# Chapter 2
# Introduction to Cardiovascular Biomechanics

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**Learning outcomes**

1. Describe the main components of the cardiovascular system.
2. Describe the organisation of the cardiovascular system into pulmonary and systemic circulations.
3. Describe the main functions of the cardiovascular system.
4. Describe the change in relevant physical quantities in different vessels of the circulation.
5. Discuss the control of blood pressure in capillaries.

This chapter will explore the biomechanics of the cardiovascular system as a whole. Other chapters discuss in more detail the biomechanics of cardiovascular system components, including the heart, arteries, veins and the microcirculation.

## 2.1 Components and Function

### 2.1.1 Organisation of the Cardiovascular System

The human cardiovascular system is illustrated in Fig. 2.1. This shows two sub-systems; the systemic circulation and the pulmonary circulation. The pulmonary circulation is concerned with obtaining oxygen from the lungs, as well as discharging carbon dioxide (a waste product of metabolism) from the blood into the alveoli of the lungs where it can be breathed out. Blood is ejected from the right ventricle into the pulmonary artery and returns to the left atrium via the pulmonary veins. The systemic circulation transports oxygenated blood to the rest of the body,

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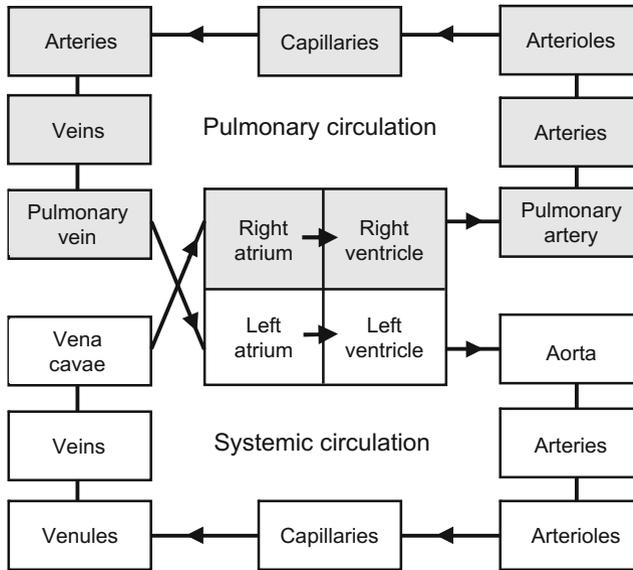e-mail: P.Hoskins@ed.ac.uk

**Fig. 2.1** Components of the cardiovascular system; systemic circulation is shown in *white*, pulmonary circulation in *grey*

returning deoxygenated blood via the veins. Blood is ejected from the left ventricle into the aorta, the largest artery in the body and returns via two large veins (the inferior and superior vena cava) to the right atrium.

## 2.1.2  Components of the Cardiovascular System

**Heart**
The structure of the heart is illustrated in Fig. 2.2. The heart has two main phases; a contraction phase when blood is ejected from the left and right ventricles, and a relaxation phase when the chambers fill with blood returning via the venous system. The heart valves prevent backflow and operate in a passive manner associated with pressure differences. During ejection, the aortic and pulmonary valves are open and the tricuspid and mitral valves closed. During filling, the aortic and pulmonary valves are closed and the other two valves are open. The left ventricle ejects blood into the relatively high-pressure systemic system, hence has a much thicker wall then the right ventricle, which ejects blood into the low-pressure pulmonary system.

**Composition of vessels**
The vessels are composed of three layers, as shown in Fig. 2.3. These layers are:

- *Adventitia*. The outermost layer, primarily consisting of collagen fibres layered in a spiral fashion.
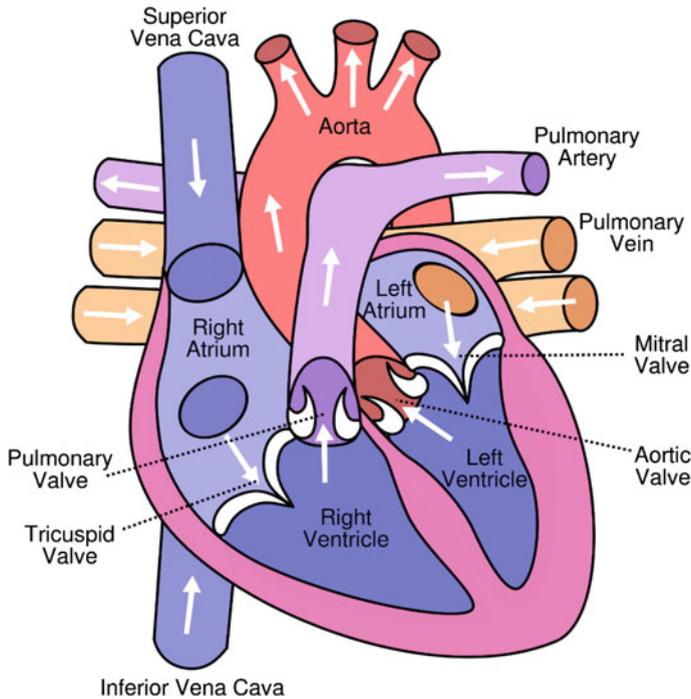
**Fig. 2.2** Principal components of the heart. Reproduced from Wikipedia according to the GNU Free Documentation License; diagram authored by Wapcaplet and Yaddah. https://commons. wikimedia.org/wiki/File:Diagram_of_the_human_heart_(cropped).svg

- *Media*. A layer consisting of smooth muscle, elastin sheets (layered circumferentially) and collagen fibres.
- *Intima*. The innermost layer consisting of a single layer of endothelial cells. These line the lumen, and hence are in contact with flowing blood. There is also a basement membrane immediately beneath the endothelium.

From a mechanical perspective, the two main constituents of the vessel wall are elastin and collagen. These are considered further in Chap. 4. Elastin is highly deformable with a low Young's modulus whilst collagen has a nonlinear behaviour with high values of Young's modulus and a high breaking strength. The ratio of elastin to collagen is the principal determinant of the overall elastic behaviour of a vessel. If the ratio is high, the vessel is elastic and deforms under increasing pressure. If the ratio is low, the vessel does not deform much under pressure.

**Types of vessel**
The vessels shown in Fig. 2.3 can be grouped and are described in this section. The microscopic structures of the different types of vessel are closely linked to the vessel's specific function.
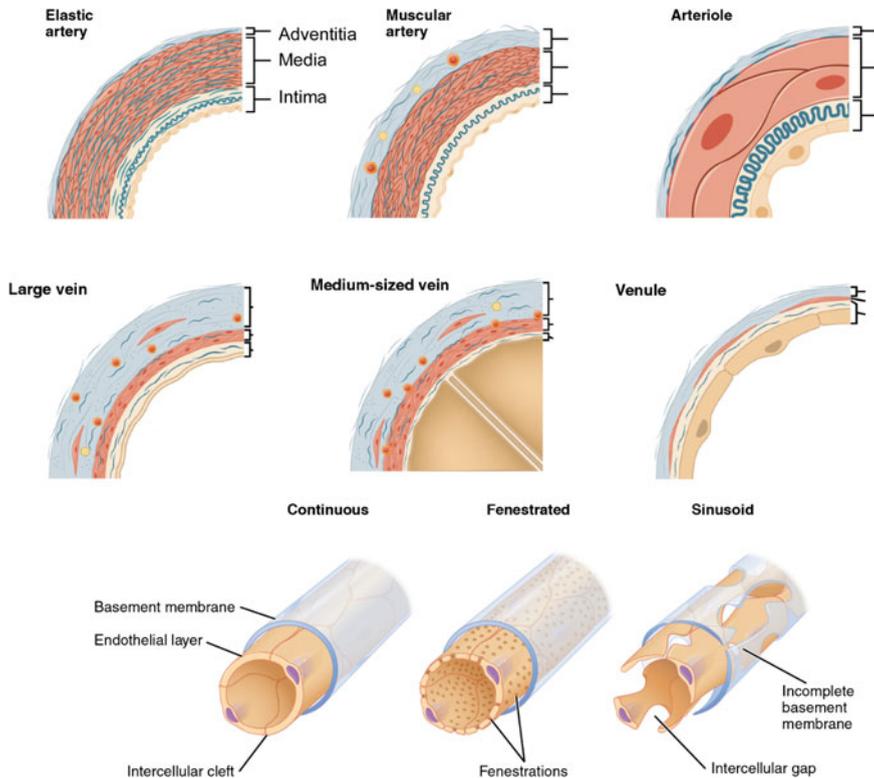
**Fig. 2.3** Principal components of vessel wall. Note that vessel curvature is not to scale. Images reproduced from 'Structure and function of blood vessels' Openstar; under a creative commons licence http://creativecommons.org/licenses/by/3.0/legalcode. Download for free at http://cnx.org/contents/58db2cce-b3d9-4904-9049-80a6cd89264b@4

- *Arteries (diameter 1–30 mm).* Arteries carry blood away from the heart. Systemic arteries must withstand relatively high pressures and so have thick walls consisting of the three basic layers described earlier. Arteries are sub-categorised, on the basis of their wall composition, into elastic and muscular arteries. Elastic arteries such as the aorta and its major branches are low resistance vessels and have a high elastin/collagen ratio. The high elastin content results in high distensibility. This allows them to accommodate the volume of blood ejected from the heart and also enables the storage of energy. More distal arteries, such those supplying the organs and those in the leg and arms, are muscular in nature. Muscular arteries have a thicker medial layer which has less elastin and more smooth muscle than that of elastic arteries. These vessels are also known as distributive arteries.
- *Arterioles (diameter 10–100 μm).* Arterioles have all three layers (adventitia, media and intima) but of much reduced thickness compared to arteries.

Proportionally, the thickness of the media is large consisting mainly of smooth muscle cells. These enable the lumen size to be controlled over a wide range. Constriction and dilatation of the arterioles controls the flow to capillaries. Diameter ranges from 100 μm to around 10 μm for the smallest (terminal) arterioles.

- *Capillaries (diameter 4–40 μm).* These have a very thin wall consisting of only endothelium and basement membrane. There are three types of capillary. The most common are the continuous capillaries; these are found in skin and muscle. Whilst the endothelial cells of these capillaries are closely coupled by tight junctions, small gaps are present which control the passage of fluids and small molecules. Fenestrated capillaries have pores (fenestrations), which give greater permeability to fluids and allow certain small molecules to pass through. They are found in the intestine and kidney. Sinusoidal capillaries are the least common and have large gaps allowing greater volume of materials to pass through. These are found in the liver, spleen and endocrine glands, for example. The diameter of continuous and fenestrated capillaries is in the range 4–10 μm, however sinusoidal capillaries can have much larger diameters of up to 40 μm. Capillaries are around one mm in length.
- *Venules (diameter 10–200 μm).* These have all three layers but are much thinner than arterioles with an almost absent medial layer.
- *Veins (diameter 1–25 mm).* Veins return the blood to the heart. The venous system has a much lower pressure than the arterial system and consequently the wall thickness of veins is much less than that of arteries. Intermediate sized veins contain valves, which prevent backflow of blood. Larger veins including the vena cava do not. The adventitial layer is thicker than the medial layer and the elastin/collagen ratio is small compared to arteries. This makes veins relatively stiff when fully distended, but when veins are under low or negative pressure they may collapse.

### 2.1.3  Functions of the Cardiovascular System

The cardiovascular system has several functions; transport of molecules, defence and healing, thermoregulation and maintenance of fluid balance between different tissues in the body.

*Transport of molecules* The cardiovascular system transports molecules from one vascular bed to another. Entry and exit of molecules into the cardiovascular system occurs through the walls of the capillaries. For example, oxygen is transported from the pulmonary vascular bed to vascular beds all over the body where oxygen is needed for metabolism. Carbon dioxide is a waste product of metabolism and is made in tissues all over the body. Carbon dioxide is transported from vascular beds to the lungs, where it is discharged into the alveoli. Glucose, amino acids, vitamins and minerals are discharged into the blood from the vascular beds of the

gastrointestinal tract. As far as transport of molecules is concerned, the function of the rest of the cardiovascular system is to provide passage of molecules from one capillary bed to another.

*Defence and healing* The cardiovascular system has two main safety systems; the immune system and the tissue repair system. These systems involve particles transported in blood, especially white cells, platelets and macromolecules such as fibrinogen.

*Thermoregulation* In order to help maintain a constant core body temperature of 37 °C, the amount of blood flowing close to the skin surface can be controlled. Under normal conditions, only some 4 % of blood flows near the skin, however, this can be increased to almost half of the cardiac output under conditions of excessive heat. Combined with sweating, the aim is to remove heat from the body.

*Fluid balance* Fluid in the body is partitioned between fluid within cells (intra-cellular fluid) and fluid outside the cells (extracellular fluid). Extracellular fluid consists of the fluid between cells (interstitial fluid), blood (in the cardiovascular system) and lymph (in the lymphatic system). These volumes need to keep within a narrow range and also their electrolyte concentration needs to be kept within a narrow range. The cardiovascular system has a major role in control of these fluid volumes and electrolyte concentration.

## 2.2 Physical Quantities

This section discusses basic physical quantities relevant to cardiovascular mechanics. Table 2.1 provides data for the different components of the systemic cardiovascular system. Definitive data covering all quantities for the human is hard to come by. Table 2.1 is based on work by Dawson (2005, 2008). These are data for the human systemic circulation extrapolated (using scaling laws) from data in the dog (Green 1944). A simplified approach is taken in which the main arteries and veins are divided into 3 sizes. For the arteries these are the aorta (the largest artery), arteries of 6 mm diameter which branch from the aorta, and arteries of 2 mm diameter. For the veins, these are veins of 2 mm diameter, veins of 10 mm diameter and the vena cava. These data allow us to explore the change in different physical quantities in the circulation.

### 2.2.1 Dimensions of the Systemic Circulation

The design of the cardiovascular system follows the need for exchange of oxygen and other molecules through capillaries. Oxygen can travel by diffusion over a distance of about 100 μm and, in practice, virtually all cells within the body lie no

**Table 2.1** Values of various physical quantities for the systemic circulation

| Vessel | Diameter (mm) | Length (mm) | Number | Volume (mL) | Cross sectional area (cm$^2$) | Mean velocity (cm s$^{-1}$) | Mean pressure (mmHg) |
|---|---|---|---|---|---|---|---|
| Aorta | 22 | 600 | 1 | 228 | 4 | 25 | 95 |
| Large arteries | 6 | 300 | 40 | 339 | 11 | 8.3 | 93 |
| Small arteries | 2 | 50 | 2400 | 377 | 75 | 1.2 | 87 |
| Arterioles | 0.02 | 3 | $1.1 \times 10^8$ | 104 | 346 | 0.3 | 54 |
| Capillaries | 0.01 | 1 | $3.3 \times 10^9$ | 259 | 2592 | 0.04 | 25 |
| Venules | 0.04 | 3 | $2.2 \times 10^8$ | 829 | 2765 | 0.03 | 7 |
| Small veins | 2 | 50 | 2400 | 377 | 75 | 1.2 | 4 |
| Large veins | 10 | 300 | 40 | 943 | 31 | 3 | 2 |
| Venae cava | 22 | 500[a] | 2 | 228 | 4 | 25 | 0 |

Data is taken and adapted from Dawson (2008). Data on pressure is taken from other sources
[a]Combined length of inferior and superior vena cava

**Fig. 2.4** Vessel diameter for vessels of the systemic circulation (see Table 2.1)
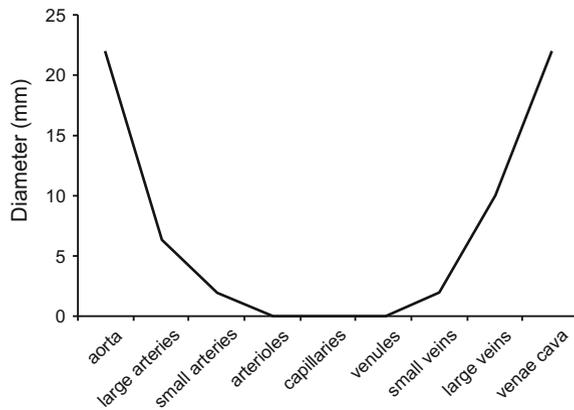


further than 100 μm from a capillary. The systemic cardiovascular system starts with a single vessel, the aorta and progressively divides, increasing the number of vessels and overall cross-sectional area. Beyond the capillary beds the vessels progressively unite, decreasing in number and overall cross-sectional area until there are just two vessels (the inferior and superior vena cava) which then connect back with the heart. Figures 2.4, 2.5 and 2.6 are based on the data in Table 2.1 and show the change in the number, diameter and cross-sectional area for the vessels of the systemic circulation.

**Fig. 2.5** Number of vessels of the systemic circulation (see Table 2.1)
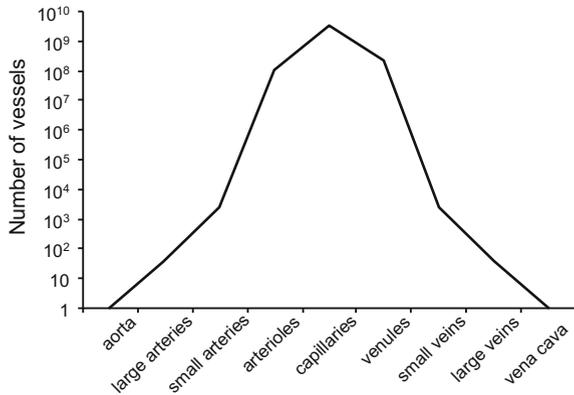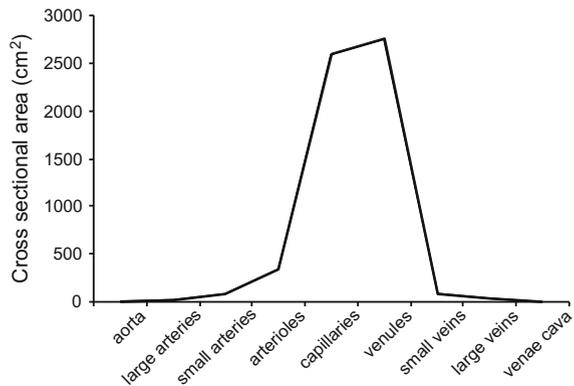


**Fig. 2.6** Total cross-sectional area of vessels of the systemic circulation (see Table 2.1)



The blood volume is not uniformly distributed within the systemic vessels. The venous system contains 65 % of the volume, almost two-thirds, the arterial system contains 28 % and the remaining 7 % is in capillaries.

## 2.2.2 Pressure in the Systemic Circulation

Figure 2.7 illustrates the pressure in the vessels of the systemic circulation. The heart ejects its contents from the left ventricle into the aorta. The aorta expands and the pressure rises. With increasing distance from the heart the pulse pressure (difference between maximum and minimum pressure) increases due to the stiffening of arteries with distance from the heart. Mean pressure falls through the remainder of the cardiovascular system, reaching its lowest value at the entrance to the right atrium. It was thought for many years that pressure (and flow) in the capillaries was steady however (as discussed below and in Chap. 8) there is some pulsatility occurring as a result of
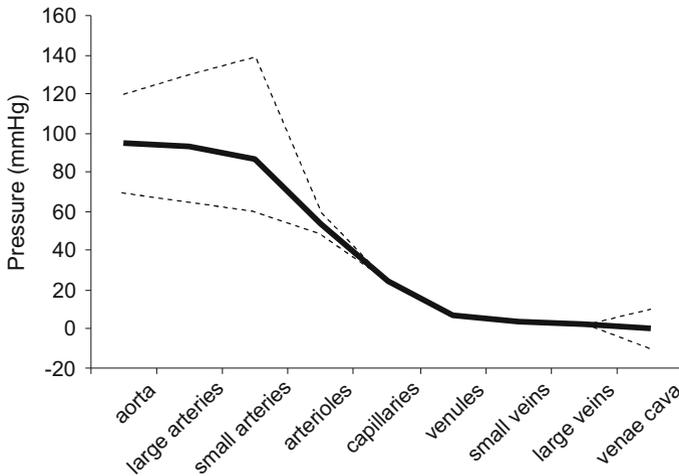
**Fig. 2.7** Mean blood pressure of vessels of the systemic circulation (see Table 2.1). Also shown are the maximum and minimum blood pressure

upstream pressure variation which is transmitted to the capillaries. Pressure in the venules and veins does not vary much, apart from the action of the muscles as discussed in Chap. 7. In veins nearer the heart, especially in the vena cava, pressure will have some variation during the cardiac cycle and, as explained below, is also influenced by pressure changes in the thorax related to breathing.

The pressure gradient in the arteries is caused by the force of ejection of blood into the aorta from the left ventricle. In the venous system, two mechanisms operate to move blood along the veins; the respiratory pump and the musculovenous pump. Breathing in (inspiration) causes an increase in pressure in the abdomen and a reduction in pressure in the thorax. This creates a suction pressure, which sucks blood along the veins towards the heart. This suction effect leads to negative pressures (pressures below zero mmHg) in the larger veins. This negative pressure can give rise to temporary venous collapse (reduction of the cross-sectional area of the vein to zero). The second main mechanism driving blood through the veins is venous compression by the musculature, as a result of walking and general movement. Blood is prevented travelling back along the veins in the limbs by valves which are present at regular intervals.

## 2.2.3 Pressure in Capillaries

Pressure in the capillaries is controlled to a high degree. Water is able to flow freely from blood to tissues through small gaps ('tight junctions') in the endothelium but the net flow rate depends on the balance between the hydrostatic pressure and the colloid
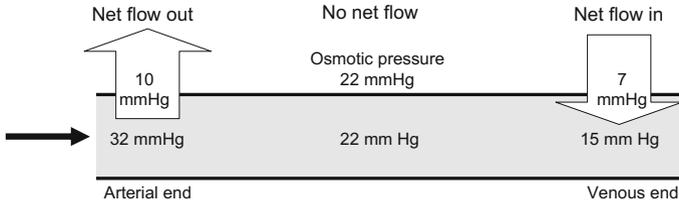
**Fig. 2.8** Pressure and cross-wall flow in the capillary. The net flow across the capillary wall is driven by the balance between blood pressure and osmotic pressure. At the arterial end the blood pressure is greater than the osmotic pressure and there is net flow outwards. At the venous end the blood pressure is less than the osmotic pressure and there is net flow inwards

osmotic pressure within the capillary (Fig. 2.8). At the arterial end of the capillary, there is a net flow of water from the capillary into the tissue whilst at the venous end, there is a net flow of water from the tissue into the capillary. In the absence of a control mechanism, the blood pressure in the capillaries would vary by huge amounts from lying down to standing up, from resting to exercising, and also with fluid intake. One of the principle regulatory functions in the microcirculation is to ensure that, no matter what the body is doing, the pressure in the capillaries is maintained at a level, which exactly balances the colloid osmotic pressure (that is, about 22 mmHg). This means that, from a mechanical point of view, the venous and arterial systems are largely decoupled and can be considered as independent systems.

## 2.2.4   Flow and Velocity in the Systemic Circulation

If it assumed that the circulation is a bifurcating system then the total flow rate at each level in the systemic circulation remains constant. Therefore, as the total cross-sectional area of vessels increases, the mean velocity decreases (Fig. 2.9).



**Fig. 2.9** Mean blood velocity of vessels of the systemic circulation (see Table 2.1)
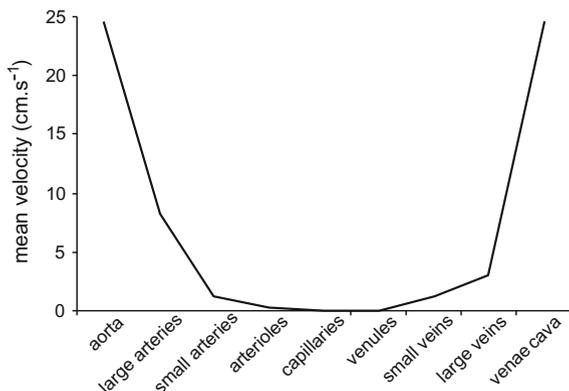
Mean velocity can be measured using a variety of techniques as discussed in later chapters. In order to provide consistency, mean velocity in Table 2.1 has been calculated by assuming a cardiac output of 5.6 L min$^{-1}$ (average for a male) and dividing by the cross-sectional area. This provides values for mean velocity, ranging from 25 cm s$^{-1}$ in the largest vessels, down to 0.3–0.4 mm s$^{-1}$ in the smallest. The assumption of a bifurcating system allows quick estimation of velocities and flow rates, giving values which are reasonably representative of actual velocities and flow rates, even down to the capillary. The blood velocity varies through the cardiac cycle in arteries and arterioles (and to some extent in capillaries) as a result of variation in pressure during the cardiac cycle; this is considered in detail in Chaps. 4 and 8.

# References

Dawson TH. Modeling of vascular networks. J Exp Biol. 2005;208:1687–94.

Dawson TH. Modeling the vascular system and its capillary networks. In: Yim PJ, editor. Vascular hemodynamics: bioengineering and clinical perspectives. New Jersey: John Wiley; 2008. p. 1–35.

Green HD. Circulation: physical principles. In: Glasser O, editor. Medical physics, vol. 1. Chicago: Year-book Publishers; 1944. p. 208–32.