

Chapter 2

The Human Cardiovascular System

2.1 Introduction

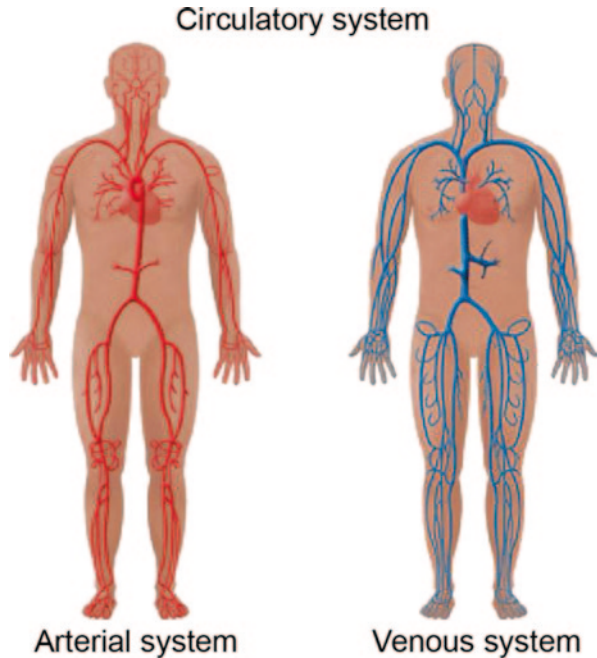
Before delving into the computational methods of CHD, this chapter provides a preliminary understanding of the circulatory system from a physiological and functional perspective, as well as related terminologies that will be used in the succeeding chapters. This includes descriptions, locations, geometry, and naming conventions for the relevant anatomy. This facilitates the process of computational reconstruction of the anatomy related to cardiovascular modelling introduced in Chaps. 3 and 4 and establish physiologically correct boundary conditions discussed in Chap. 5. The models arising from this process are linked to haemodynamic analyses that are discussed in Chaps. 7 and 8. Knowledge of the anatomy and its functions provides a smooth transition towards understanding cardiovascular function, and its CHD modelling requirements, while also stimulating interest in the reader after having established the background knowledge.

2.1.1 Functions of the Circulatory System

The circulatory system comprises the cardiovascular system that transports blood, and the lymphatic system that distributes lymph throughout the body. The circulatory system, which is a network of blood vessels that transports nutrients in the form of amino acids, electrolytes, lymph (fluid containing white blood cells), hormones, and oxygenated blood to tissues or organs in the human body. This maintains homeostasis, the immune system, and stabilizes body temperature and pH levels.

The human cardiovascular network is a closed loop system that enables the transport of oxygenated blood to the tissues and organs of the human body and the de-oxygenated blood to the respiratory organs. The heart pumps approximately 5 L of blood through the cardiovascular network to vital organs of the human body, providing nutrients and oxygen that are needed, and then transporting the waste products and harmful chemicals away from them. The cardiovascular system

Fig. 2.1 Vasculature of the human body. Circulation is based on the vascular network system of arteries and veins that is distributed throughout the entire body. Oxygenated blood (*red*) is supplied by the aorta to the rest of the human body by an intricate network of small arteries and arterioles. Deoxygenated blood (*blue*) from these organs is transported via the venules, veins and finally the vena cava back to the heart for oxygenation in the respiratory system

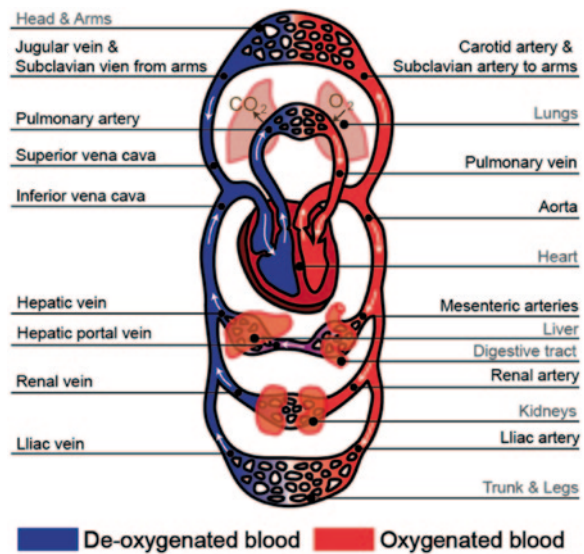


comprises the pulmonary system; the coronary system; and the systemic system. It is common to combine both the pulmonary system with the coronary system to form a system known as the cardiopulmonary system.

The cardiovascular system is an inter-connection of arteries and veins that branch at multiple levels to reach all parts of the human body via an intricate network of vessels (Fig. 2.1). Functionally there are the arterial and venous networks that supply oxygenated and return de-oxygenated blood respectively. Blood circulation is achieved by the vascular system such that oxygenated blood (represented in red) is transported from the heart via the aorta to all parts of the body. The de-oxygenated blood (represented in blue) results after oxygen is depleted from the blood and used by the cells to produce energy and waste within the body. As illustrated, oxygenation and de-oxygenation occurs at designated tissues and organs in the system of vascular networks. In CHD modelling we focus primarily on this system. Cardiac health issues arise when this system fails transport the blood through the network.

The lymphatic system is made up of lymph vessels and nodes forming an open network of intricate tubes to transport lymph throughout the body, thus acting as the secondary circulatory system. As it moves through the body it maintains fluid levels in the body and filters out bacteria by collects waste products and disposes them through certain organs in the body such as the bladder, bowel, lungs, and skin. A major difference between the cardiovascular and the lymphatic system is that the latter does not have a pump (e.g. heart) to move the lymph and instead relies on muscle contractions and gravity to move it through the body.

Fig. 2.2 The cardiovascular system. Gas exchange takes place in the lungs that oxygenate the blood by diffusion of oxygen into the blood stream through the alveoli. The oxygenated blood is then returned via the vena cava back to the heart, and is then transported around the body to the organs. To move the blood around the body through the organs and lungs, the heart acts as the central pump for the entire cardiovascular system



2.1.2 Organization of the Cardiovascular System

The cardiovascular system can be sub-categorised further into the pulmonary, systemic circulation, and coronary circulation (Fig. 2.2) based on the routes that the blood takes (i.e. circulates). The *pulmonary circulation*, as its name suggests, involves blood transfer to and from the heart and lung. In this circulation, deoxygenated blood is transported to the lungs and freshly oxygenated blood is taken back to the left side of the heart. The *systemic circulation*, deals with the whole body and the heart whereby oxygenated blood is circulated to the tissues and deoxygenated blood returns to the right side of the heart. The *coronary circulation* involves the blood that circulates in the heart itself.

2.1.2.1 Pulmonary Circulation

When blood is deprived of oxygen and contains waste materials, such as carbon dioxide the de-oxygenated blood enters via two large veins called the *vena cavae* into the right atrium of the heart (lower chamber), which then contracts (systole) and pushes the blood into the right ventricle (upper chamber) via the tricuspid valve (right atrioventricular valve). The right ventricle then contracts forcing the fluid out via the pulmonary semilunar valve into the pulmonary artery and into the lungs, whereby gas exchange occurs (Fig. 2.3).

The oxygenated blood is then returned to the left atrium via the pulmonary vein, which is pumped into the left ventricle of the heart and expelled through the aorta, the largest artery in the body (to withstand the high pressures), to the other portions of the body. There are a series of valves within the heart and within the

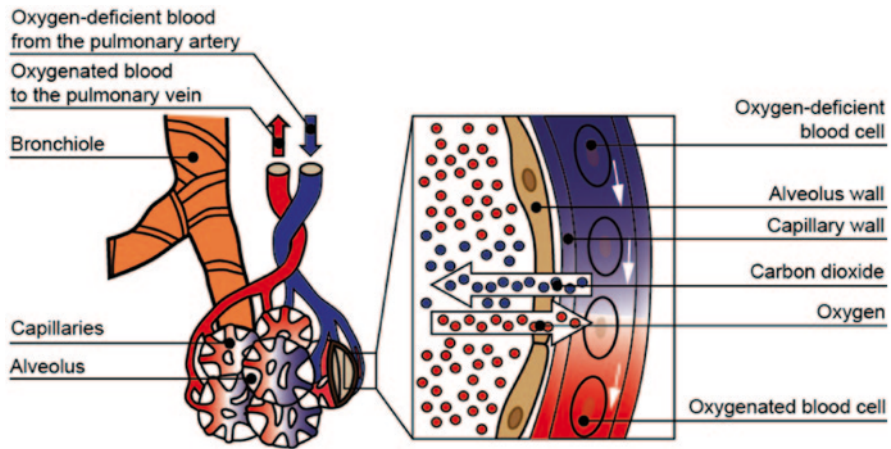


Fig. 2.3 Oxygen and carbon dioxide gas exchange. During breathing, gas exchange takes place in the alveoli where oxygen is passed into the bloodstream while carbon dioxide and other waste products are expelled. In the pulmonary circulatory system, the pulmonary artery is responsible for transporting de-oxygenated blood away from the heart to the lungs. The pulmonary vein transports oxygenated blood back to the heart. The oxygenation and de-oxygenation processes take place simultaneously at the alveolar-capillary interface in the deep lung airways

veins around the body that prevent backflow from occurring by sealing off the vessels when the heart is expanding (diastole), causing a lower pressure upstream.

2.1.2.2 Systemic Circulation

High pressure is exerted on the blood as it is squeezed out of the aorta in the left ventricle to pass through to the whole body. Within this flow, the blood will absorb nutrients attained from the digestion, which is then used to provide fuel for energy and storage. The waste are taken away through the liver and then expelled from the body. The vessel walls are smooth enough to allow for ease of flow and strong enough to withstand the high pressure of the flow. Eventually, the de-oxygenated blood carrying the waste product is returned to the heart. Due to greater distances to be transported, the left ventricle muscle is stronger and provides the blood with sufficient pressure to circulate it further.

2.1.2.3 Coronary Circulation

Oxygenated blood circulates through the heart via the coronary arteries, while deoxygenated blood is taken away to the lungs through the cardiac veins. The coronary circulatory system is very much like the systemic circulatory system in the sense that blood is supplied to the heart but via the coronary arteries. The heart and the

coronary arteries are analogous to the organs of the human body and the cardiovascular network of arteries.

2.2 Physiology of the Cardiovascular System

2.2.1 Anatomy of the Heart

The heart supplies oxygenated blood to the rest of the body and then transports the de-oxygenated blood to the respiratory system for oxygen replenishment (Fig. 2.4). The heart comprises the right ventricle and left atrium, separated by a partition septum. Each half consists of two chambers; a thin-walled atrium and a thick-walled ventricle. The atria receive blood from the veins, while the ventricles pump blood out of the heart and through the circulatory system. The right atrium is the upper right chamber of the heart collecting de-oxygenated blood from the vena cava, and then passes it via the tricuspid valves. This goes into the right ventricle for pumping into the lungs through the pulmonary valve and via the pulmonary artery for oxygenation. The oxygenated blood returns via the pulmonary vein into the left atrium, which then pumps the blood into the left ventricle through the mitral valve. The left ventricle is the strongest chamber of the heart that supplies the oxygenated blood to the rest of the human body via the aorta after passing through the aortic valves. The valves in the tricuspid,

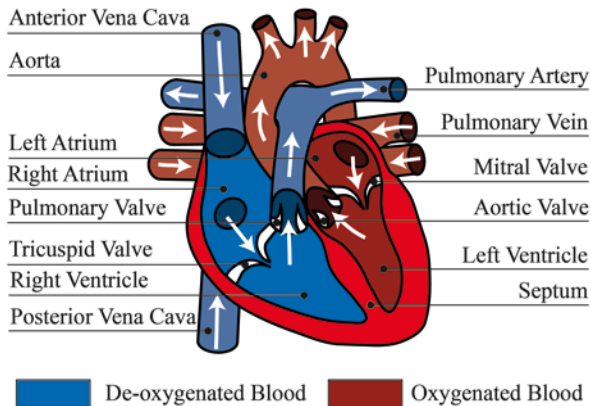
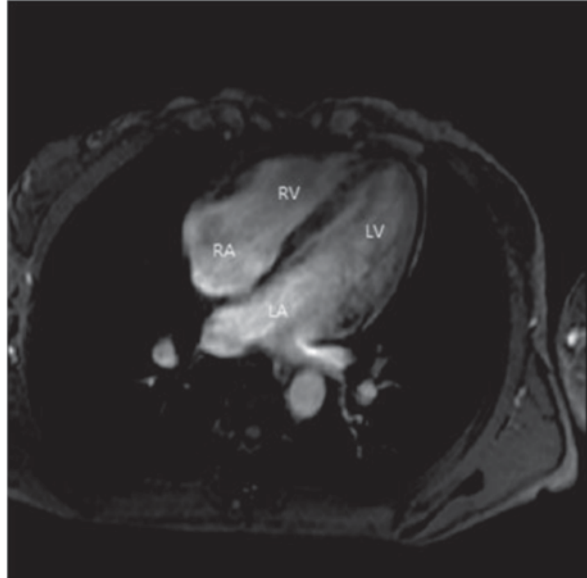


Fig. 2.4 Cardiovascular circulation of the heart. The heart comprises the *left and right atria*, which are responsible for collecting de-oxygenated and oxygenated blood from the vena cava and pulmonary vein respectively. The *right ventricle* is a heart chamber that pumps de-oxygenated blood to the respiratory system, and *left ventricle* is the most muscular chamber that pumps the oxygenated blood to all parts of the body. Heart valves are present at the connections of the atria and ventricles, as well as the pulmonary artery and aorta to achieve a single flow direction circuit. The *white arrows* indicate the direction of blood flow

Fig. 2.5 A magnetic resonance showing how the heart is positioned in a human. The image shows a slice through all the four heart chambers during ventricular filling. The image is seen from the feet so the right side in the picture is the subjects left side. The MR acquisitions were performed at St. Olavs University Hospital, Trondheim. (Image from Dahl 2012)



pulmonary, mitral and aortic valves of the heart ensure that blood flows in the circulatory system effectively without reversing its direction in the circuit.

The magnetic resonance image in Fig. 2.5 shows a slice through all four heart chambers during ventricular filling. The subject is lying supine and the image is seen from the feet which mean that the right side in the picture is the subjects left side. Fig. 2.2 shows the heart situated in the chest cavity in between the two lungs and behind and slightly left of the sternum (breastbone). The narrow end of the heart is called the apex and the broad end is called the base. The apex is pointing downwards and to the left, whereas the base is directed upwards and to the right. The left ventricle, the right ventricle, the left atrium and the right atrium (RA) are indicated in the scanned image.

2.2.2 Cardiac Cycle¹

The sequence of events that occur in the heart during one heart beat is called the cardiac cycle. The events occur nearly simultaneously for both sides of the heart. The typical resting heart rate in adults is 60–90 beats/min (bpm). A physically fit person has a lower heart rate compared to an inactive person. Each heart beat is commonly divided into two main phases: systole and diastole. Systole and diastole are synonymous with contraction and relaxation of a heart muscle, respectively. Both the

¹ Contribution from Dahl, S.K. (2012) Numerical Simulations of Blood Flow in the Left Side of the Heart. PhD Thesis, Norwegian University of Science and Technology.

Blood flow through the heart

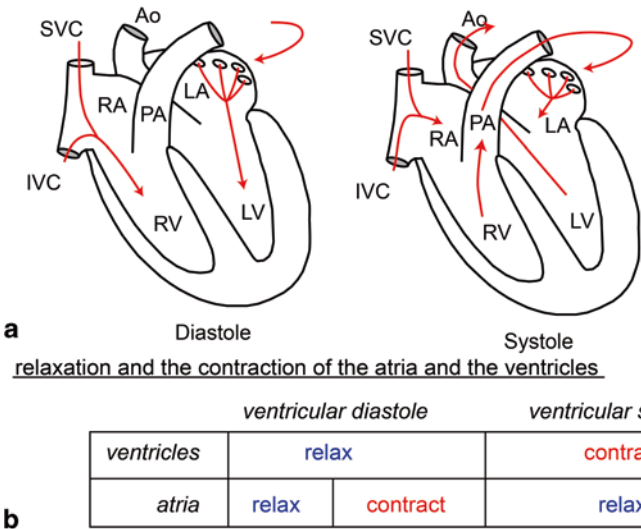


Fig. 2.6 **a** Blood flow through the heart during ventricular diastole and systole (*adapted from Klabunde (2005), cvphysiology.com*). **b** Correspondence between the relaxation and the contraction of the atria and the ventricles with respect to the ventricular diastole and systole

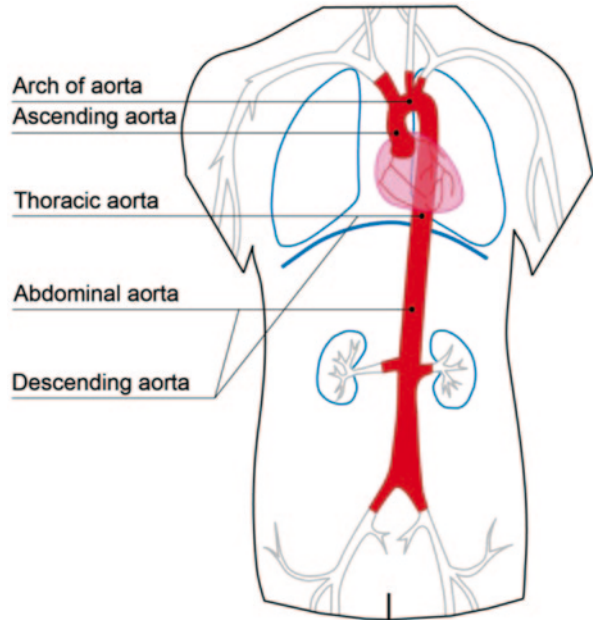
atria and the ventricles go through these two stages every heartbeat, but the terms diastole and systole alone, often refer to the ventricular stages. Figure 2.6 shows how the blood travels through the heart during ventricular diastole and systole and the correspondence between the relaxation and the contraction of the chambers with respect to the ventricular phases.

2.2.3 Physiology of the Aorta

The aorta, which extends from the left ventricle in the upward direction and then channels down towards the abdomen, is the largest and strongest artery in the human body. Oxygenated blood is transported via this artery to the body organs through the systemic circulation. Anatomically, the entire aorta is made up of three main segments: Ascending aorta; Aortic arch; and the Descending aorta (that comprises the Thoracic aorta and the Abdominal aorta), labelled in Fig. 2.7.

The aorta is a heterogeneous combination of smooth muscle, nerves, intimal cells, endothelial cells, fibroblast-like cells, and a complex extracellular matrix. Its wall is made up of several layers—the tunica adventitia, tunica media, and tunica intima, which are mainly composed of collagen giving it stability by helping to anchor it to nearby organs. Once blood is squeezed out from the left ventricle, it transports the high pressure and pulsatile blood to the rest of the body. Being distensible

Fig. 2.7 Segments of the aorta. The components of the aorta are the ascending aorta, aortic arch, and the descending aorta (*that comprises the thoracic aorta, and the abdominal aorta*). The aorta is the largest and strongest artery in the human body and the main channel through which blood is pumped from the left ventricle. A network of vessels is further branched from the aorta to distribute blood to the vital organs



and elastic, the blood pressure decreases in strength and becomes less pulsatile from the aorta to arteries and to capillaries.

The blood spreads from the aorta down to the rest of the arteries which disperse through the body in a branching pattern. This gives rise to the term the arterial tree to describe the branching pattern of all the arteries in the body. The blood travels through the arteries in a pulsatile manner. Reflected waves rebound at bifurcations back to the semilunar valves and the aorta, which create a dicrotic notch in the aortic pressure waveform when they push onto the aortic semilunar valve. This can be visualised in the cardiac cycle profile (Fig. 2.8) which shows a small dip that coincides with the aortic valve closure. This dip is immediately followed by a short rise, referred to as the dicrotic wave, then declines gradually.

As a body ages, the artery stiffens and causes the pulse wave to circulate faster and the reflected waves return to the heart at a higher speed before the semilunar valve closes, and resulting in higher blood pressure. Determining the pulse wave velocity via invasive or non-invasive techniques can assess the arterial stiffness, which is related to the degree of the disease.

2.2.4 Physiology of the Carotid Bifurcation

The carotid bifurcation, which includes the Common Carotid Artery (CCA), External Carotid Artery (ECA) and Internal Carotid Artery (ICA), transports oxygenated

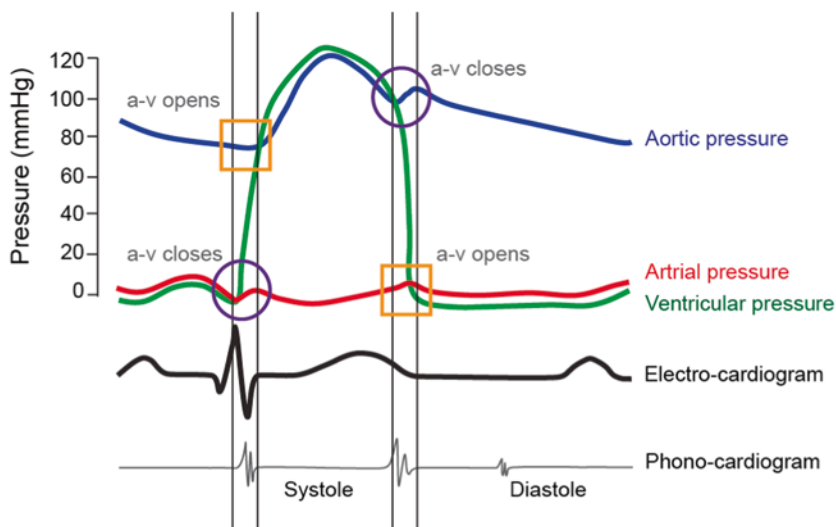


Fig. 2.8 Cardiac cycle events occurring in the *left ventricle*. The *square symbols* represent the aortic valve (a-v) opening while the *circle symbols* represent closing

blood to the head and neck regions (Fig. 2.9). The CCA is the main channel for supplying this oxygenated blood. It commonly exists as a bifurcation from which the ECA and ICA are originated.

The left and right CCA branches out from the aortic arch in the thoracic region and the brachiocephalic artery respectively (Fig. 2.10). This artery, which is also

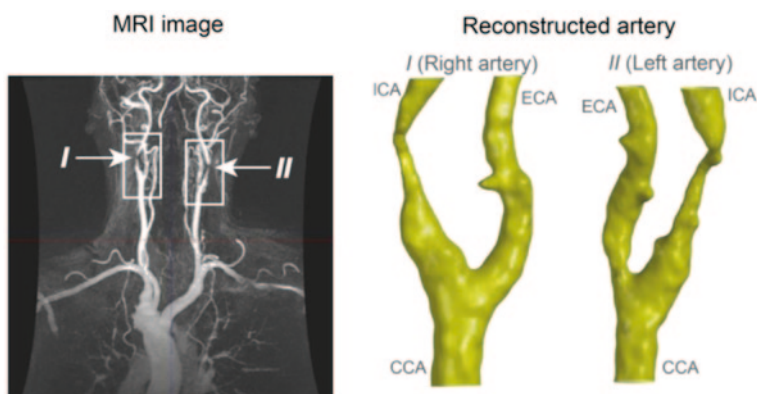
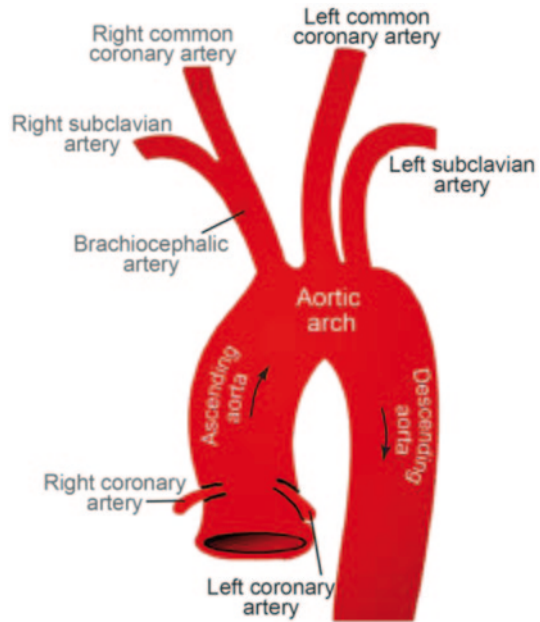


Fig. 2.9 Components of the carotid arterial network. The carotid bifurcation comprises the Common Carotid Artery (CCA), the Internal Carotid Artery (ICA) and the External Carotid Artery (ECA) at the neck and the head. The carotid artery serves the function of supplying oxygenated blood to the cerebral region

Fig. 2.10 Components of the aortic arch. The *right and left* common coronary arteries (CCA) branch from the aortic arch. The *right CCA* extends from the brachiocephalic artery



known as the trunk or innominate artery, extends from the first branch of the aortic arch, and divides into the right common carotid artery and the right subclavian artery. It connects to the mediastinum that supplies blood to the head and neck as well as the right arm.

The ICA and ECA branches supply blood to different organs through arteries at their downstream. In particular, the brain and eyes located at the downstream of ICA branch are the most active and important part of the human body, which consume a high quantity of oxygen and require a high volume of blood supply per unit time. Therefore the blood flow volume through the ICA branch is greater than that of the ECA.

Common Carotid Artery (CCA) The Common Carotid Artery ascends through the superior mediastinum² anterolaterally in the neck and lies medial to the jugular vein³. The two CCA are not symmetrical, with the left artery having greater length than the right artery. This accounts for the longer path from the aortic arch. The carotid artery, jugular vein, and vagus nerve are enclosed in the carotid sheath. The CCA bifurcates into the internal carotid artery and the external carotid artery at the superior border of the thyroid cartilage with inter-individual variations in terms of angle of bifurcation and asymmetry. The diameter of the CCA in adults ranges from 0.2–0.8 cm with an average value of 0.7 cm (Xu 2002).

² The *mediastinum* is the central compartment in the thorax that contains a group of structures that includes the heart, the esophagus, the trachea, and the lymph nodes of the central chest.

³ The *jugular vein* is part of the venous network of vessels that bring deoxygenated blood from the head back to the heart via the superior vena cava (see Fig. 2.2).

Computational Hemodynamics – Theory, Modelling and
Applications

Tu, J.; Inthavong, K.; Wong, K.K.L.

2015, XVI, 351 p. 272 illus., 203 illus. in color.,

Hardcover

ISBN: 978-94-017-9593-7