative effects of resistance. Venous valves, large lumens, functional adaptations (muscular and respiratory pumps), and sympathetic nervous system activity promote venous return.

Maintaining Blood Pressure (pp. 704–711)

1. Blood pressure varies directly with CO, peripheral resistance (*R*), and blood volume. Vessel diameter is the major factor determining resistance, and small changes in the diameter of vessels (chiefly arterioles) significantly affect blood pressure.

Cardiovascular System; Topic: Measuring Blood Pressure, pp. 1–13.

2. BP is regulated by autonomic neural reflexes involving baroreceptors or chemoreceptors, the cardiovascular center (a medullary center that includes the cardiac and vasomotor centers), and autonomic fibers to the heart and vascular smooth muscle.
3. Activation of the receptors by falling BP (and to a lesser extent by a rise in blood CO_2, or falling blood pH or O_2 levels) stimulates the vasomotor center to increase vasoconstriction and the cardioacceleratory center to increase heart rate and contractility. Rising BP inhibits the vasomotor center (permitting vasodilation) and activates the cardioinhibitory center.

4. Higher brain centers (cerebrum and hypothalamus) may modify neural controls of BP via medullary centers.
5. Hormones that increase BP by promoting vasoconstriction include epinephrine and NE (these also increase heart rate and contractility), ADH, and angiotensin II (generated in response to renin release by kidney cells). Hormones that reduce BP by promoting vasodilation include atrial natriuretic peptide, which also causes a decline in blood volume.
6. The kidneys regulate blood pressure by regulating blood volume. Rising BP directly enhances filtrate formation and fluid losses in urine; falling BP causes the kidneys to retain more water, increasing blood volume.
7. Indirect renal regulation of blood volume involves the renin-angiotensin-aldosterone mechanism, a hormonal mechanism. When BP falls, the kidneys release renin, which triggers the formation of angiotensin II. Angiotensin II causes (1) release of aldosterone, stimulating salt and water retention, (2) vasoconstriction, (3) release of ADH, and (4) thirst.

iP Cardiovascular System; Topic: Blood Pressure Regulation, pp. 1–31.

8. Pulse and blood pressure measurements are used to assess cardiovascular efficiency.
9. The pulse is the alternating expansion and recoil of arterial walls with each heartbeat. Pulse points are also pressure points.
10. Blood pressure is routinely measured by the auscultatory method. Normal BP in adults is 120/80 mm Hg (systolic/diastolic).
11. Chronic hypertension (high blood pressure) is persistent BP readings of 140/90 or higher. It indicates increased peripheral resistance, which strains the heart and promotes vascular complications of other organs, particularly the eyes and kidneys. It is a major cause of myocardial infarction, stroke, and renal disease. Risk factors are high-fat, high-salt diet, obesity, diabetes mellitus, advanced age, smoking, stress, and being a member of the black race or a family with a history of hypertension.
12. Hypotension, or low blood pressure (below 90/60 mm Hg), is rarely a problem except in circulatory shock.

iP Cardiovascular System; Topic: Measuring Blood Pressure, pp. 11–12.

Blood Flow Through Body Tissues: Tissue Perfusion (pp. 711–720)

1. Blood flow is involved in delivering nutrients and wastes to and from cells, gas exchange, absorbing nutrients, and forming urine.
2. Blood flows fastest where the cross-sectional area of the vascular bed is least (aorta), and slowest where the total cross-sectional area is greatest (capillaries). The slow flow in capillaries allows time for nutrient-waste exchanges.
3. Autoregulation is the local adjustment of blood flow to individual organs based on their immediate requirements. It involves myogenic controls that maintain flow despite changes in blood pressure, and local chemical factors. Vasodilators include increased CO_2, H^+, and nitric oxide. Decreased O_2 concentrations also cause vasodilation. Other factors, including endothelins, decrease blood flow.

iP Cardiovascular; Topic: Autoregulation and Capillary Dynamics, pp. 1–13.

4. In most instances, autoregulation is controlled by the accumulation of local metabolites and the lack of oxygen. However, autoregulation in the brain is controlled primarily by a drop in pH and by myogenic mechanisms; and pulmonary circuit vessels dilate in response to high levels of oxygen.
5. Nutrients, gases, and other solutes smaller than plasma proteins cross the capillary wall by diffusion; larger molecules are actively transported via pinocytotic vesicles or caveolae. Water-soluble substances move through the clefts or fenestrations; fat-soluble substances pass through the lipid portion of the endothelial cell membrane.
6. Bulk flow of fluids at capillary beds determines the distribution of fluids between the bloodstream and the interstitial space. It reflects the relative effects of hydrostatic and osmotic pressures acting at the capillary (outward minus inward pressures). In general, fluid flows out of the capillary bed at the arterial end and reenters the capillary blood at the venule end.

iP Cardiovascular; Topic: Autoregulation and Capillary Dynamics, pp. 14–38.

7. Lymphatic vessels collect the small net loss of fluid and protein into the interstitial space and return it to the cardiovascular system.
8. Circulatory shock occurs when blood perfusion of body tissues is inadequate. Most cases of shock reflect low blood volume (hypovolemic shock), abnormal vasodilation (vascular shock), or pump failure (cardiogenic shock).

PART 3 Circulatory Pathways: Blood Vessels of the Body

The Two Main Circulations of the Body (p. 721)

1. The pulmonary circulation transports O_2-poor, CO_2-laden blood to the lungs for oxygenation and carbon dioxide unloading. Blood returning to the right atrium of the heart is pumped by the right ventricle to the lungs via the pulmonary trunk. Blood issuing from the lungs is returned to the left atrium by the pulmonary veins. (See Table 19.3 and Figure 19.19.)
2. The systemic circulation transports oxygenated blood from the left ventricle to all body tissues via the aorta and its branches. Venous blood returning from the systemic circuit is delivered to the right atrium via the venae cavae.

Systemic Arteries and Veins: Differences in Pathways and Courses (p. 721)

1. All arteries are deep while veins are both deep and superficial. Superficial veins tend to have numerous interconnections. Dural venous sinuses and the hepatic portal circulation are unique venous drainage patterns.

Principal Vessels of the Systemic Circulation (pp. 721–745)

1. Tables 19.3 to 19.13 and Figures 19.20 to 19.30 illustrate and describe vessels of the systemic circulation.

Developmental Aspects of Blood Vessels (p. 745)

1. The fetal vasculature develops from embryonic blood islands and mesenchyme and functions in blood delivery by the fourth week.
2. Fetal circulation differs from circulation after birth. The pulmonary and hepatic shunts and special umbilical vessels are normally occluded shortly after birth.
3. Blood pressure is low in infants and rises to adult values. Age-related vascular problems include varicose veins, hypertension, and atherosclerosis. Hypertension and associated atherosclerosis are the most important causes of cardiovascular disease in the aged.

Review Questions

Multiple Choice/Matching

(Some questions have more than one correct answer. Select the best answer or answers from the choices given.)

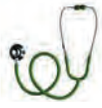
1. Which statement does not accurately describe veins? **(a)** Have less elastic tissue and smooth muscle than arteries, **(b)** contain more fibrous tissue than arteries, **(c)** most veins in the extremities have valves, **(d)** always carry deoxygenated blood.
2. Smooth muscle in the blood vessel wall **(a)** is found primarily in the tunica intima, **(b)** is mostly circularly arranged, **(c)** is most abundant in veins, **(d)** is usually innervated by the parasympathetic nervous system.
3. Peripheral resistance **(a)** is inversely proportional to the length of the vascular bed, **(b)** increases in anemia, **(c)** decreases in polycythemia, **(d)** is inversely related to the diameter of the arterioles.
4. Which of the following can lead to decreased venous return of blood to the heart? **(a)** an increase in blood volume, **(b)** an increase in venous pressure, **(c)** damage to the venous valves, **(d)** increased muscular activity.
5. Arterial blood pressure increases in response to **(a)** increasing stroke volume, **(b)** increasing heart rate, **(c)** atherosclerosis, **(d)** rising blood volume, **(e)** all of these.
6. Which of the following would *not* result in the dilation of the feeder arterioles and opening of the precapillary sphincters in systemic capillary beds? **(a)** a decrease in local tissue O_2 content, **(b)** an increase in local tissue CO_2, **(c)** a local increase in histamine, **(d)** a local increase in pH.
7. The structure of a capillary wall differs from that of a vein or an artery because **(a)** it has two tunics instead of three, **(b)** there is less smooth muscle, **(c)** it has a single tunic—only the tunica intima, **(d)** none of these.
8. The baroreceptors in the carotid sinus and aortic arch are sensitive to **(a)** a decrease in CO_2, **(b)** changes in arterial pressure, **(c)** a decrease in O_2, **(d)** all of these.
9. The myocardium receives its blood supply directly from the **(a)** aorta, **(b)** coronary arteries, **(c)** coronary sinus, **(d)** pulmonary arteries.
10. Blood flow in the capillaries is steady despite the rhythmic pumping of the heart because of the **(a)** elasticity of the large arteries, **(b)** small diameter of capillaries, **(c)** thin walls of the veins, **(d)** venous valves.
11. Using the letters from column B, match the artery descriptions in column A. (Note that some require more than a single choice.)

Column A	Column B
____ (1) unpaired branch of abdominal aorta	**(a)** right common carotid
____ (2) second branch of aortic arch	**(b)** superior mesenteric
____ (3) branch of internal carotid	**(c)** left common carotid
____ (4) branch of external carotid	**(d)** external iliac
____ (5) origin of femoral arteries	**(e)** inferior mesenteric
	(f) superficial temporal
	(g) celiac trunk
	(h) facial
	(i) ophthalmic
	(j) internal iliac

12. Tracing the blood from the heart to the right hand, we find that blood leaves the heart and passes through the aorta, the right subclavian artery, the axillary and brachial arteries, and through either the radial or ulnar artery to arrive at the hand. Which artery is missing from this sequence? **(a)** coronary, **(b)** brachiocephalic, **(c)** cephalic, **(d)** right common carotid.
13. Which of the following do not drain directly into the inferior vena cava? **(a)** inferior phrenic veins, **(b)** hepatic veins, **(c)** inferior mesenteric vein, **(d)** renal veins.
14. Suppose that at a given point along a capillary, the following forces exist: capillary hydrostatic pressure (HP_c) = 30 mm Hg, interstitial fluid hydrostatic pressure (HP_{if}) = 0 mm Hg, capillary colloid osmotic pressure (OP_c) = 25 mm Hg, and interstitial fluid colloid osmotic pressure (OP_{if}) = 2 mm Hg. The net filtration pressure at this point in the capillary is **(a)** 3 mm Hg, **(b)** −3 mm Hg, **(c)** −7 mm Hg, **(d)** 7 mm Hg.

Short Answer Essay Questions

15. How is the anatomy of capillaries and capillary beds well suited to their function?
16. Distinguish between elastic arteries, muscular arteries, and arterioles relative to location, histology, and functional adaptations.
17. Write an equation showing the relationship between peripheral resistance, blood flow, and blood pressure.
18. (a) Define blood pressure. Differentiate between systolic and diastolic blood pressure. (b) What is the normal blood pressure value for an adult?
19. Describe the neural mechanisms responsible for controlling blood pressure.
20. Explain the reasons for the observed changes in blood flow velocity in the different regions of the circulation.
21. How does the control of blood flow to the skin for the purpose of regulating body temperature differ from the control of nutrient blood flow to skin cells?
22. Describe neural and chemical (both systemic and local) effects exerted on the blood vessels when you are fleeing from a mugger. (Be careful, this is more involved than it appears at first glance.)
23. How are nutrients, wastes, and respiratory gases transported to and from the blood and tissue spaces?
24. (a) What blood vessels contribute to the formation of the hepatic portal circulation? (b) Why is a portal circulation a "strange" circulation?
25. Physiologists often consider capillaries and postcapillary venules together. (a) What functions do these vessels share? (b) Structurally, how do they differ?



Critical Thinking and Clinical Application Questions

1. Mrs. Johnson is brought to the emergency room after being involved in an auto accident. She is hemorrhaging and has a rapid, thready pulse, but her blood pressure is still within normal limits. Describe the compensatory mechanisms that act to maintain her blood pressure in the face of blood loss.
2. A 60-year-old man is unable to walk more than 100 yards without experiencing severe pain in his left leg; the pain is relieved by resting for 5–10 minutes. He is told that the arteries of his leg are becoming occluded with fatty material and is advised to have the sympathetic nerves serving that body region severed. Explain how such surgery might help to relieve this man's problem.
3. Your friend Joanie, who knows little about science, is reading a magazine article about a patient who had an "aneurysm at the base of his brain that suddenly grew much larger." The surgeons' first goal was to "keep it from rupturing," and the second goal was to "relieve

the pressure on the brain stem and cranial nerves." The surgeons were able to "replace the aneurysm with a section of plastic tubing," so the patient recovered. Joanie asks you what all this means. Explain. (Hint: Check this chapter's Related Clinical Terms below.)

4. The Agawam High School band is playing some lively marches while the coaches are giving pep talks to their respective football squads. Although it is September, it is unseasonably hot (88°F/31°C) and the band uniforms are wool. Suddenly, Harry the tuba player becomes light-headed and faints. Explain his fainting in terms of vascular events.
5. When we are cold or the external temperature is low, most venous blood returning from the distal part of the arm travels in the deep veins where it picks up heat (by countercurrent exchange) from the nearby brachial artery en route. However, when we are hot, and especially during exercise, venous return from the distal arm travels in the superficial veins and those veins tend to bulge superficially in a person who is working out. Explain why venous return takes a different route in the second situation.
6. Edema (swelling due to an increase in interstitial fluid) is a common clinical problem. On one of your first days of an introductory clinical experience, you encounter four patients who all have severe edema for different reasons. Your challenge is to explain the cause of the edema. In each case, try to explain the edema in terms of either an increase or a decrease in one of the four pressures that causes bulk flow at capillaries (see Figure 19.17).
   (1) First you encounter Mrs. Taylor in the medical ward awaiting a liver transplant. What is the connection between liver failure and her edema? (Hint: Think about the liver's role in producing plasma proteins.)
   (2) Next you follow a resident to the obstetric ward, where Mrs. So is experiencing premature labor. Which of the pressures that drive bulk flow might be altered here? (Hint: What might the expanded uterus be pressing on?)
   (3) Then you are called to emergency, where Mr. Herrera is in anaphylactic shock. In anaphylactic shock, the capillaries become leaky, allowing plasma proteins that are normally kept inside the blood vessels to escape into the interstitial fluid. Which of the pressures driving bulk flow is altered in this case and in what direction is the change?
   (4) Finally, you go to the oncology ward where Mrs. O'Leary is recovering from surgery for advanced breast cancer that had infiltrated her right breast and axillary lymph nodes. All of her axillary lymph nodes were removed and unfortunately, this severed most of the lymphatic vessels draining her right arm. You notice that her right arm is quite edematous. Why? Mrs. O'Leary is given a compression sleeve to wear on this arm to help relieve the edema. Which of the pressures driving bulk flow at the capillaries will be altered by the compression sleeve?

AT THE CLINIC

Related Clinical Terms

Aneurysm (an′u-rizm; *aneurysm* = a widening) A balloonlike outpocketing of an artery wall that places the artery at risk for rupture; most often reflects gradual weakening of the artery by chronic hypertension or atherosclerosis. The most common sites of aneurysms are the abdominal aorta and arteries feeding the brain and kidneys.

Angiogram (an′je-o-gram″; *angio* = a vessel; *gram* = writing) Diagnostic technique involving the infusion of a radiopaque substance into the circulation for X-ray examination of specific blood vessels. The major technique for diagnosing coronary artery occlusion and risk of a heart attack.

Diuretic (*diure* = urinate) A chemical that promotes urine formation, thus reducing blood volume. Diuretic drugs are frequently prescribed to manage hypertension.

Phlebitis (flĕ-bi′tis; *phleb* = vein; *itis* = inflammation) Inflammation of a vein accompanied by painful throbbing and redness of the skin over the inflamed vessel. It is most often caused by bacterial infection or local physical trauma.

Phlebotomy (flĕ-bot′o-me; *tomy* = cut) A venous incision or puncture made for the purpose of withdrawing blood or bloodletting.

Sclerotherapy Procedure for removing varicose or spider veins. Tiny needles are used to inject hardening agents into the abnormal vein. The vein scars, closes down, and is absorbed by the body.

Thrombophlebitis Condition of undesirable intravascular clotting initiated by a roughened venous lining; often follows severe episodes of phlebitis. An ever-present danger is that the clot may detach and form an embolus.

Case Study Cardiovascular System: Blood Vessels

Mr. Hutchinson, another middle-aged victim of the collision on Route 91, has a tourniquet around his thigh when admitted in an unconscious state to Noble Hospital. The emergency technician who brings him in states that his right lower limb was pinned beneath the bus for at least 30 minutes. He is immediately scheduled for surgery. Admission notes include the following:

- Multiple contusions of lower limbs
- Compound fracture of the right tibia; bone ends covered with sterile gauze
- Right leg blanched and cold, no pulse
- Blood pressure 90/48; pulse 140/min and thready; patient diaphoretic (sweaty)

1. Relative to what you have learned about tissue requirements for oxygen, what is the condition of the tissues in the right lower limb?
2. Will the fracture be attended to, or will Mr. Hutchinson's other homeostatic needs take precedence? Explain your answer choice and predict his surgical treatment.
3. What do you conclude regarding Mr. Hutchinson's cardiovascular measurements (pulse and BP), and what measures do you expect will be taken to remedy the situation before commencing surgery?

(Answers in Appendix H)