15

Overview of Circulation

LEARNING OBJECTIVES

Upon completion of this chapter, the student should be able to answer the following questions:

1. How does the arrangement of heart and vessels enable unidirectional flow of well-oxygenated blood to the body?
2. How do the differing compositions (smooth muscle, fibrous and elastic tissue) of blood vessels contribute to their respective functions?
3. How does the blood pressure change throughout the circulatory system? How do these changes arise, and what is their general importance in cardiovascular function?
4. How does total cross-sectional area of the systemic vascular system change, and what is the significance of this?

The circulatory system transports and distributes essential substances to tissues and removes metabolic by-products. This system also participates in homeostatic mechanisms such as regulation of body temperature, maintenance of fluid balance, and adjustment of O_2 and nutrient supply in various physiological states. The cardiovascular system, which accomplishes these tasks, is composed of a pump (the heart), a series of distributing and collecting tubes (blood vessels), and an extensive system of thin vessels (capillaries) that enable rapid exchange between the tissues and vascular channels. Blood vessels throughout the body are filled with a heterogeneous fluid (blood) that is essential for the transport processes performed by the heart and blood vessels. This chapter is a general, functional overview of the heart and blood vessels, whose functions are analyzed in much greater detail in subsequent chapters.

The Heart

The heart consists of two pumps in series: one pump propels blood through the lungs for exchange of O_2 and CO_2 (the **pulmonary circulation**) and the other pump propels blood to all other tissues of the body (the **systemic circulation**). Flow of blood through the heart is in one direction (unidirectional). Unidirectional flow through the heart is achieved by the appropriate arrangement of flap valves. Although cardiac output is intermittent, continuous flow to body tissues (periphery) occurs by distention of the aorta and its branches during ventricular contraction **(systole)** and by elastic recoil of the walls of the large arteries with forward propulsion of the blood during ventricular relaxation **(diastole).**

The Cardiovascular Circuit

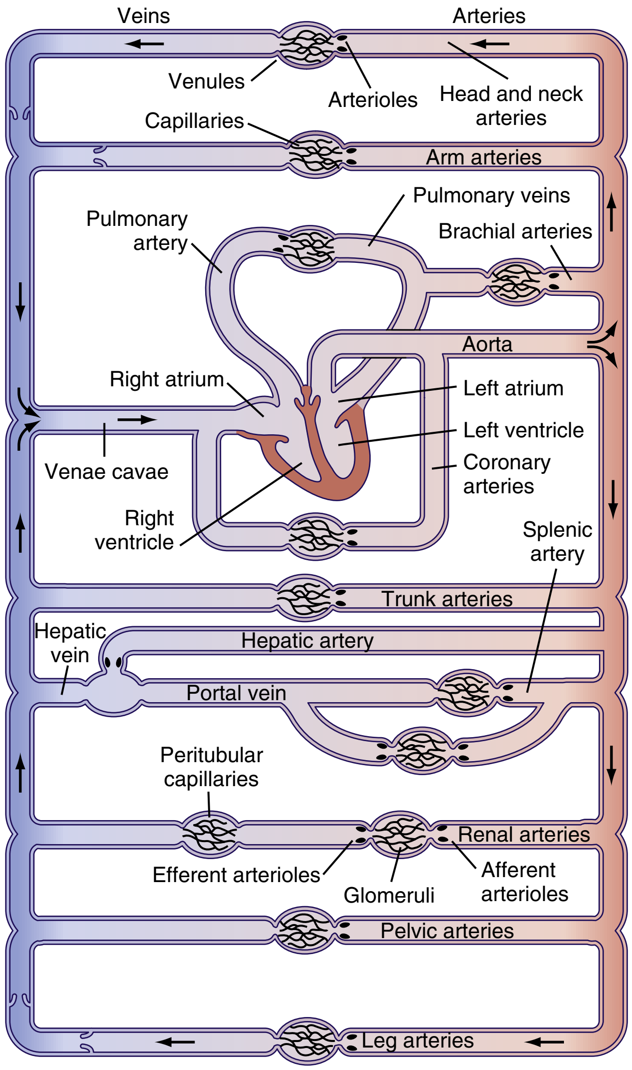
In the normal intact circulation, the total volume of blood is constant, and an increase in the volume of blood in one area must be accompanied by a decrease in another. However, the distribution of blood circulating to the different regions of the body is determined by the output of the left ventricle and by the contractile state of the resistance vessels (arterioles) of these regions. The circulatory system is composed of conduits arranged in series and in parallel (Fig. 15.1). This arrangement, which is discussed in subsequent chapters, has important implications in terms of resistance, flow, and pressure in blood vessels.

Blood entering the right ventricle via the right atrium is pumped through the pulmonary arterial system at a mean pressure about one-seventh that in the systemic arteries. The blood then passes through the lung capillaries, in which CO_2 in the blood is released and O_2 is taken up. The O_2-rich blood returns via the pulmonary veins to the left atrium, where it is pumped from the powerful left ventricle into the aorta and on to the systemic blood vessels, which thus completes the cycle.

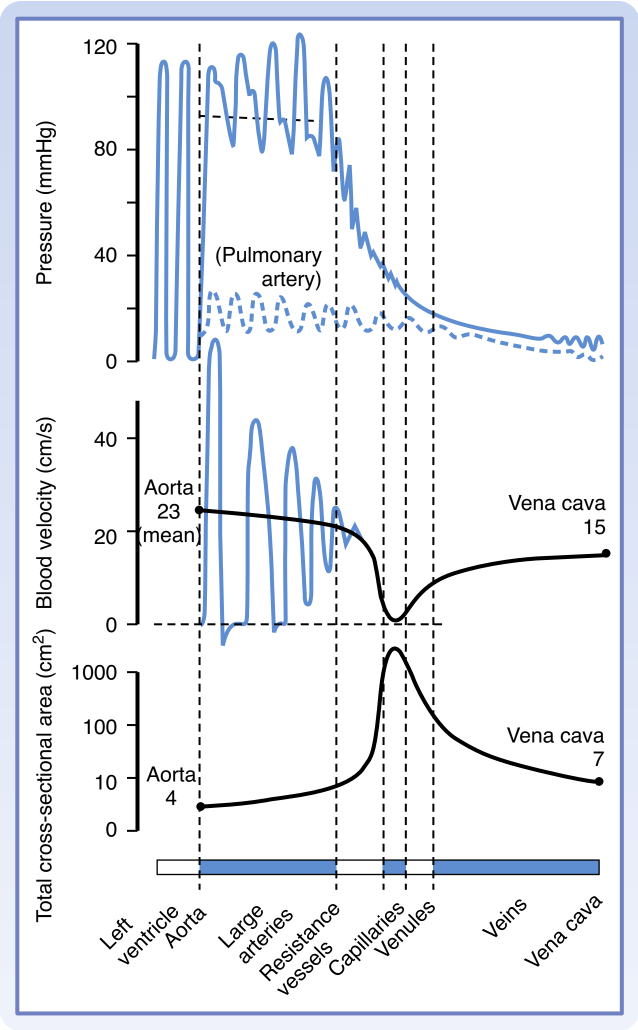
Blood Vessels

Blood moves rapidly through the aorta and its arterial branches. As these branches approach the periphery, the branches narrow, and their walls become thinner. The relative proportions of elastic tissue, smooth muscle, and fibrous tissue (largely collagen) change in each type of blood vessel, conferring significantly different physical and physiological properties on them. The aorta is a predominantly elastic structure, but the peripheral arteries become more muscular until, at the arterioles, the muscular layer predominates (Fig. 15.2).

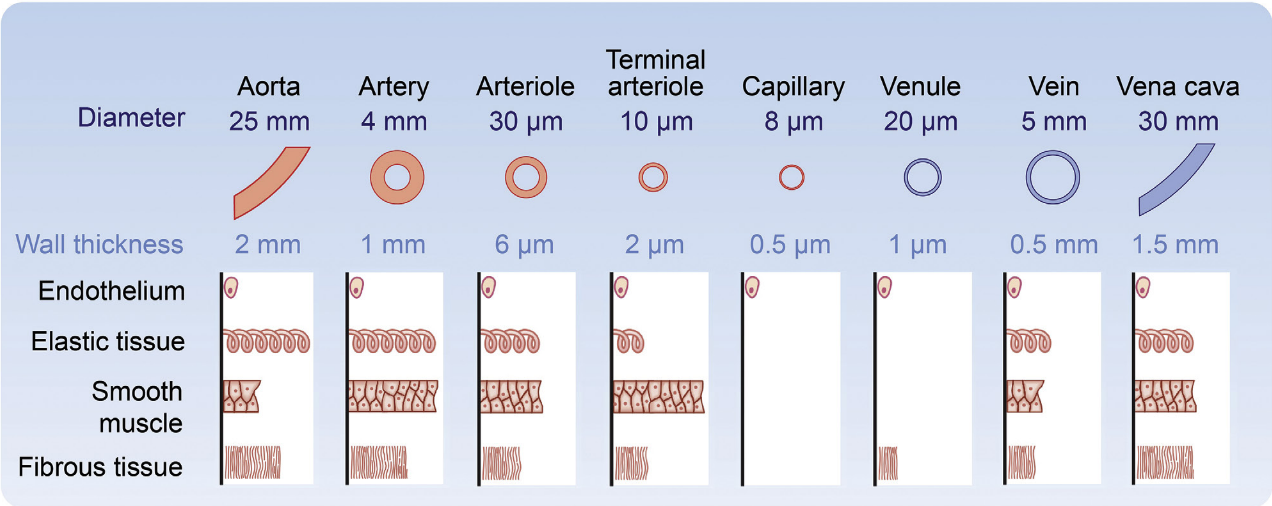
In the large arteries, frictional resistance is relatively small, and pressures are only slightly less than those in the aorta. The small arteries, on the other hand, offer moderate resistance to blood flow. This resistance reaches a maximal level in the arterioles, which are sometimes referred to as the "stopcocks" of the vascular system. Hence, the pressure "drop" (*viz.*, the decrease in pressure) is greatest across the terminal segment of the small arteries and the arterioles (Fig. 15.3). Adjustment in the degree of contraction of the circular muscle of these small vessels allows regulation of tissue blood flow and aids in the control of arterial blood pressure.



• **Fig. 15.1** Schematic diagram of the parallel and series arrangement of the vessels that constitute the circulatory system. The capillary beds are represented by *thin lines* connecting the arteries (on the right) with the veins (on the left). The *crescent-shaped thickenings* proximal to the capillary beds represent the arterioles (resistance vessels). (Redrawn from Green HD. In: Glasser O, ed. *Medical Physics.* Vol 1. Chicago: Year Book; 1944.)



• **Fig. 15.3** Phasic pressure, velocity of flow, and cross-sectional area of the systemic circulation. The important features are the major pressure drop across the small arteries and arterioles, the inverse relationship between blood flow velocity and cross-sectional area, and the maximal cross-sectional area and minimal flow rate in the capillaries. (From Levick JR. *An Introduction to Cardiovascular Physiology.* 5th ed. London: Hodder Arnold; 2010.)



• **Fig. 15.2** Internal diameter, wall thickness, and relative amounts of the principal components of the vessel walls of the various blood vessels that constitute the circulatory system. Cross-sections of the vessels are not drawn to scale because of the huge range in size from aorta and venae cavae to capillary. (Redrawn from Burton AC. Relation of structure to function of the tissues of the wall of blood vessels. *Physiol Rev.* 1954;34:619.)

In addition to the reduction in pressure along the arterioles, there is a change from pulsatile to steady blood flow (see Fig. 15.3). Pulsatile arterial blood flow, caused by the intermittent ejection of blood from the heart, is damped at the capillary level by the distensibility and elasticity of the large arteries combined with the higher frictional resistance to blood flow in the small arteries and arterioles.

The human body contains an estimated 10 billion capillaries, with many capillaries arising from every arteriole. Thus, the total cross-sectional area of the capillary bed is very large despite the fact that the cross-sectional area of each capillary is less than that of each arteriole. As a result, blood flow velocity becomes quite slow in the capillaries (see Fig. 15.3), which is analogous to the decrease in velocity of flow in the wide regions of a river. Because of the low blood flow velocity, and because capillaries consist of short tubes with walls that are only one cell thick, the conditions in the capillaries are ideal for the exchange of diffusible substances between blood and tissue.

On its return to the heart from the capillaries, blood passes through venules and then through veins of increasing size. Pressure within these vessels progressively decreases until the blood reaches the right atrium (see Fig. 15.3). Near the heart, the number of veins decreases, the thickness and composition of the vein walls change (see Fig. 15.2), the total cross-sectional area of the venous channels diminishes, and the velocity of blood flow increases (see Fig. 15.3). The velocity of blood flow and the cross-sectional area at each level of the vasculature are essentially mirror images (see Fig. 15.3).

Data from humans (Table 15.1) indicate that between the aorta and the capillaries, the total cross-sectional area increases about 500-fold. The volume of blood in the systemic vascular system is greatest in the veins and venules (64%). Only 6% of total blood volume exists in the capillaries, and 14% of total blood volume is found in the aorta, arteries, and arterioles. In contrast, blood volume in the pulmonary vascular bed is about equally divided among the arterial, capillary, and venous vessels. The cross-sectional area of the venae cavae is larger than that of the aorta. Therefore, the velocity of flow is slower in the venae cavae than in the aorta (see Fig. 15.3).

TABLE 15.1 Distribution of Blood Volume*

Location	Absolute Volume (mL)	Relative Volume (%)
Systemic Circulation		
Aorta and large arteries	300	6.0
Small arteries	400	8.0
Capillaries	300	6.0
Small veins	2300	46.0
Large veins	900	18.0
Total	4200	84.0
Pulmonary Circulation		
Arteries	130	2.6
Capillaries	110	2.2
Veins	200	4.0
Total	440	8.8
Heart (End-Diastole)	360	7.2
Total	5000	100

*Values refer to a 70-kg woman.

Data from Boron WF, Boulpaep EL. *Medical Physiology.* 2nd ed. Philadelphia: Elsevier Saunders; 2009.

IN THE CLINIC

In a patient with hyperthyroidism **(Graves' disease),** basal metabolism is elevated and often associated with arteriolar vasodilation. This reduction in arteriolar resistance diminishes the damping effect on pulsatile arterial pressure and is manifested as pulsatile flow in the capillaries, as observed in the fingernail beds of patients with this ailment.

Key Points

1. The circulatory system consists of a pump (the heart), a series of distributing and collecting tubes (blood vessels), and an extensive system of thin vessels (capillaries) that enable rapid exchange of substances between tissues and blood.
2. After arterial blood pressure is elevated by contraction of the left ventricle, little decrease ("drop") in average, or mean, pressure occurs in the system of large arteries. This ensures the constant availability of adequate pressure to drive flow in all tissues. The resistance to blood flow and hence the pressure drop in the arterial system are greatest at the level of the small arteries and arterioles.
3. Pulsatile pressure is progressively damped by the elasticity of the arterial walls and the frictional resistance of the small arteries and arterioles in such a way that capillary blood flow is essentially non-pulsatile.
4. Blood flow to the capillary beds of particular tissues, which is a primary determinant of oxygen delivery, is regulated by the "stopcocks" of the circulation, the precapillary sphincters, terminal arterioles, and terminal regions of small arteries.